MICROBUBBLE TREATMENT OF GAS SUPERSATURATED WATER

Contract No. GS-23F-0339K/01PE810319

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December 2001

U.S. Department of Interior
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Gas supersaturation is a result of air mixing with water under pressure and is often caused by rocks and riprap in a river or turbulent conditions such as those occurring near waterfalls or dams. Under these conditions, high pressures can be experienced and air can be entrained into the flow. Research and experience has shown that these supersaturated conditions, specifically high levels of dissolved nitrogen, can result in large fish kills caused by gas bubble disease (GBD). These high dissolved gas levels can also cause problems with irrigation pumps and municipal water treatment plants and intake structures. Reclamation has identified and conducted preliminary testing of a novel patented method for treating gas supersaturated water. The treatment is accomplished by introducing microbubbles that act as collection sites to remove the excess nitrogen. This report summarizes the development activities conducted in fiscal year 2000 and the test and evaluation conducted in fiscal year 2001.

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Mission Statements

U.S. Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Glossary

AFS – American Fisheries Society

BP – Barometric pressure

BuRec – Bureau of Reclamation

cfs – Cubic feet per second

D_p – Pore diameter

DO – Dissolved oxygen

EIS – Environmental impact statement

EPA – Environmental Protection Agency

EPDM – Ethylene propylene diene monomer

FY – Fiscal year

g – Acceleration of gravity

GBD – Gas bubble disease

JHA – Job hazard analysis

NEPA – National Environmental Policy Act

O&M – Operation and Maintenance

P_{H2O} – Vapor pressure of water

PSA – Pressure swing adsorption

PVC – Polyvinyl chloride

R_b – Radius of a microbubble

SOW – Scope of work

SpC – Specific conductivity

S_t – Surface tension

STP –Standard temperature and pressure

T – Temperature

TDG – Total dissolved gas

VSA – Vacuum swing adsorption

USACE – U.S. Army Corps of Engineers

β – Bunsen coefficient for oxygen

ρ_g – Gas density

ρ_l – Liquid density

ΔP – Pressure difference between the total gas pressure and local barometric pressure

EXECUTIVE SUMMARY

Gas supersaturation is a result of air mixing with water under pressure and is often caused by rocks and riprap in a river or turbulent conditions such as those occurring near waterfalls or dams. Under these conditions, high pressures can be experienced and air can be entrained into the flow. Research and experience has shown that these supersaturated conditions, specifically high levels of dissolved nitrogen, can result in large fish kills caused by gas bubble disease (GBD). These high dissolved gas levels can also cause problems with irrigation pumps and municipal water treatment plants and intake structures. Once these supersaturated conditions are created, it may take an extended period of time for the water to return to equilibrium. In an effort to maintain water quality and prevent large fish kills caused from gas-supersaturated water, the U.S. Environmental Protection Agency (EPA) and the State of Washington have established a limit of 110% for total dissolved gases (TDG). This limit has proven to be difficult to meet for several Bureau of Reclamation (BuRec) facilities, including large dams such as Grand Coulee Dam in the Pacific Northwest.

The BuRec has identified and conducted preliminary testing of a novel patented method for treating gas-supersaturated water. The treatment is accomplished by introducing microbubbles that act as collection sites to remove the excess nitrogen. Previous studies, which were conducted as a proof-of-concept, show that this treatment approach works on a small scale in the laboratory. Upon successful proof-of-concept testing, this dissolved gas treatment study was initiated to demonstrate that this novel approach provides an effective and practical solution, which can be easily scaled up to address the problems encountered at Grand Coulee Dam and other BuRec facilities. This report summarizes the development activities conducted in fiscal year 2000 (FY2000) and the test and evaluation conducted in FY2001. Preliminary conclusions and recommendations on future activities are also provided.

Scope of Work

The dissolved gas treatment study has been conducted in two separate phases: 1) development of the process; and 2) test and evaluation of the treatment process. The BuRec Water Treatment Engineering and Research Group conducted the development phase of the project, while the test and evaluation portion was conducted as a combined effort between ARCADIS and BuRec in FY2001. The scope of work (SOW) for each phase of the project included the following activities:

I. Process Development

- Development of methods for generating gas-supersaturated water
- Investigation of methods for generating microbubbles
- Investigation of process efficiency and optimum bubble size
- Conducting preliminary laboratory testing
- Conducting preliminary field testing

II: Test and Evaluation

- Collecting and evaluating additional data from the Columbia River
- Continuing development, testing, and evaluation of modified diffusers
- Identifying and evaluating variables of interest
- Conducting additional lab testing

- Conducting additional field testing
- Evaluating oxygen-enriching techniques
- Preparing preliminary performance and cost models for full-scale system
- Preparing summary report with conclusions and recommendations

Conclusions and Recommendations

The activities outlined in the SOW were successfully executed and indicate the technology has potential for large-scale treatment of gas-supersaturated water. Specific conclusions and recommendations resulting from each phase of the project are presented below.

Treatment Process Development Phase

The objective in the development phase of the project was to develop a means for implementing the treatment and to obtain a better understanding of the principles and fundamental relationships behind microbubble generation. The following conclusions and recommendations are a result of the process development phase of the project.

a. The concept of treating gas-supersaturated water using microbubbles was demonstrated successfully at a field site using modified diffusers and oxygen as the treatment gas. The results provide a 'proof of concept' on a larger scale, and indicate that further work should be conducted to determine if this process would be effective and practical on a scale such as the Columbia River. Additional data relative to efficiency should be evaluated in future tests.

b. Various methods for generating microbubbles were investigated including: 1) hollow-fiber membranes; 2) cylindrical diffusers such as ceramic piping and porous hose; and 3) flat-plate diffusers fabricated from either rubber membranes or ceramic. The diffuser most suitable for this application is the flat-plate ceramic air diffuser. This type of diffuser is capable of generating microbubbles in fairly large quantity without using excessive amounts of gas, and since ceramic is an inert material, the diffuser surface can easily be cleaned with sandpaper or acid.

c. The main variables that determine the bubble size produced by a diffuser are: 1) pore size; 2) surface tension at the gas/water/diffuser interface; and 3) density of the gas. After evaluating these variables in a series of experiments, the project team concluded that controlling the surface tension at the interface provides the best option for optimizing the size of the microbubbles and optimizing the efficiency of the process. Further work needs to be conducted toward characterizing the optimum bubble size in an effort to optimize the treatment process.

d. Diffusers were modified to produce microbubbles that are much smaller than those produced by a standard diffuser. Although this modification is not permanent and results in only a temporary improvement, the reduction in bubble size is considered a significant accomplishment since the efficiency of the dissolved gas treatment was greatly increased. The details of the diffuser modification are currently proprietary, and additional work must be performed to perfect the modification.

e. Oxygen and air were used as treatment gases and compared in the laboratory and at the field-test site. The oxygen appears to generate smaller microbubbles, which provide greater contact time and greater surface area for nitrogen removal. In addition, oxygen microbubbles provide greater nitrogen removal due to the increased concentration gradient between the water and the bubbles. As a result, treatment with oxygen is more effective than air.

Test and Evaluation Phase

The objective of the test and evaluation portion of the project was to determine how effective the technology may be on a small and large scale, and to develop a better understanding of the variables affecting performance and cost. The following conclusions and recommendations are a result of activities conducted in this phase.

a. Previous research conducted on gas supersaturation assumes that naturally dissolved gases always exist in proportions similar to air. However, data collected during the preliminary phase indicates that this is not the case. An evaluation of data collected at various locations along the Columbia River verifies that dissolved gas concentrations are independent of each other and highly dependent on solubility. Therefore, it is possible to be supersaturated in only one gas.

b. The causes of GBD were investigated further to confirm that the results of the treatment would reduce fish kills. The following conclusions were a result of this process:

   - Since nitrogen has a smaller molecular weight than oxygen, it is passed across the gas-permeable membranes (i.e. eyes, gills, fins, etc.) much easier
   - TDG (or differential pressure) and individual gas concentrations are the driving forces behind the diffusion of the gas across the membrane tissue

c. Variables affecting the solubility of gases and the performance of the treatment were identified and evaluated. These variables include dissolved gas concentrations, ambient conditions (water temperature, salinity, barometric pressure), river conditions (flowrate, velocity, depth, turbulence), and treatment variables (diffuser area, diffuser properties, treatment gas flowrate, and treatment gas properties). Relationships of these variables were determined and are presented in detail in the report.

d. To determine how dissolved oxygen (DO) concentrations affect the treatment effectiveness, similar tests were conducted at two field locations with different DO levels. Evaluation of the test results indicates that the treatment is more effective in reducing dissolved nitrogen in a high DO environment, and more effective in reducing TDG in a low DO environment.

e. Although it was previously assumed that the relationship between diffuser area and the effectiveness of the treatment is linear (i.e. doubling diffuser area should double the gas removal), field tests were conducted at both locations to verify this relationship. Evaluation of the results indicates that removal of nitrogen is fairly linear, however the data were inconclusive relative to TDG removal. Additional data must be collected in the future.

f. Gas flowrate is a critical variable in determining the practicality of the technology. It has a significant impact on energy consumption and capital and operation and maintenance (O&M) costs of the system. To determine the effect of gas flowrate, field tests were conducted at different flowrates, and performance was monitored. The results show that the amount of excess nitrogen removed was fairly constant, while the TDG removal decreased with a higher gas flowrate. This indicates that a lower flowrate is more effective. This is encouraging relative to energy consumption. Most likely, the higher flowrates are less effective due to the generation of larger microbubbles, which decreases the effective surface area for the treatment. Therefore, it can be concluded that there is an optimum gas flowrate. Further testing should be conducted in the future to determine the optimum flowrate.

g. To confirm that oxygen is the preferred treatment gas, a field test was conducted using each gas under similar conditions. The data verifies that oxygen is more effective as a treatment gas.

h. An evaluation of oxygen-enriching techniques was conducted to determine the practicality of using oxygen as the treatment gas. Pressure Swing Adsorption (PSA) is the most practical and cost effective method for this application.

i. Preliminary performance and cost models were developed to determine practicality of the technology on a larger scale. The models were based on field-test data collected during the Test and Evaluation phase of the project. Based on these models, it can be concluded that the technology will be practical on a large scale, with estimated capital costs at Grand Coulee ranging from $1.2 to $2.4 million and annual operating costs from $88 to $164 thousand. Additional work should be conducted to ensure the models are accurate prior to conducting large-scale pilot testing.

1. INTRODUCTION

Gas supersaturation occurs when air is mixed with water under pressure. It is often caused by the presence of rocks and riprap in a river or under turbulent conditions such as those occurring near waterfalls or dams. Under these conditions, high pressures can be experienced and air can be entrained into the flow. Research and experience has shown that these supersaturated conditions, specifically high levels of dissolved nitrogen, can result in large fish kills caused by gas bubble disease (GBD). Furthermore, these high dissolved gas levels can cause problems with irrigation pumps and municipal water treatment plants and intake structures. Once these supersaturated conditions are created, it may take an extended period of time for the water to return to equilibrium. In an effort to maintain water quality and prevent large fish kills caused from gas-supersaturated water, the U.S. Environmental Protection Agency (EPA) and the State of Washington have established a limit of 110% for total dissolved gases (TDG). This limit has proven to be difficult to meet for several Bureau of Reclamation (BuRec) facilities, including large dams in the Pacific Northwest.

At Grand Coulee Dam, located on the Columbia River, the water entering the reservoir is often supersaturated with dissolved gases due to conditions and dams upstream. Compounding the supersaturation problem, the BuRec must occasionally spill excess water to avoid potential flooding conditions. The spilling process, which typically occurs in the spring, can significantly increase the dissolved gas levels. As a result, water in excess of 110% TDG is occasionally present downstream of the dam. In the past, levels higher than 130% TDG have been observed and resulted in documented fish kills. Although various solutions to this problem have been suggested, they are generally costly and effective only under spill conditions. The challenge is to find a cost-effective process for treating gas-saturated water entering the reservoir, as well as water that has spilled over the dam.

The BuRec has identified and conducted preliminary testing of a novel method for treating gas-supersaturated water. The process was patented in 2000 (U.S. Patent No. 6,176,899). Upon successful proof-of-concept testing, this dissolved gas treatment study was initiated to demonstrate that this novel approach provides an effective and practical solution, which can be easily scaled up to address the problems encountered at Grand Coulee Dam and other BuRec facilities. This report summarizes the development activities conducted in fiscal year 2000 (FY2000) and the test and evaluation conducted in FY2001. Preliminary conclusions and recommendations on future activities are also provided.

1.1. Gas Bubble Disease

Since GBD has resulted in fish kills in the past, it is a primary concern at many BuRec facilities and one of the drivers for developing this water treatment process. GBD in fish is similar to what divers experience with decompression sickness (i.e. the bends) from rising to the surface too quickly. The principle behind these illnesses is that gases that are supersaturated in water will move toward any medium where the dissolved gas concentrations are lower in an effort to achieve equilibrium. In the case of GBD, the gases escape from the supersaturated water by diffusing into the blood or other body fluids of the fish. The gases then cause bubbles to form inside capillaries and under the skin. The result is restricted blood flow, the formation of hemorrhages and clots, and in many cases, death.

Evidence of GBD in fish is most commonly seen in the yolk sacs, gills, fins, and eyes since these areas have membranes that are more gas permeable. Fish with GBD often show signs of swimming upside down or vertically, as though they are gasping for air. Smaller fish are affected more easily since the membranes that the gas has to permeate through are thinner, while larger fish are generally only affected at higher supersaturation levels. Research has shown that different species of fish have significantly differing tolerance levels, but in some cases gas supersaturation levels of less than 105% can be high enough to put very small fish at risk.

1.2. Regulatory Considerations

In addition to the concern of GBD, supersaturated water can create cavitation problems with irrigation pumps and intakes at municipal treatment facilities. To maintain water quality and minimize these issues, both the EPA and the State of Washington have established water quality standards for surface waters that include criteria for TDGs. Under these regulations, TDGs shall not exceed 110% of saturation at any point of sample collection. Standards for minimum dissolved oxygen (DO) concentration depend on the classification of the water and range from 4.0 mg/L for fair water to 9.5 mg/L for water classified as extraordinary. In addition, the DO may only be degraded by 0.2 mg/L by human-caused activities. These regulations do not apply when the stream flow exceeds the 7-day, 10-year frequency flood.

The State of Washington has provided several exceptions to these regulations, which apply to special conditions along the Snake and Columbia Rivers. The TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a State of Washington, Department of Ecology approved gas abatement plan. As an example of this guideline, the average daily TDG must not exceed 120% as measured in the tailrace of each dam. In addition, the hourly average must not exceed 125%. These elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than would be caused by turbine fish passage.

1.3. Description of Proposed Treatment Method

The method identified for treating gas-supersaturated water involves the introduction of microbubbles of oxygen or air into the flow stream. These microbubbles act as collection sites removing the excess nitrogen as they rise to the surface. The process is illustrated in Figure 1.

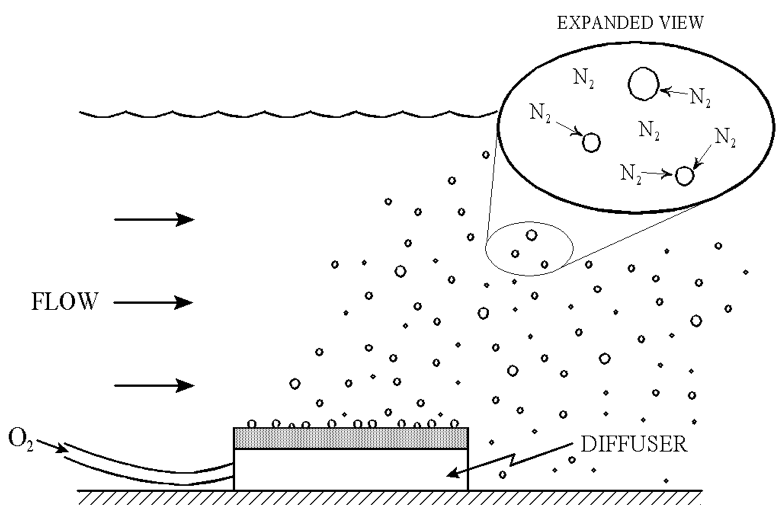

Figure 1. Schematic of Gas-Supersaturation Treatment Using Microbubbles

As the supersaturated nitrogen molecules come in contact with these small microbubbles, they are drawn into the bubble with an increase in velocity and an overall increase in entropy to the system. Previous studies, which were conducted as a proof-of-concept, show that this treatment approach works on a small scale in the laboratory.

There are several advantages to this method of degasification. The most obvious advantage is the fact that the process can be used anywhere along the river, and is not limited to dam locations. This satisfies the challenge of treating the water upstream of the reservoir. In addition, the system is modular and can be designed in a manner to allow easy access for operation and maintenance (O&M) activities.

Due to the simplicity of the process and the relatively small amount of air required, preliminary cost estimates show that this process may be much less expensive and more versatile than a modification to the dam. To further reduce the cost and energy consumption, the operation of the diffusers can be automated to activate only when dissolved gas levels are high. By optimizing the process and minimizing the energy consumption, it is believed that this process may prove to be practical and effective. As outlined in this report, numerous activities have been conducted to test and evaluate this technology.

1.4. Scope of Work

The dissolved gas treatment study has been conducted in two separate phases: 1) development of the process; and 2) test and evaluation of the treatment process. The BuRec Water Treatment Engineering and Research Group conducted the development phase of the project, while the test and evaluation portion was conducted as a combined effort between ARCADIS and BuRec in FY2001. The scope of work (SOW) for each phase of the project included the following activities:

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- Preparing summary report with conclusions and recommendations

1.5. Report Organization

This report is organized to correspond with the SOW presented above. Section 2 lists conclusions and recommendations regarding future activities. Section 3 provides a summary of work conducted during the development phase of the project, and Section 4 provides an overview of the goals, procedures, and findings from the test and evaluation phase, which was conducted in FY2001.

2. CONCLUSIONS AND RECOMMENDATIONS

The activities outlined in the SOW were successfully executed and indicate the technology has potential for large-scale treatment of gas-supersaturated water. Specific conclusions and recommendations resulting from each phase of the project are presented below.

2.1 Treatment Process Development Phase

The objective in the development phase of the project was to develop a means for implementing the treatment and to obtain a better understanding of the principles and fundamental relationships behind microbubble generation. The following conclusions and recommendations are a result of the process development phase of the project.

a. The concept of treating gas-supersaturated water using microbubbles was demonstrated successfully at a field site using modified diffusers and oxygen as the treatment gas. The results provide a ‘proof of concept’ on a larger scale, and indicate that further work should be conducted to determine if this process would be effective and practical on a scale such as the Columbia River. Additional data relative to efficiency should be evaluated in future tests.

b. Various methods for generating microbubbles were investigated including: 1) hollow-fiber membranes; 2) cylindrical diffusers such as ceramic piping and porous hose; and 3) flat-plate diffusers fabricated from either rubber membranes or ceramic. The diffuser most suitable for this application is the flat-plate ceramic air diffuser. This type of diffuser is capable of generating microbubbles in fairly large quantity without using excessive amounts of gas, and since ceramic is an inert material, the diffuser surface can easily be cleaned with sandpaper or acid.

c. The main variables that determine the bubble size produced by a diffuser are: 1) pore size; 2) surface tension at the gas/water/diffuser interface; and 3) density of the gas. After evaluating these variables in a series of experiments, the project team concluded that controlling the surface tension at the interface provides the best option for optimizing the size of the microbubbles and optimizing the efficiency of the process. Further work needs to be conducted toward characterizing the optimum bubble size in an effort to optimize the treatment process.

d. Diffusers were modified to produce microbubbles that are much smaller than those produced by a standard diffuser. Although this modification is not permanent and results in only a temporary improvement, the reduction in bubble size is considered a significant accomplishment since the efficiency of the dissolved gas treatment was greatly increased. The details of the diffuser modification are currently proprietary, and additional work must be performed to perfect the modification. This modification should be a priority for the project team, as it may further improve the efficiency of the process.

e. Oxygen and air were used as treatment gases and compared in the laboratory and at the field-test site. The oxygen appears to generate smaller microbubbles, which provide greater contact time and greater surface area for nitrogen removal. In addition, oxygen microbubbles provide greater nitrogen removal due to the increased concentration gradient between the water and the bubbles. As a result, treatment with oxygen is more effective than air.

2.2 Test and Evaluation Phase

The objective of the test and evaluation portion of the project was to determine how effective the technology may be on a small and large scale, and to develop a better understanding of the variables affecting performance and cost. The following conclusions and recommendations are a result of activities conducted in this phase.

a. Previous research conducted on gas supersaturation assumes that naturally dissolved gases always exist in proportions similar to air. However, data collected during the preliminary phase indicates that this is not the case. An evaluation of data collected at various locations along the Columbia River verifies that dissolved gas concentrations are independent of each other and highly dependent on solubility. Therefore, it is possible to be supersaturated in only one gas.

b. The causes of GBD were investigated further to confirm that the results of the treatment would reduce fish kills. The following conclusions were a result of this process:

    - Since nitrogen has a smaller molecular weight than oxygen it is passed across the gas-permeable membranes (i.e. eyes, gills, fins, etc.) much easier
    - TDG (or differential pressure) and individual gas concentrations are the driving forces behind the diffusion of the gas across the membrane tissue

c. Variables affecting the solubility of gases and the performance of the treatment were identified and evaluated. These variables include dissolved gas concentrations, ambient conditions (water temperature, salinity, barometric pressure), river conditions (flowrate, velocity, depth, turbulence), and treatment variables (diffuser area, diffuser properties, treatment gas flowrate, and treatment gas properties). Relationships of these variables were determined and are presented in detail in the report.

d. To determine how dissolved oxygen (DO) concentrations affect the treatment effectiveness, similar tests were conducted at two field locations with different DO levels. Evaluation of the test results indicates that the treatment is more effective in reducing dissolved nitrogen in a high DO environment, and more effective in reducing TDG in a low DO environment.

e. Although it was previously assumed that the relationship between diffuser area and the effectiveness of the treatment is linear (i.e. doubling diffuser area should double the gas removal), field tests were conducted at both locations to verify this relationship. Evaluation of the results indicates that removal of nitrogen is fairly linear, however the data were inconclusive relative to TDG removal. Additional data must be collected in the future.

f. Gas flowrate is a critical variable in determining the practicality of the technology. It has a significant impact on energy consumption and the capital and O&M costs for the system. To determine the effect of gas flowrate, field tests were conducted at different flowrates, and performance was monitored. The results show that the amount of excess nitrogen removed was fairly constant, while the TDG removal decreased with a higher gas flowrate. This indicates that a lower flowrate is more effective. This is encouraging relative to energy consumption. Most likely, the higher flowrates are less effective due to the generation of larger microbubbles, which decreases the effective surface area for the treatment. Therefore, it can be concluded that there is an optimum gas flowrate. Further testing should be conducted in the future to determine the optimum flowrate.

g. To confirm that oxygen is the preferred treatment gas, a field test was conducted using each gas under similar conditions. The data verifies that oxygen is more effective as a treatment gas.

h. An evaluation of oxygen-enriching techniques was conducted to determine the practicality of using oxygen as the treatment gas. Pressure Swing Adsorption (PSA) is the most practical and cost effective method for this application.

i. Preliminary performance and cost models were developed to determine practicality of the technology on a larger scale. The models were based on field-test data collected during the Test and Evaluation phase of the project. Based on these models, it can be concluded that the technology will be practical on a large scale, with estimated capital costs at Grand Coulee ranging from $1.2 to $2.4 million and annual operating costs from $88 to $164 thousand. Additional work should be conducted to ensure the models are accurate prior to conducting large-scale pilot testing.

3. TREATMENT PROCESS DEVELOPMENT

The objective of this portion of the project was to develop a means for effectively implementing the treatment and to obtain a better understanding of the principles and fundamental relationships behind microbubble generation. The scope of work for development of the treatment process included: 1) development of method for generating gas-supersaturated water; 2) investigation of methods for generating microbubbles; 3) investigation of process efficiency and optimum bubble size; 4) conducting preliminary laboratory testing; and 5) conducting preliminary field testing.

3.1 Automated Generation of Gas-Supersaturated Water

Prior to conducting the proof-of-concept testing in the initial stages of this project, an apparatus was fabricated to automatically generate gas-supersaturated water as shown in Figure 2.

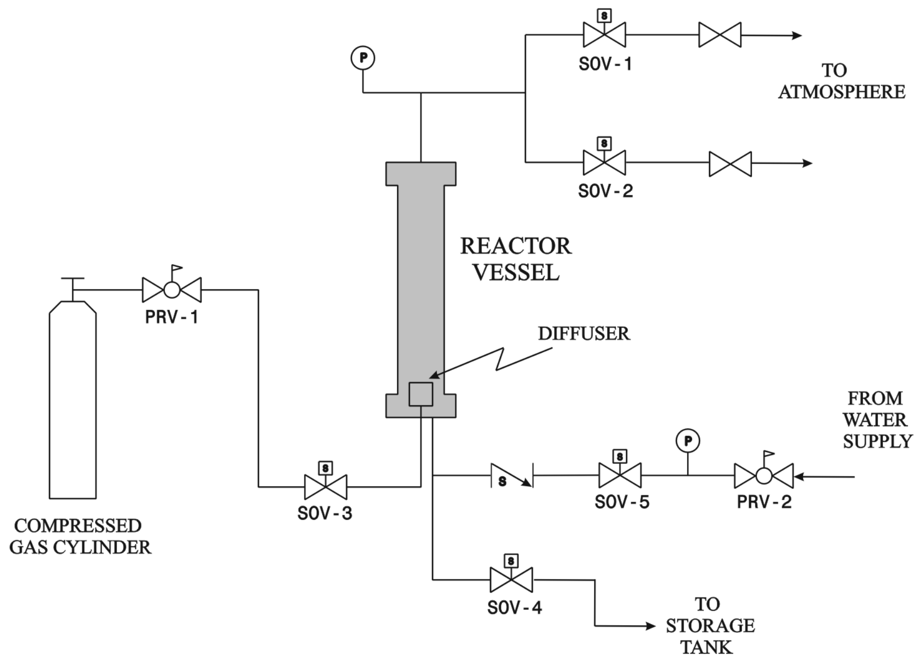

Figure 2. Automated Apparatus for Generating Gas-Supersaturated Water

The apparatus generates the supersaturated water through a process that is fully automated using a set of timer relays. First, the reactor vessel is filled with water by opening solenoid valves SOV2 and SOV5. Air is then sparged through the diffuser by opening SOV1 and SOV3. A needle valve is used to control the pressure drop across the diffuser and in turn, the amount of air used. After the sparging is completed, all valves are automatically closed, and the pressure is held for a period of time (<30 seconds). SOV2 is opened to release the pressure. A needle valve is used to set the rate at which the pressure is released. The water in the vessel is then drained into a storage tank by opening SOV2 and SOV4. By repeating this process, large quantities of supersaturated water can be produced. To generate the desired supersaturation levels, minimize production time, and conserve air, the system was optimized using a fractional factorial design (Murphy et. al., 1998). The device was used throughout all phases of this project to generate supersaturated water as needed.

3.2 Generation of Microbubbles

Microbubbles are used in various small-scale applications from medical imaging to aquaculture. However, these applications generally require small quantities of bubbles, which can be fairly easy to produce. Obviously, treating supersaturated water in a river will require production of microbubbles on a much larger scale. Several devices and techniques for generating microbubbles in large quantities were investigated as detailed below. These include hollow-fiber membranes, cylindrical diffusers, and flat-plate diffusers.

3.2.1 Hollow-Fiber Membranes

When the proof-of-concept testing was conducted (Murphy et. al., 1998), hollow-fiber membranes provided by A/G Technology Corporation of Needham, MA were used for microbubble generation. The process worked by filling the hollow fibers with air and pumping water through hollow-fiber vessel to cause diffusion of air across the membrane. This process generated a single-phase solution of air/water under pressure. When the solution was brought to atmospheric pressure, thousands of microbubbles were formed and the solution was used for treatment. A needle valve at the outlet of the vessel was used to control flowrate, pressure, and the generation of the microbubbles.

These hollow-fiber membranes, often used for gas separation, are ideal for generating microbubbles on a small scale in the laboratory due to their large surface area and small pore size. Unfortunately, using hollow-fiber membranes on a large scale presents many problems and would not be practical. Concerns of fouling, pressure differentials, and the volume of air required for degassing on a large scale forced the project team to look for alternatives.

3.2.2 Cylindrical Diffusers

Several cylindrical diffusers including porous hose diffusers were tested in the laboratory. The bubbles tend to coalesce easily due to the geometry, especially under fairly low pressures. This type of diffuser is better suited for applications where bubble size is not critical. As a result of these tests, an idea was conceived for fabricating a custom cylindrical diffuser using a section of ceramic piping inside of a section of polyvinyl chloride (PVC) pipe. This concept is somewhat similar to the hollow-fiber membrane configuration tested during proof-of-concept testing. By operating at higher pressures, but with a small pressure differential across the ceramic piping, it was believed that small bubbles could be generated on a fairly large scale. However, due to the high cost of ceramic piping and the limited surface area, this idea was abandoned and the project team began focusing on other air diffusers.

3.2.3 Flat-Plate Diffusers

Flat-plate air diffusers are used extensively in wastewater and fish hatchery applications for aeration. The bubbles generated by these diffusers are relatively large compared to the hollow fiber membranes, but they can be generated in significant quantity and do not require pumping the river water through a device. The next logical step was to conduct a thorough search of commercially available air diffusers to determine if any are suitable for treating supersaturated water. After an exhaustive search, two types of diffusers were selected and purchased for testing.

The first diffuser tested was a FlexDisc™, manufactured by U.S. Filter in Waukesha, WI. The diffuser body is molded in polypropylene and the ethylene propylene diene monomer (EPDM) membrane is designed to last from 5 to 10 years. The FlexDisc™ is inexpensive and appears to be an excellent diffuser for standard aeration applications, but the bubbles were too large for effectively treating dissolved gases.

The second diffuser tested was a 1-2 micron ceramic flat-plate diffuser. The microbubbles produced by these diffusers are small and can be generated in fairly large quantity without significant energy requirements. Of the devices tested, this type of diffuser is the most practical for the application. The diffusers tested were purchased from Point Four Systems, Inc., in British Columbia, Canada, and from Dryden Aqua Ltd. in Scotland, UK. This type of diffuser typically has a fairly rugged construction and uses a fine pore ceramic plate as the diffuser surface. Because the diffuser is flat, bubbles do not coalesce as easily as with a circular diffuser. Furthermore, the diffuser surface can easily be cleaned with sandpaper or acid since ceramic is an inert material.

Based on a comparison of all devices tested, the ceramic plate diffusers had the best potential of providing the optimum bubble size for this application. According to the manufacturer's data, this type of diffuser can provide a cloud of extremely fine bubbles, ranging from 100 to 500 microns in diameter. Determination of the optimum bubble size for this treatment process is described in detail below.

3.3 Optimum Microbubble Size

The optimum size for a microbubble in this application depends on many factors and will vary somewhat with site conditions such as diffuser depth, velocity of the water, and even water quality. In theory, the optimum microbubble is large enough that it will not dissolve, yet small enough to effectively remove excess dissolved gases. Achieving the optimum bubble size will maximize the surface area of the microbubbles and minimize the quantity of gas required. It should be noted that previous research has shown that microbubbles cannot be arbitrarily small because of practical limits, so the optimum bubble size may not always be achievable.

While conducting the initial experiments, it became obvious that the optimum bubble size is much smaller than those produced by the flat-plate ceramic diffusers under laboratory conditions. Decreasing the size of the microbubbles presents many advantages. Not only is it more difficult for smaller bubbles to coalesce, they are also less buoyant and will not rise to the surface as quickly. Based on observations in the laboratory, it was logical that the efficiency increases with contact time and thus a less buoyant bubble is desirable. Smaller bubbles also provide a much greater surface area per volume, which should result in an increase in efficiency and a lower energy requirement. Based on the need for generating a smaller bubble, an investigation into the variables effecting bubble size was launched. The findings are described below.

If we assume the site-specific variables are constant, the bubble size can be approximated by the following simplified relationship:

$$R_b = \left[\frac{(S_t)(D_P)}{g(\rho_l - \rho_g)} \right]^{1/3} \tag{3-1}$$

where: R_b = bubble radius (cm) S_t = surface tension (g cm/s^2)
D_P = orifice diameter (cm) g = acceleration of gravity (cm/s^2)
ρ_l = density of liquid (g/cm^3) ρ_g = density of gas (g/cm^3)

Analyzing this relationship shows that there are three variables effecting bubble size. Therefore, the following three options exist for potentially reducing the size of the microbubbles:

1. Decrease the diameter of the pores on the diffuser (variable D_P)
2. Reduce the surface tension at the air-water-orifice interface (variable S_t)
3. Decrease the density of the gas (variable ρ_g)

Literature was collected relative to these three variables, and several laboratory experiments were designed to independently evaluate each variable.

3.4 Preliminary Laboratory Testing

3.4.1 Diffuser Pore Size

To determine the effect of pore size, several ceramic diffusers were special ordered from Refractron Technologies Corp. in Newark, New York. The average diffusers were manufactured in two pore sizes: 0.25 micron and 1 micron. The diffusers were operated at several different air pressures and visual observations were recorded. It was concluded that there are no noticeable differences in bubble size and thus no benefits to reducing the pore size. This would indicate that a 1-micron pore size is at or below the practical limit, which is a result of surface tension or other factors dominating the bubble formation. As a result of this finding, no further testing was done relative to diffuser pore size.

3.4.2 Surface Tension

An evaluation of the forces required for a bubble to "break away" from the diffuser surface shows that the bubble separates from the diffuser when the buoyancy becomes greater than the surface tension at the air/water/diffuser interface. Therefore, as surface tension is reduced, less buoyant (and smaller) bubbles can be produced.

This was verified in the laboratory by adding a small amount of ethyl alcohol to the water to reduce the surface tension. As soon as the alcohol was added, the microbubble size decreased dramatically, providing a cloudy curtain of microbubbles. The results of this test demonstrated that the optimum bubble size was most likely achievable under the right conditions.

However, reducing surface tension of river water is not viable. The first step was to determine if the surface tension of 'real' water differs from the water used in the laboratory. To accomplish this, samples were collected at the field site, returned to the laboratory, and surface tension was measured using a tensiometer. The measured values were compared to values for deionized and tap water. This analysis verified that the surface tension varies only slightly with water type, and that the water used in the experiments is representative of real-world conditions.

Next, the project team began focusing on reducing the surface tension of the treatment gas and the ceramic plate. In an attempt to reduce the surface tension of the ceramic plate, several coatings were tested in the laboratory. When hydrophobic coatings were tested, the bubble size increased to greater than 0.1 inches in all cases. For the next experiment, diffusers were procured from Refractron Technologies with a hydrophilic coating that was applied during the manufacturing process. The coating had a similar effect, but the increase in bubble size was not as significant.

Several weeks were spent investigating additional methods of reducing the surface tension at the diffuser. Fortunately, a diffuser modification was developed that allowed the project team to generate extremely small bubbles in the laboratory. Since this modification is currently proprietary, no specific details are included in this report. The success in reducing the bubble size is a significant step toward optimizing the process. Therefore, further development of this modification will be a major focus in FY2002.

3.4.3 Density of Gas

To determine the effect of gas density, a laboratory experiment was designed to compare oxygen and air as treatment gases. Two 200-L tanks of supersaturated water were prepared using the automated apparatus described in Section 3.1. Then, each tank was treated for 6 minutes using a different gas. Upon conclusion of the treatment, measurements were taken to determine the amount of dissolved gas removed. The results of this experiment are presented in Appendix C, Table C-1. The experiment was conducted twice to verify the conclusions.

The results show that oxygen successfully removed over 50% more dissolved gases than air. Surprisingly, this is exactly the opposite of what was originally expected. Since oxygen has a higher density than air, the project team anticipated that the microbubbles generated with oxygen would be somewhat larger than those generated with air. To confirm that the oxygen microbubbles were actually smaller in size, several additional tests were conducted and visual observations were recorded. In the end, it was confirmed that the oxygen microbubbles are smaller than those generated with air. After further consideration, the conclusion was made that the decrease in bubble size is most likely due to a change in surface tension at the gas/water/diffuser interface.

Based on the results of the laboratory experiments, the decision was made to focus on surface tension to reduce the microbubble size and achieve maximum removal of dissolved gases. Several field tests were scheduled to assess the technology on a larger scale and in a more realistic environment.

3.5 Preliminary Field Testing

3.5.1 Site Selection and Test Preparation

The ideal location for field testing is easily accessible, has high levels of dissolved nitrogen, and has fairly low flows. Based on these criteria, the decision was made to conduct the tests at the Franklin Eddy Canal just north of Alamosa, Colorado. This canal is part of the Closed Basin Project, which is operated by the BuRec's Alamosa Field Office. The 40-mile canal is used to deliver groundwater to the Rio Grande using a series of vertical turbine pumps that feed the canal. These pumps are responsible for generating high levels of supersaturation.

The site selected for treatment is at the upper most end of the canal, along Highway 17, where water flows from a pipe into the open canal. The flow rate at this point in the canal fluctuates somewhat throughout the year, but was fairly constant at 3 ft^3/s (cfs) during the field tests. Nitrogen saturation levels in excess of 130% are common at this location. As a result, there are virtually no fish in the upper 6 miles of the canal, although aquatic weeds and algae are abundant. These factors combined to make this an ideal testing location.

Prior to conducting any field tests, an Environmental Impact Statement (EIS) was prepared and submitted to the BuRec's Albuquerque Projects Office. Once approved, arrangements were made with the Alamosa Field Office to provide assistance.

Equipment for laboratory and field testing was procured including saturometers from Sweeney Aquametrics and Common Sensing to measure dissolved gas parameters and a water quality probe from Hydrolab (Quanta model) to provide water quality data. A Hach Titration Kit was borrowed from the Alamosa Field Office for measuring dissolved carbon dioxide.

3.5.2 Testing Procedures

Upon arriving on site, several monitoring locations were identified in the upper mile of the canal. These sites are 0, 120, 310, 528, 1320, and 2640 feet from the beginning of the canal. Prior to each field test, baseline data were collected at each site including the date, time, monitoring location, and each of the parameters listed in Table 1.

Table 1. Field-Testing Equipment and Measured Parameters

Saturometers	**Hydrolab®**	**Hach Test Kits**
Differential Gas Pressure (ΔP)	BP	Dissolved Carbon Dioxide (Titration Kit)
Temperature (T)	T	
Barometric Pressure (BP)	Specific Conductance (SpC)	
% TDG	pH	
	Dissolved Oxygen (DO)	

Once these data were collected, the baseline dissolved gas saturation levels were calculated using the equations shown in Appendix A, and the gas treatment was initiated.

To effectively evaluate the dissolved gas treatment, it was critical to know exactly how far the treated water had traveled. To accomplish this, a peristaltic pump was used to inject approximately 0.2 ppb of Rhodamine WT dye into the canal. This tracer dye was used to identify the section of treated water and was measured downstream using a Fluorometer manufactured by Turner Designs of Sunnyvale, California. To ensure that the dye did not interfere with the tests, it was injected immediately before and after the treatment.

Throughout the test, data were collected at each monitoring site to evaluate the effectiveness of treatment. Visual observations were made and air pressure was monitored and recorded. All data were recorded in a field notebook (Lichtwardt, 2000) since maintaining accurate records of the field tests was critical. In addition, photographs were taken and all tests were documented on video.

3.5.3 Preliminary Demonstration

The preliminary field tests were conducted on April 18-21, 2000. The purpose of these tests was to demonstrate that supersaturated nitrogen levels could be reduced using the diffusers that were selected.

Air was used as the treatment gas. The test involved four 2-foot long and two 1-foot long flat-plate ceramic diffusers. As mentioned above, baseline data was collected prior to treatment, and data were collected at each of the monitoring sites downstream.

When the results of the preliminary field-testing were evaluated on site, it became obvious that the treatment was not effective in reducing nitrogen levels. Either more diffusers were needed, or the bubbles generated by the diffusers were too large and buoyant to effectively remove the excess dissolved gases. In either case, the efficiency of the process was too low. The manufacturer claims the diffusers will produce bubbles ranging from 100 to 500 micron in diameter, but it appeared the bubbles were coalescing due to the water flowing across the diffuser surface. Several different positions and diffuser configurations were tested with no evidence of lowering the levels of supersaturation. Therefore, optimizing the bubble size to increase the efficiency of the process became top priority.

3.5.4 Naturally Occurring Gases

Prior to the preliminary demonstration, the project team noticed that there were a large amount of gas bubbles present on the weeds and algae in the canal. The decision was made to analyze the gases to determine if they could affect the results of the treatment. Gas samples were collected using specialized sample vials. The vials were equipped with a septum to minimize the possibility of contamination, and allow the sample to be transferred to a Gas Chromatograph (GC) using a syringe. The U.S. Department of Labor, Mine Safety and Health Administration analyzed the samples. The results are attached in Appendix B. The gases were shown to have essentially the same composition as air with the exception of slightly elevated levels of methane gas. The conclusion was made that these gases were a byproduct of natural algae decomposition and photosynthesis, and would not affect the results of the treatment.

3.5.5 Comparison of Diffusers

As mentioned in Section 3.4.2, a modified diffuser was developed that is capable of generating smaller microbubbles, and most likely significantly increasing the efficiency of the treatment process. After the first field test appeared unsuccessful, the modified diffuser was developed further and compared against a standard diffuser in the laboratory. As expected, the modified diffuser appeared to produce much smaller microbubbles.

On June 28, 2000, a field test was conducted to compare a modified diffuser with a standard diffuser. Both diffusers were placed in the canal and operated at identical pressures. Visual observations were collected, and photographs and video were taken. The results were encouraging as the modified diffuser left a 15 to 20 foot cloud of microbubbles, while the bubbles from the standard diffuser appeared to rise to the surface almost immediately. However, it was discovered that the bubbles from the modified diffuser get larger over time indicating the modification is somewhat temporary. Based on these results, it was evident that further development of the modified diffuser was necessary. Nonetheless, all further testing was conducted using modified diffusers.

3.5.6 Comparison of Treatment Gases

To further evaluate and compare the effectiveness of air and oxygen as treatment gases, a field comparison was devised. The procedures outlined in Section 3.5.2 were used. On August 1, 2000, a field test was conducted using air as the treatment gas, and on August 3, 2000, oxygen from a compressed gas cylinder was used. Both tests were conducted using ten 2-foot long modified ceramic plate diffusers configured in three rows as follows: 1st row had two diffusers placed 4’3” from the pipeline outlet; 2nd row had four diffusers placed 9’6” from the outlet; and 3rd row had four diffusers placed 15’4” from the outlet. The diffusers in each row were attached end-to-end and placed perpendicular to the flow. The results of these tests are presented in Appendix C, Table C-2, and are discussed below.

3.5.6.1 Air

Since modified diffusers were used, the microbubbles generated using air were much smaller than those in the previous field test. This was consistent with observations made in the laboratory. The bubbles were much less buoyant and created at least 30 feet of cloudy water downstream of the diffusers. However, no noticeable drop in dissolved nitrogen was experienced. Most likely, the bubbles were still too large and did not provide enough surface area. Therefore, the microbubble size must be decreased further or additional diffusers will be required.

3.5.6.2 Oxygen

When oxygen was used as a treatment gas, approximately 70 feet of cloudy water was created downstream of the diffusers. From a visual perspective, there was a substantial improvement over the bubbles generated with air. As experienced in the laboratory, the bubbles appeared to be much smaller and did not rise to the surface as quickly. Most likely, oxygen provides a lower surface tension at the interface resulting in the small bubbles. Sampling indicated a significant drop in dissolved nitrogen, as well as an increase in dissolved oxygen. Approximately 310 feet downstream of the diffusers excess nitrogen was removed by as much as 34%.

It is possible that the effectiveness of the treatment was improved due to the relatively low levels of dissolved oxygen in the canal, but most likely the smaller bubbles allowed for a longer contact time and increased the efficiency of the process. Calculations show that oxygen was added to the treated water at efficiencies ranging from 66-81%. More comprehensive testing was planned during the test and evaluation phase of the project to verify these results and further evaluate the process.

Carbon dioxide levels consistently measured between 12 and 14 mg/L and did not change as a result of the either treatment. It should be noted that the titration method used to measure dissolved CO_2 is subjective and may involve significant error.

3.6 Summary of Results

By successfully implementing the SOW, significant advances were made in the development of microbubble treatment for gas-supersaturated water. Several key elements of the development phase of the project are summarized in Section 2, *Conclusions and Recommendations*.

4. TEST AND EVALUATION

The test and evaluation phase was initiated upon completion of the treatment process development. The goal for this portion of the project was to determine how practical and effective the technology will be on both a small and large scale, and to develop a better understanding of the variables affecting performance and cost. The SOW for this phase included: 1) collecting and evaluating additional data from the Columbia River; 2) continuing development, testing, and evaluation of modified diffusers; 3) identifying and evaluating variables of interest; 4) conducting additional lab testing; 5) conducting additional field testing 6) evaluating oxygen-enriching techniques; 7) preparing preliminary performance and cost models for a full-scale system; and 8) preparing a summary report with conclusions and recommendations.

4.1 Correlation Between Dissolved Gases

In the initial stages of the project, an extensive review of previous gas supersaturation work was conducted. Numerous studies have been conducted over the last few decades. Although a significant amount of data are available on TDG concentrations, very little data have been collected relative to dissolved nitrogen and oxygen levels. These previous studies generally assume that the dissolved gases are present in proportions similar to air (78.08% nitrogen, 20.45% oxygen, 0.93% argon, and 0.03% carbon dioxide). Since gases have varying rates of solubility, this assumption is not necessarily true. In fact, the field test site in Alamosa is supersaturated in nitrogen with low DO concentrations. Therefore, it was necessary to further investigate the relationship between these gases and the rates at which they dissolve.

To determine typical correlations of dissolved gases along the Columbia River, 24 hours of TDG data were obtained from the U.S. Army Corps of Engineers (USACE), North Pacific Region website (http://www.nwd-wc.usace.army.mil/report/tdg.htm) for several monitored locations. The data were plotted to determine the relationship between dissolved nitrogen and TDG. As shown in Figure 3, there is not a direct correlation between the two parameters. In other words, TDG and % nitrogen can change independently of each other. Therefore, it is possible to be supersaturated in nitrogen and not in oxygen under real-world conditions.

4.2 Investigation of GBD

Since the correlation between dissolved gases is not constant, it was necessary to obtain an understanding of how each gas relates to the formation of GBD. To accomplish this task, several reports on GBD were obtained and reviewed to determine what gas concentrations are safe, and how the various gases affect the fish. According to American Fisheries Society (AFS, 1984), “Supersaturation of a single gas may not produce gas bubble disease. Total gas pressure or the ΔP (pressure difference between the total gas pressure and local barometric pressure) are much more significant parameters for the characterization of dissolved gas levels.” However, studies to determine how certain fish species are affected by dissolved gases indicate that high levels of nitrogen are much worse than high levels of DO. Based on this information, the project team concluded the following:

- Since nitrogen has a lower molecular weight than oxygen, it passes across the gas-permeable membranes (i.e. eyes, gills, fins, etc.) much easier

- TDG (or differential pressure) and individual gas concentrations are the driving forces behind the diffusion of the gas across the membrane tissue

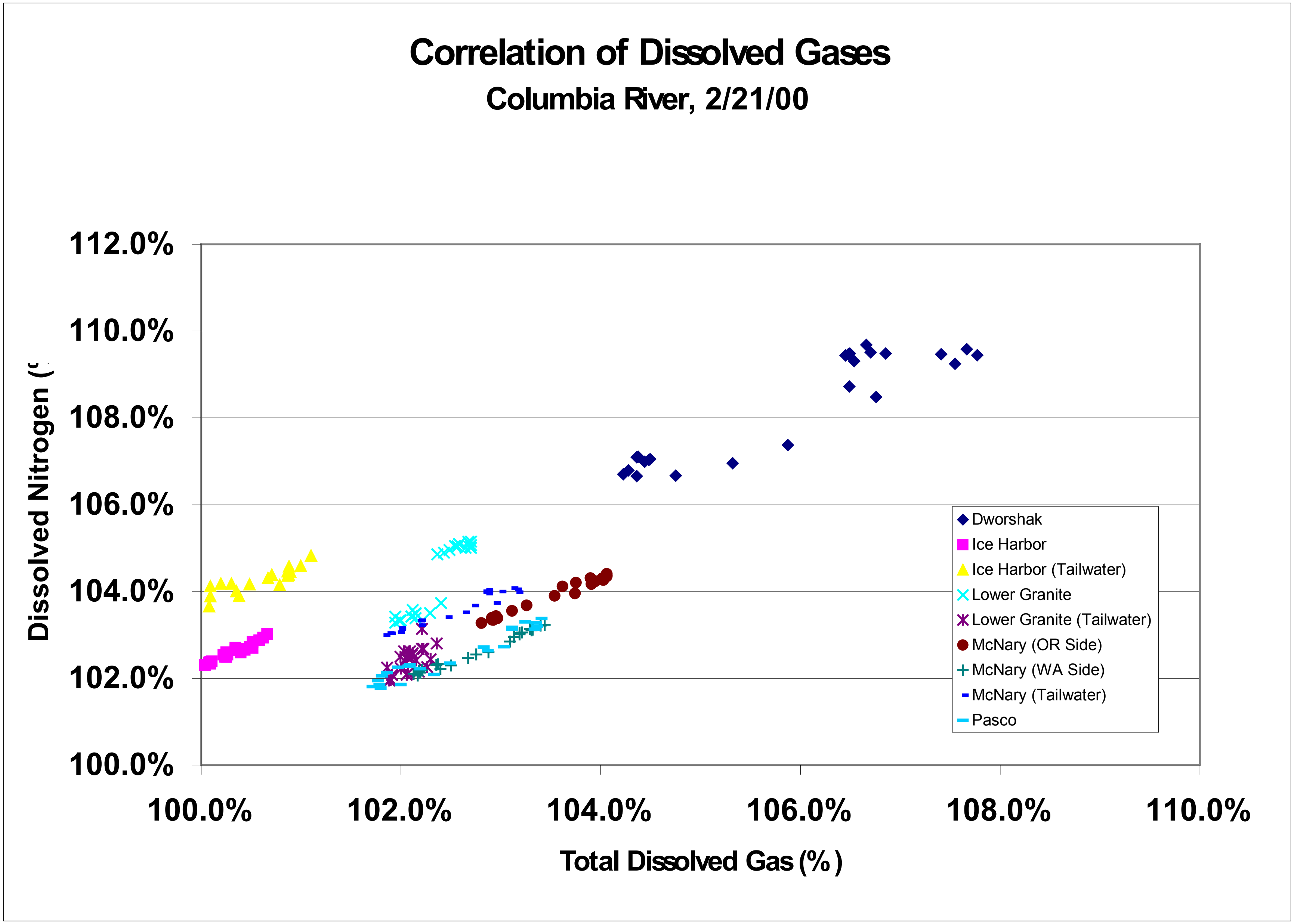

Figure 3. Correlation of Dissolved Gases, Columbia River, 2/21/00

These points are critical as they indicate that any process which reduces either TDG or % nitrogen should have a positive impact on the aquatic population. Preliminary testing indicates that this treatment method results in a lower TDG, lower dissolved nitrogen and increased DO, it can be concluded that the method will reduce the risk of GBD in fish.

4.3 Thermodynamic Analysis of the Treatment Process

To obtain a better understanding of the treatment process, a thermodynamic analysis was conducted. The control volume included a microbubble of oxygen placed in a volume of water that is supersaturated in dissolved gases.

Based on the First and Second Laws of Thermodynamics, a system will move toward equilibrium when internal constraints are removed. If we analyze the control volume, the dissolved gases are supersaturated in the water, but only saturated in the microbubbles. This difference in concentration will drive the dissolved gases toward the microbubbles, so the microbubbles essentially provide a mechanism that allows the system to move toward equilibrium.

If we assume constant temperature and pressure, the diffusion of gases can be described using Gibbs potential (or Gibbs free energy). An analysis of Gibbs potential shows that the treatment should increase in effectiveness with increasing gas supersaturation levels. Further thermodynamic analysis should be conducted for verification as more field data is collected.

4.4 Columbia River Data

Since DO levels at the FY2000 field test site were much lower than expected, several questions were raised as to how the efficiency of the treatment was affected. To resolve these questions, the project team initiated a review of historical gas data and traveled to Grand Coulee Dam to collect additional data.

4.4.1 Historical and Real-Time TDG Measurements

As part of the Dissolved Gas Abatement Study, a program run by the USACE with cooperation from BuRec and others, several gas saturometers have been installed along the Columbia and Snake rivers to monitor dissolved gas levels and assist in managing operation of the numerous dams. At Grand Coulee, there is a saturometer located upstream of the dam in Roosevelt reservoir and another 6 miles downstream of the dam. Although DO is not monitored at these sites, TDG values are collected hourly. This data was available in real-time at http://www.nwd-wc.usace.army.mil/report/tdg.htm and was reviewed/evaluated throughout the course of this project to determine if any high (>110%) concentrations were experienced in 2001. TDG concentrations rarely exceeded 105% during the period.

In addition, several reports with historical TDG data were reviewed. One of the most up-to-date and comprehensive reports available from the USACE shows historical data from 1984 to 1995 (USACE, 1995). Over this period, typical TDG concentrations ranged from ~100% to ~120%, with occasional peaks as high as 140%. Although not stated in the report, it is assumed that the high peaks occurred during periods in which waivers were issued by the state to spill over the dam in an effort to increase fish passage. If this is correct, 120% is the maximum TDG concentration over the period and should be used as a design guideline.

4.4.2 DO Data

Although extensive TDG data have been collected by the USACE and others over the past several decades, limited DO data are available. By traveling to the site with Saturometers manufactured by Common Sensing Inc. of Clark Fork, Idaho, the team was able to collect data from locations upstream and downstream of the dam, as well as interview key personnel for information on typical DO levels. Relevant data collected by the project team are shown in Table D-1 located in Appendix D. The data indicate that typical DO levels are near 100% and confirm there is not a direct correlation between dissolved nitrogen and DO concentrations.

4.5 Variables of Interest

Throughout the course of the project, variables of interest have been identified and evaluated through literature searches and testing. These variables have a direct impact on the solubility of gases, the development of microbubbles, or the performance of the microbubble treatment. Details of each variable of interest are discussed below and the relationships are shown in Table 2.

4.5.1 Dissolved Gas Concentrations

Both TDG and the individual gas concentrations have an impact on the amount of treatment required, as well as on the effectiveness of the treatment. Dissolved nitrogen, DO, and TDG have all been evaluated to determine their effect on treatment. Although the treatment was originally expected to be more effective in a low DO environment, field tests described in Section 4.4 show that this is not the case. In fact, the treatment is most effective in situations with high DO and high nitrogen, similar to the conditions in the Columbia River.

4.5.2 Ambient Conditions/Properties

The solubility of gases in water can be described in terms of the Bunsen coefficient, β, as shown in the equations in Appendix A. The Bunsen coefficient is defined as the volume of gas at standard temperature and pressure (STP) absorbed per unit volume of liquid at a given temperature and salinity when the partial pressure of the gas is one standard atmosphere. Therefore, ambient conditions have a direct impact on the solubility of gases and the saturation level (or equilibrium). The specific properties of interest are temperature, pressure, and salinity as discussed below.

- *Water temperature* – Solubility of gases decreases with increasing temperature. As a result, when the water temperature increases, the degree of supersaturation can increase significantly. In addition to solubility, water temperature changes have a very small effect on water properties including surface tension and density. However, these property changes have a minimal affect on the performance of the treatment process and can be considered negligible.

- *Barometric pressure* – Barometric pressure is a function of elevation and local atmospheric conditions. As barometric pressure decreases, the solubility of gases also decreases.

Table 2. Relationship Between Variables of Interest

Parameter	Solubility	Microbubble Size	Treatment Efficiency & Performance	Energy Consumption
1. *Dissolved Gas Concentrations*			x	x
2. *Ambient Conditions*				
- Water Temperature	x			
- Salinity	x			
- Barometric Pressure	x			
3. *River Conditions*				
- Flowrate			x	x
- Velocity		x		
- Depth*	x		x	
- Turbulence*			x	
4. *Treatment Variables*				
- Diffuser Area			x	
- Diffuser Properties				
Surface Tension		x	x	
Pore Size		x	x	
Pressure Drop				x
- Gas Flowrate		x	x	x
- Gas Properties		x	x	x

* Additional testing will be conducted in FY02 to determine/verify effect on performance.

- *Salinity* – Solubility of gases decreases with increasing salinity. However, since changes in salinity for a given river system are generally minimal, the resulting changes in solubility are generally negligible.

4.5.3 River Conditions

As with any treatment technology, site-specific conditions must be used to design the system and will have an impact on the efficiency and effectiveness. In this case, the parameters of interest include the flowrate, velocity, depth, and the turbulence intensity of the river system.

- *Flowrate* – The flowrate is a critical variable as it is directly proportional to the amount of gas that must be removed.

- *Velocity* – The velocity of the river system influences bubble size by shearing the bubbles from the diffuser before they have fully developed. Although this can have a positive affect by creating smaller bubbles, a high velocity may also cause coalescing, which will have a negative impact on performance.

- *Depth* – Depth is also a critical variable, as it will affect the residence time of the bubble and the operating pressure required to generate microbubbles. Although the operating pressures are higher for deeper water, the increased residence time can significantly improve gas transfer and improve treatment efficiency. In addition, solubility will also vary with depth, with the lowest solubility experienced at the surface.

- *Turbulence* – Turbulence will increase both the dispersion of the bubbles and the residence time, so it is assumed that an increase in turbulence will have a positive impact on the effectiveness of the treatment. The actual impact will be determined in the near future, prior to preparing computer models of the treatment performance.

4.5.4 Treatment Variables

Variables that are specific to the diffusers, system design, and treatment gas will affect microbubble size and/or treatment effectiveness.

- *Diffuser area* – The number of microbubbles generated is a function of the diffuser area. The effect of diffuser area was evaluated in field tests as outlined in Section 4.7.

- *Diffuser surface tension* – As shown in Equation 3.1 and demonstrated in laboratory tests, surface tension has a significant impact on the size of the microbubbles and appears to be the most important variable in affecting treatment efficiency.

- *Diffuser pore size* – As discussed in Equation 3.1, microbubble size is a function of the average pore diameter. As pore size decreases, smaller bubbles are produced. However, it should be noted that there is a practical limit at which pore diameter no longer has a significant effect on microbubble size. Previous laboratory tests indicate that this limit is around 2 microns in size.

- *Diffuser pressure drop* – The pressure drop across the diffuser is influenced by the thickness, pore diameter, uniformity, and manufacturing process. An increased pressure drop will require higher operating pressures and result in higher energy usage.

- *Gas flowrate* – Gas flowrate will directly affect the microbubble size and the number of bubbles generated. The effect on performance was evaluated further in FY2001 as discussed in Section 4.7.

- *Gas properties* – Laboratory and field tests have confirmed that gas properties have an affect on the bubble size, which ultimately influences the treatment efficiency and the energy consumption. As mentioned previously, oxygen appears to be more effective than air due to the difference in density and partial pressure (also known as gas tension). Additional field testing was conducted to confirm this finding.

4.6 Laboratory Testing

4.6.1 Diffuser Modification

In an effort to further develop diffusers capable of generating optimum-sized microbubbles, the project team enlisted the assistance of Dr. Murugaverl in the Chemistry Department at the University of Denver. Although diffusers were successfully modified for previous field testing, the difficulty lies in developing a modification that is more permanent. In addition, the modification must be simple to be practical, and must produce a uniform stream of microbubbles. Throughout the course of this work, several modifications were tested and evaluated in the laboratory with encouraging results. However, additional work will be required for the modification to meet the criteria desired by the project team.

Diffuser modification involved a significant amount of time from the entire project team, and comprised a large portion of the work conducted in both the development and test/evaluation phases of the project. However as mentioned previously, specific details of these modifications and tests are currently considered proprietary and have been omitted from this report.

4.6.2 Additional Diffuser Testing

Several additional tests were conducted using hollow-fiber and ceramic diffuser microbubble generation to confirm findings from the development phase of the project. This involved generating supersaturated water using the automated apparatus, and evaluating treatment effectiveness as a function of treatment gas, surface tension, and pore diameter. The results were similar to the previous tests, so the conclusions from the development phase were verified.

4.7 Field Testing

To evaluate the effectiveness of this treatment technology and to determine if it is practical, it is critical to determine the relationships between each of the variables of interest. Since the solubility of dissolved gases and the effect of ambient conditions is well understood, an emphasis was placed on further evaluation of the site-specific conditions and treatment variables.

4.7.1 Site Selection

Several sites were considered for field testing including several BuRec facilities and Ralston Reservoir located north of Golden, Colorado. The Ralston facility is operated by Denver Water and used to supply several water treatment plants. Although it is convenient for the project team, the flowrates are fairly high which would increase the cost of field testing. The other BuRec facilities that were considered had higher flowrates or did not meet other requirements for testing.

Therefore, the project team returned to the Franklin Eddy Canal where the previous tests were conducted. As it turns out, this was the ideal location for conducting tests at different DO concentrations.

In May of 2001, data were collected at several sites along the canal to determine dissolved gas concentrations, flowrates, and temperatures. This information was used to select sites for testing and to develop the plan for test and evaluation in the field. The two main test sites selected were at the beginning of the canal (Highway 17) and at Check 6 located 3 miles downstream from Highway 17. Data relative to these sites are presented with test data below.

4.7.2 Environmental Documents/Job Hazard Analysis

In accordance with BuRec requirements, a detailed project summary was prepared and submitted to the Albuquerque Projects Office prior to conducting any field testing. This was used to prepare the necessary National Environmental Policy Act (NEPA) documents for approval, to ensure that the project will not have an adverse impact on the environment.

In addition to the environmental documents, a Job Hazard Analysis (JHA) was developed to identify potential safety hazards and ensure all on-site personnel were aware of hazards, emergency procedures, and required safety equipment.

4.7.3 Tests

To adequately test and evaluate the microbubble treatment process, several field experiments were developed and implemented as outlined below.

4.7.3.1 Effect of DO

Examination of the previous field test data shows that the field site had very low DO concentrations, which are not representative of the Columbia River. Based on the thermodynamic analysis, it is evident that these low DO levels might have impacted the results from the previous tests. Therefore, a field test was devised to determine the effect of DO concentrations on the treatment.

To implement this test, similar treatments were conducted at the two sites along the Franklin Eddy Canal. As mentioned previously, both sites have different DO levels. The first site is where the previous field-tests were conducted, at the upper most end of the canal along Highway 17. DO at this site are generally less than 1 mg/L. The second test site is at Check 6, a gate structure located approximately 3 miles downstream from the first site. The site is usually saturated in oxygen with DO concentrations ranging from 5 to 9 mg/L.

The test protocol involved treatment using oxygen and 16 diffusers. As with previous tests, baseline data were collected as the control. Due to different flowrates and TDG concentrations at each site, it was not possible to conduct identical tests at each location. Therefore, the gas pressures were increased at the second site to account for higher flowrates. Data from this test are presented in Appendix D, Table D-2.

Evaluation of the results indicates that the treatment is more effective in reducing dissolved nitrogen in a high DO environment, but more effective in reducing TDG in a low DO environment. Since most problems with high TDG concentrations are a result of entrained air, the majority of locations requiring treatment are expected to be near saturation with respect to DO. Therefore, this is a positive result relative to removal of nitrogen.

4.7.3.2 Diffuser Area

Although it was previously assumed that the relationship between diffuser area and the effectiveness of the treatment is linear (i.e., doubling diffuser area should double the gas removal), field tests were conducted at both locations to verify this relationship. A manifold was fabricated to allow treatment with 4, 8, 12, or 16 diffusers. The protocol for these tests involved holding the flowrate per unit area constant and treating the flow with each diffuser configuration, thus changing the diffuser area. Data related to these tests are presented in Table D-3 located in Appendix D.

Evaluation of the results indicates that removal of nitrogen is fairly linear, however the data were inconclusive relative to TDG removal. Additional data will be collected in the near future.

4.7.3.3 Gas flowrate

Gas flowrate is a critical variable in determining the practicality of the technology. It has a significant impact on energy consumption and capital and O&M costs of the system. To determine the effect of gas flowrate, a test was conducted at the Highway 17 test site using 12 diffusers with oxygen as the treatment gas. Gas flowrates tested were 15, 25, 35, and 45 scfh. The data collected during this test are shown in Appendix D, Table D-4.

The results show that the amount of excess nitrogen removed was fairly constant around 9%. However, the TDG removal decreased with a higher gas flowrate indicating a lower flowrate is more effective. This is encouraging relative to energy consumption. Most likely, the higher flowrates are less effective due to the generation of larger microbubbles, which decreases the effective surface area for the treatment. Therefore, it can be concluded that there is an optimum flowrate that is less than 25 scfh for the configuration used. Further testing should be conducted in the future to determine the optimum flowrate.

4.7.3.4 Air vs. O_2

To verify the effect of air vs. oxygen as the treatment gas, a field test was conducted at the Check 6 test site using 16 diffusers and each of the gases. To compare the pressure drop across the diffusers as a function of treatment gas, the gas pressure was held constant at 30 psi. This resulted in an air flowrate of 70 scfh and an oxygen flowrate of 51 scfh. The data are presented in Appendix D, Table D-5.

Evaluation of the data verifies that oxygen is much more effective than air for removal of both TDG and dissolved nitrogen. Based on this result, the decision was made to initiate the investigation into methods for producing oxygen-enriched air as described below.

4.8 Oxygen Enriching Techniques

Compressed gas cylinders were used throughout the laboratory and field testing. Obviously, this is not practical for a permanent installation, particularly on a large scale. Since oxygen is more effective in the treatment, methods for generating oxygen on site were investigated and evaluated. The most common methods include pressure swing adsorption (PSA), vacuum swing adsorption (VSA), cryogenics, and membrane separation.

4.8.1 Pressure Swing Adsorption

PSA is used in many medical and industrial applications. The technology is used for systems as small as a few cubic feet per day and as large as 6,000 scfh. Adsorption and diffusion are the principle mechanisms behind PSA systems. Each gas has a characteristic adsorption rate that is a function its ionic charge and individual properties.

A PSA unit is installed after an air compressor and is capable of producing oxygen on demand. The unit uses two adsorption towers as shown in Figure 4. Each tower is a molecular sieve bed composed of zeolite. At high pressures, the sieve attracts nitrogen through adsorption, and at low pressures the nitrogen is desorbed and can be released into the atmosphere. Since different gases have characteristic adsorption rates, oxygen and argon can pass through the system.

To begin the process, compressed air is filtered and dried to remove entrained liquid, oil, and solid particles. The clean compressed air is then fed into the first tower, where nitrogen is adsorbed and oxygen and argon are allowed to pass through and can be piped to a storage tank. Air is fed into the first tower until the sieve becomes loaded with nitrogen. At this point, the compressed air is diverted to the second tower where the process continues. When the first sieve bed is depressurized, the trapped nitrogen is desorbed from the zeolite and vented into the atmosphere. To complete the regeneration process, the bed is purged with oxygen. When the second bed becomes saturated, the air is diverted to the first tower, and the process continues.

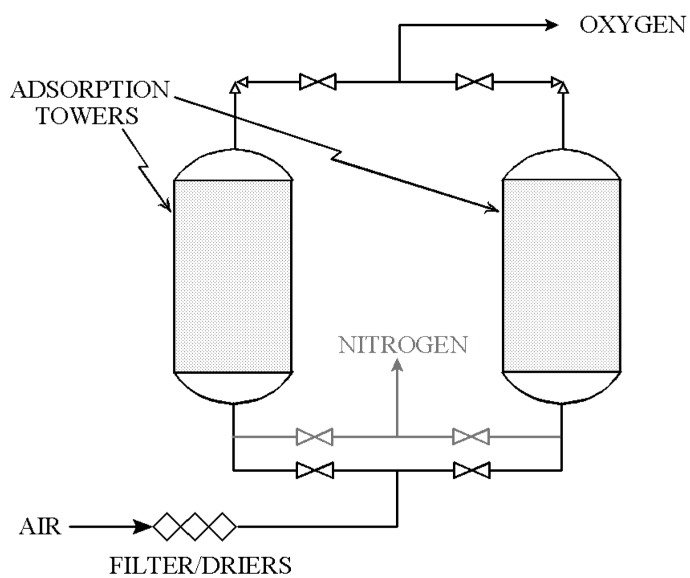

Figure 4. Production of Oxygen-Enriched Air Using Pressure Swing Adsorption

Evaluation of this technology indicates that it is well suited for producing oxygen-enriched air for our use in microbubble treatment of gas-supersaturated water. PSA can provide pressurized oxygen that is 90-95% pure, which will provide effective treatment.

4.8.2 Vacuum Swing Adsorption

VSA systems are constructed and operate similar to PSA systems, except the adsorbent material that is used is capable of adsorbing nitrogen at atmospheric pressures. Therefore, a vacuum must be used to regenerate the bed. Since compressed air is not required, VSA systems are considered to be more energy efficient than PSA systems. However, in this application where pressurized oxygen is desired, the energy consumption of VSA would actually be higher since a compressor and vacuum pump would both be used. Therefore, PSA is better suited for generation of microbubbles for treatment of gas-supersaturated water.

4.8.3 Cryogenics

Cryogenic air separation relies on the use of very low temperatures to separate the gases. The process begins by purifying and compressing huge volumes of atmospheric air. The air is cooled to about –185°C (–300°F) and the elemental components are separated in the form of liquid nitrogen, oxygen, and argon based on their different boiling points.

Several factors were considered in evaluating this process for use with gas-supersaturation treatment. Compared to the other oxygen generation technologies discussed in this section, cryogenics are generally intended for use on a large scale ranging from 50,000 to 300,000 scfh, with some of the largest operational systems exceeding 3 million scfh. Smaller systems are not used primarily due to the large capital costs. Operational costs associated with these systems also tend to be fairly high due to the high energy costs associated with cooling the process air to cryogenic temperatures. For this reason, cogeneration (with industrial process steam) is often used when possible. Therefore, if liquid oxygen were used for a treatment installation at Grand Coulee Dam, it would be more economical to have it delivered and stored on site. This possibility was investigated, but based on the availability of liquid oxygen relative to the remote location, transportation costs, vaporization, and storage requirements, a PSA system is much more practical.

4.8.4 Membrane Separation

Membrane separation of gases has been used for about a decade, but is still considered a fairly novel approach that requires additional development. The process works by introducing compressed air to the surface of the semi-permeable membrane, which selectively allows the transfer of nitrogen, and impedes the transfer of oxygen as shown in Figure 5.

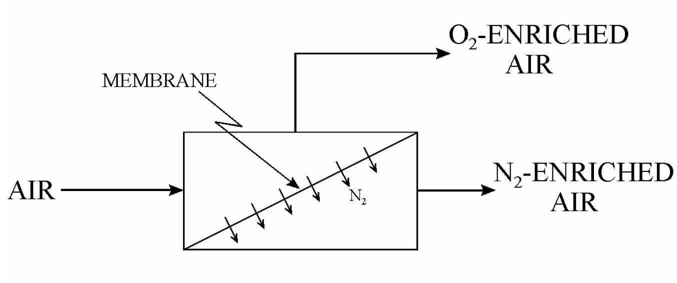

Figure 5. Production of Oxygen-Enriched Air Using Membrane Separation

The nitrogen is transferred through the membrane since it has a smaller molecular weight than oxygen. For this reason, membrane separation is usually used to produce concentrated nitrogen. However, this nitrogen-enriching process results in a waste stream that is high in oxygen content. The evaluation of this process indicates that it would be difficult to produce a stream with more than 80% oxygen content. Therefore, the PSA method is preferred over membrane separation.

However, since no tests have been conducted with 20-90% oxygen-enriched air, this method has not been ruled out entirely and may be tested in the future.

4.9 Columbia River Design Criteria

Prior to developing the preliminary performance and cost models, information relevant to Grand Coulee Dam was collected to assist in determining the appropriate design criteria for treatment of the Columbia River. Specifications and information on the dam are listed below:

- Dam Type: Concrete, Gravity
- Location: Coulee City, WA
- Reservoir: Franklin D. Roosevelt Lake
- Structural Height: 550 ft
- Crest Elevation: 1311 ft
- Total Storage to El. 1290: 9,562,000 acre-ft
- Hydraulic Height: 380 ft
- Service Spillway Capacity: 1,000,000 cfs
- Outlet Works Capacity: 265,000 cfs
- Power Outlet Capacity: 207,000 cfs

The 7-year/10-day frequency flood level for Grand Coulee has been established at 210,000 cfs. Since compliance with the 110% TDG level is not required when the river flow exceeds this level, 210,000 cfs will be used as the design flowrate for treatment of the Columbia River. In addition to the design flowrate, an average flowrate of 109,000 cfs was established based on historical data.

Since the effectiveness of the treatment is a function of the depth in the river system, contours of the river bottom were obtained from Grand Coulee personnel and evaluated. It was determined that the useful depth of the river ranges from 50 to 80 feet at a distance about 3000 feet downstream of the dam. To be conservative with preliminary cost estimates and design assumptions, 50 feet was selected as the design depth.

4.10 Computer Modeling

To evaluate if the treatment method is practical based on cost, preliminary performance and cost models were developed. The performance and cost estimates are intended as rough approximations since analytical relationships have not been developed for all of the variables of interest.

Two cases were developed for implementing the technology at Grand Coulee: a realistic case, and a worst case that assumes a 100% contingency for the number of diffusers. Output from the performance and cost models are provided in Appendix E. The models and assumptions are discussed below.

4.10.1 Performance Model

The performance model was developed based on typical results from the field tests at the Franklin Eddy Canal. The key parameter in determining performance is the depth of the river, or the depth at which the diffusers are installed. The depth has a direct influence on the buoyancy of the bubbles. While the bubbles increase in size as they rise to the surface (and become more buoyant), turbulence should provide a longer residence time and improve gas transfer. For the preliminary models developed for Grand Coulee, it has been assumed that the buoyancy and turbulence factors cancel each other. More specifically, it has been assumed that the effect of water depth is linear (i.e. a bubble released at 40 feet can remove twice as much TDG as one released at 20 feet). The treatment effectiveness from the number of diffusers was also assumed linear. Although this assumption is not entirely accurate, it is believed to be sufficient for use in preliminary calculations.

Since the treatment appears to be more effective in reducing dissolved nitrogen than TDG, the model has been based on TDG concentrations. The diffuser size (4 ft x 8 ft) was determined as reasonable based on the calculated weight.

The annual energy usage is based on the quantity of oxygen required, the assumed efficiency, assumed annual usage, and a power factor for producing oxygen-enriched air. Annual usage was assumed at 2000 hours, as a control system will be installed to allow operation when necessary. The power factor was calculated for a PSA system, using manufacturer's data. To confirm the approximation of energy usage, the required horsepower was calculated for the actual field-testing conditions and compared to readings taken during testing.

4.10.2 Cost Model

The cost of each component was estimated based on minimal quotes from vendors since the design has not been fully developed. The assumptions, which are believed to be conservative, are listed with the each cost analysis in Appendix E. The realistic case shows a total capital cost of $1.2 million with an annual O&M cost of $89,000, and the worst-case analysis (with a contingency on the number of diffusers) provides costs that are approximately double. Compared to the alternatives (such as dam modification), the technology should be cost-effective.

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Appendix A

Dissolved Gas Equations

Dissolved Gas Equations

Total Dissolved Gases - % Saturation

$$\%TDG = \left[\frac{(BP + \Delta P)}{BP} \right] 100 \qquad \text{(A-1)}$$

Nitrogen and Argon - % Saturation

(Argon is typically negligible)

$$\%N_2 + Ar = \left[\frac{BP + \Delta P - \left[\frac{DO}{\beta_{O_2}} (0.5318) \right] - P_{H_2O}}{\left(BP - P_{H_2O} \right) 0.7902} \right] 100 \qquad \text{(A-2)}$$

Oxygen - % Saturation

$$\%O_2 = \left[\frac{\frac{DO}{\beta_{O_2}} (0.5318)}{\left(BP - P_{H_2O} \right) 0.20946} \right] 100 \qquad \text{(A-3)}$$

Where,

- BP – Barometric pressure in mm Hg
- DO – Dissolved oxygen concentration in mg/L
- P_{H2O} – Vapor pressure of water in mm Hg
- β_{O2} – Bunsen's coefficient for oxygen at ambient temperature and salinity
- ΔP – Differential gas pressure in mm Hg measured by membrane-diffusion method

Reference: American Fisheries Society, *Computation of Dissolved Gas Concentrations in Water as Functions of Temperature, Salinity, and Pressure*, AFS Special Publication 14, Bethesda , Maryland, 1984.

Appendix B

Air Sample Record

(Analysis of Gas Samples Collected Under Water at the Franklin Eddy Canal, Alamosa, Colorado)

Air Sample Record

U.S. Department of Labor
Mine Safety and Health Administration

Check if Needed:

☐ Mailers ☐ Plastic Vials ☐ Vacuum Bottles ☐ Bistables ☐ Forms Sheet of

1. Mine/Mill
BDR
2.
3. Mine ID Number
4.
5. Collector
6
7. Field Office
8

ENVIRONMENTAL SAMPLING SUPPLY

LOT #
SAMPLE ID FEC I
SAMPLED BY TIM
DATE 6/28/00
TIME 2:00pm
LOCATION FRANKLIN EDDY CANAL
PRESERVATIVE NA
ANALYSIS GASES
CLIENT

9601 San Leandro Street, Oakland, California 94603
(510) 562-4988 (800) 233-8425

- **SAMPLING DATA**

	1	2	3	4	5	6
9. Pre-seal Number						
10. Sample Number						
11. Sample Type						
12. Date Collected						
13. Time Collected						
14. Sample Location						
15. Methane (est. %)						
16. Flow Rate (lpm)						
17. Analysis Desired						

- **WEIGHING DATA**

18. Received By and Date						
19. Post-seal Number						
20. Sample Weight (mg)						
21. Weighed By and Date						
22. Fiber Count						
23. Counted By and Date						

- **LABORATORY ANALYSIS**

Received By and Date						
Seal Number						
Laboratory Number	run 1	run 2	run 3			
☐ Quartz (mg)						
☐ Fiber Count (f/ml)						
☐ Fiber ID						
☐ Elemental						
☐ Oxygen (%)	16.0000	15.9500	16.0100			
☐ Methane (%)	1.5150	1.5490	1.5280			
☐ Carbon Monoxide (%)	.0000	.0000	.0000			
☐ Carbon Dioxide (%)	.5200	.4900	.4420			
☐ ethane (%)	.0000	.0000	.0000			
☐ nitrogen	81.963	81.002	81.618			
☐						
☐						
☐						
☐						
☐						
☐						
TWA						
TLV						
Analysis Completed By & Date						
Analysis Mailed By & Date						

MSHA Form 4000-29, Mar 80

Appendix C

Preliminary Laboratory and Field Test Data/Plots

Table C-1. Laboratory Comparison of Air and Oxygen as a Treatment Gas

										Measured	Calculated Values		% Reduction
Date	Gas	Test	Time	BP	Delta P	DO	Temp	ß(O_2)	P (H_2O)	% Saturation	% Saturation	% N_2/Ar	of excess N_2
26-Jul	Air	Baseline	14:13	622	279	15.00	19.7	0.03122	17.22	144.8%	144.9%	131.5%	
		Treated		621	134	12.40	19.7	0.03122	17.22	121.5%	121.6%	110.4%	**67.1%**
	Oxygen	Baseline	14:45	621	334	13.01	19.8	0.03116	17.32	154.0%	153.8%	150.0%	
		Treated		621	160	12.80	19.8	0.03116	17.32	126.0%	125.8%	114.3%	**71.4%**
27-Jul	Air	Baseline	14:20	622	258	14.92	20.0	0.0311	17.54	141.5%	141.5%	127.2%	
		Treated		622	201	13.19	20.0	0.0311	17.54	132.4%	132.3%	121.4%	**21.1%**
	Oxygen	Baseline	14:35	622	279	14.93	19.9	0.0311	17.54	144.6%	144.9%	131.5%	
		Treated		622	209	13.33	19.9	0.0311	17.54	133.6%	133.6%	122.6%	**28.3%**

Table C-2. Field Test Data and Comparison of Air and Oxygen as a Treatment Gas

Date: 8/1/00
Treatment Gas: **Air**

		Baseline Data - Before Treatment					Test Data - After Treatment					Test Results	
Location	**Distance From Outlet**	**Time**	**Temp (°C)**	**DO (mg/L)**	**TDG (%)**	**% Nitrogen**	**Time**	**Temp (°C)**	**DO (mg/L)**	**TDG (%)**	**% Nitrogen**	**% Reduction in TDG**	**% Reduction in Nitrogen**
Hwy 17	0	8:29	11.5	0.17	108%	136%	0	11.5	0.09	110%	139%	-22%	-7%
120'	120	8:50	11.7	0.44	107%	134%	120	11.7	0.92	107%	133%	-3%	4%
310'	310	9:05	12.0	0.81	105%	131%	310	12.8	1.39	106%	130%	-17%	3%
528'	528						528	13.7	2.56	110%	131%		
.25 mi	1320	10:44	13.9	3.11	115%	135%							
.5 mi	2640	11:06	14.0	3.45	115%	135%	0	11.5	0.09	110%	139%		

Date: 8/3/00
Treatment Gas: **Oxygen**

		Baseline Data - Before Treatment					Test Data - After Treatment					Test Results	
Location	**Distance From Outlet**	**Time**	**Temp (°C)**	**DO (mg/L)**	**TDG (%)**	**% Nitrogen**	**Time**	**Temp (°C)**	**DO (mg/L)**	**TDG (%)**	**% Nitrogen**	**% Reduction in TDG**	**% Reduction in Nitrogen**
Hwy 17	0	10:35	11.5	0.10	111%	140%							
120'	120	9:55	11.8	0.60	110%	137%	11:58	12.1	2.68	109%	130%	4%	19%
310'	310	11:00	12.5	1.12	111%	137%	12:19	13.1	3.57	107%	124%	32%	34%
528'	528	8:50	12.2	1.50	111%	136%	12:33	13.7	4.15	114%	131%	-23%	16%
.25 mi	1320	9:08	14.5	4.36	117%	134%	2:15	16.6	6.64	115%	122%	16%	36%
.5 mi	2640	9:31	12.8	1.77	110%	134%							

Note: % Nitrogen, % Reduction in TDG, and % Reduction in Nitrogen are all calculated values. All other values represent direct field measurements.

Appendix D

Test and Evaluation Data/Plots

Table D-1. Grand Coulee Dissolved Gas Measurements

										Calculated Values		
Date	Location	Time	BP	Delta P	DO	Temp	ß(O_2)	P (H_2O)	Measured % Saturation	% Saturation	% N_2/Ar	% O_2
18-Jun	Downstream (~500')	16:26	743	36	10.44	11.8	0.03665	10.38	104.0%	104.8%	106.6%	98.7%
	Upstream	17:26	734	66	10.12	19.3	0.03151	16.69	108.0%	109.0%	108.1%	113.7%
19-Jun	Downstream Inst. Station	8:16	746	24	10.51	11.5	0.03689	10.18	104.0%	103.2%	104.6%	98.3%
	Downstream (~500')	9:25	745	5	10.30	11.9	0.03657	10.45	102.0%	100.7%	101.6%	97.4%
	Upstream	9:45	737	23	9.70	16.1	0.03348	13.73	103.0%	103.1%	103.6%	101.7%
	Feeder Canal	12:04	729	55	10.69	12.6	0.03601	10.94	107.0%	107.5%	108.4%	105.0%

Table D-2. Effect of Dissolved Oxygen on Treatment Effectiveness

Date	Location	Configuration	Time	Canal Flow (cfs)	Gas Pressure (psi)	Gas Flow (scfh)	BP	Delta P	SpC (mS/cm)	DO (mg/L)	pH	Temp (°C)	Bunsen Coefficient	P H_2O	Measured TDG (%)	TDG (%)	% Excess TDG Removed	N_2 & Ar (%)	% Excess N_2 Removed
9-Aug	Hwy 17	Baseline	8:50	8.34	0	0	585	71	0.486	1.08	7.68	11.3	0.03714	9.98	112.3	112.1		138.8	
		Low DO	10:05	8.34	23	31	586	56	0.484	2.84	7.68	11.5	0.03697	10.11	109.2	09.6	21.3	129.9	22.9
	Chk 6	Baseline	14:45	12.44	0	0	579	128	0.535	8.16	7.35	19.9	0.03110	17.43	122.1	122.1		124.0	
		High DO	16:58	12.44	32	65	579	101	0.581	9.21	7.38	19.2	0.03151	16.69	117.7	117.4	21.1	114.3	40.3

Notes:

1. Data collected 175 feet downstream of diffusers
2. Tests conducted with 16 diffusers

Table D-3. Test and Evaluation - Effect of Diffuser Area on Treatment Effectiveness

Date	Location	Configuration	Time	Canal Flow (cfs)	Gas Pressure (psi)	Gas Flow (scfh)	BP	Delta P	SpC (mS/cm)	DO (mg/L)	pH	Temp (°C)	Bunsen Coefficient	P H_2O	Measured TDG (%)	TDG (%)	% Excess TDG Removed	N_2 & Ar (%)	% Excess N_2 Removed
7-Aug	Hwy 17	Baseline	13:26	8.34	0.0	0	584	82	0.469	0.96	7.68	11.7	0.03673	10.31	114.1	114.0		141.6	
		8-Diffusers	13:55	8.34	25.0	20	584	71	0.467	1.98	7.68	11.7	0.03673	10.31	112.2	112.2	13.4	135.9	13.7
		12-Diffusers	14:15	8.34	26.5	30	584	59	0.466	2.30	7.68	11.6	0.03689	10.18	110.3	110.1	28.0	132.2	22.4
		16-Diffusers	14:50	8.34	27.0	40	584	55	0.465	2.59	7.68	11.4	0.03706	10.04	109.6	109.4	32.9	130.5	26.7
10-Aug	Chk 6	Baseline	13:38	10.23	0.0	0	582	151	0.456	8.49	7.56	19.1	0.03163	16.48	126.0	125.9		128.4	
		4-Diffusers	14:00	10.23	23.0	12	581	142	0.456	8.45	7.56	19.3	0.03151	16.69	124.6	124.4	5.8	126.4	7.0
		8-Diffusers	14:20	10.23	19.5	24	581	144	0.456	8.78	7.56	19.5	0.03134	17.00	125.0	124.8	4.5	125.4	10.4
		12-Diffusers	14:46	10.23	26.0	36	581	134	0.456	9.25	7.56	19.1	0.03157	16.59	123.3	123.1	11.1	121.7	23.7
		16-Diffusers	15:15	10.23	23.5	48	581	128	0.456	9.61	7.56	19.1	0.03157	16.59	122.3	122.0	15.1	119.0	33.3

Notes:

1. Data collected 175 feet downstream of diffusers.

Table D-4. Field Data - Effect of Gas Flowrate on Treatment Effectiveness

Date	Location	Configuration	Time	Canal Flow (cfs)	Gas Pressure (psi)	Gas Flow (scfh)	BP	Delta P	SpC (mS/cm)	DO (mg/L)	pH	Temp (°C)	Bunsen Coefficient	P H_2O	Measured TDG (%)	Calculated TDG (%)	% Excess TDG Removed	N_2 & Ar (%)	% Excess N_2 Removed
7-Aug	Hwy 17	Baseline	15:45	8.34	0.0	0	583	59	0.464	1.38	7.69	11.6	0.03681	10.24	110.2	110.12		135.2	
		15 scfh	16:00	8.34	17.0	15	583	51	0.466	1.84	7.69	11.6	0.03689	10.18	108.9	108.75	13.6	132.0	9.2
		25 scfh	16:24	8.34	22.5	25	583	52	0.467	1.70	7.69	11.5	0.03689	10.18	109.1	108.92	11.9	132.6	7.3
		35 scfh	16:51	8.34	25.0	35	583	55	0.471	2.13	7.69	11.5	0.03697	10.11	109.6	109.43	6.8	131.9	9.2
		45 scfh	17:15	8.34	27.0	45	583	64	0.470	2.69	7.69	11.5	0.03697	10.11	111.1	110.98	(8.5)	132.1	8.6

Notes:

1. Data collected 175 feet downstream of diffusers
2. Tests conducted using 12 diffusers

Table D-5. Test and Evaluation - Effect of Air vs. Oxygen on Treatment Effectiveness

Date	Location	Configuration	Time	Canal Flow (cfs)	Gas Pressure (psi)	Gas Flow (scfh)	BP	Delta P	SpC (mS/cm)	DO (mg/L)	pH	Temp (°C)	Bunsen Coefficient	P H_2O	Measured TDG (%)	TDG (%)	% Excess TDG Removed	N_2 & Ar (%)	% Excess N_2 Removed
9-Aug	Chk 6	Baseline	11:25	10.44	0	0	582	116	0.502	6.43	7.45	17.5	0.03262	14.91	120.1	119.9		129.0	
		Air	11:57	10.44	30	70	582	109	0.502	6.77	7.45	17.9	0.03231	15.38	118.9	118.7	6.0	126.0	10.5
		Baseline	15:48	10.44	0	0	581	148	0.503	7.96	7.52	18.9	0.03169	16.38	125.5	125.5		129.8	
		Oxygen	16:25	10.44	30	51	581	122	0.501	8.56	7.53	19.4	0.03140	16.90	121.1	121.0	17.6	121.4	28.2
		Oxygen	16:39	10.44	30	51	581	115	0.502	9.48	7.53	19.2	0.03157	16.59	119.9	119.8	22.3	116.5	44.5
		Oxygen	16:50	10.44	30	51	581	113	0.502	9.30	7.53	19.1	0.03157	16.59	119.6	119.4	23.6	116.8	43.7

Notes:

1. Data collected 175 feet downstream of diffusers
2. Tests conducted with 16 diffusers

Appendix E

Preliminary Performance/Cost Models

Preliminary Performance Analysis

Diffuser Treatment of Gas Supersaturation

Case No. 1 - Realistic Case

Grand Coulee, WA		Units	Source	Alamosa Field Test *	Units	Source
Design Parameters						
Design Flow Rate	210,000	cfs	(Grand Coulee (G.C.) - 7 day/10 year statute)			
River Depth	50	ft	(Estimated from G.C. documents, conservative, fluctuates by ~30')	4	ft	(Actual)
Useable Width	200	ft	(Estimated from G.C. documents)	15	ft	(Actual)
Avg. Flow Rate	109,000	cfs	(G.C.)	12.4	cfs	(Actual)
Max. TDG	120	%	(Historical data, assumed maximum w/o regulatory exemptions)	126	%	(Actual)
Target TDG Concentration	110	%	(Regulatory requirement)	119.4	%	(Actual)
Diffuser System						
Diffuser Width	4	ft		0.27	ft	(Actual)
Diffuser Length	8	ft		2.29	ft	(Actual)
Diffuser Surface Area	32	ft^2	(Calculated)	0.62	ft^2	(Actual)
Diffuser weight/ft^2	6.4	lb/ft^2	(4.4 lbs for ceramic, 2 lbs for frame/housing)			
Diffuser weight	204.8	lbs	(Calculated)			
** Treatment Effectiveness	164.82	cfs/ft^2	(Cfs treated per square foot of diffuser, calculated from flow, depth, etc.)	19.98	cfs/ft^2	(Calculated)
*** Contingency	-	%	(Added due to uncertainty in treatment effectiveness, see notes)			
Total Diffuser Area	1274.08	ft^2	(Calculated)	9.93	ft^2	(Calculated)
Number of Diffusers	40		(Calculated)	16		(Actual)
Gas	O_2		(Assume 90%+ oxygen)	O_2		
Operating Pressure	51.7	psi	(Calculated)	30	psi	(Actual)
Boyle's Law Correction	-		(To be added later, expected to be minimal)	-		
Gas Flow Rate/Area	5.14	scfh/ft^2	(Actual from field tests)	5.14	scfh/ft^2	(Calculated)
Gas Flow Rate	6543	scfh	(Calculated)	51	scfh	(Actual)
"	109	scfm	(Calculated)	0.85	scfm	(Calculated)
Gas Density	0.0828	lb/scf	(Standard tables)	0.0828	lb/scf	
Mass Flow Rate	542	lb/h	(Calculated)	4	lb/h	
Power Factor for O_2	25.00		(Estimated power multiplier to produce 90%+ oxygen, very conservative)	25.00		
Fluid Horsepower	51.1	hp	(Calculated)	0.23	hp	
Efficiency	22	%	(Estimated from typical compressor efficiency values)	22	%	
Actual Horsepower	232	hp	(Calculated)	1.05	hp	
Annual Hours of Operation	2000	hrs	(Estimated average)			
Annual Energy Usage	348703	kWh	(Calculated, confirmed using 3.5 kWh/ft^3 of oxygen produced)			

* The Alamosa field test data was collected in August 2001 and is representative of similar conditions in the Columbia River.

** 'Treatment Effectiveness' is an estimated formula based on current knowledge of the process.
This formula will be refined to further consider turbulence, bubble bouyancy, and other parameters as the project proceeds.

*** Contingency added to total diffuser area based on current uncertainty. Will be revised as additional testing proceeds.

Preliminary Cost Analysis

Diffuser Treatment of Gas Supersaturation

Case No. 1 - Realistic Case

Grand Coulee, WA

	Unit	Unit Cost	Quantity	Total	Source/Assumptions
Capital Cost					
Treated Diffusers	ft^2	$ 200	1280	$ 256,000	(Calculated based on assumed cost/ft^2)
Oxygen-Enriching System/Compressors	ls*		1	$ 196,000	(Estimate based on $30 per scfh at full pressure, conservative)
High Pressure Tank	ls		1	$ 33,000	(Rough estimate, $5 per scfh required)
Control System	ls		1	$ 10,000	(Estimate)
Mounting Structure	ls		1	$ 382,000	(Rough estimate, $300 per ft^2 of diffuser)
Piping/Valves/Hoses	ls		1	$ 80,000	(Estimate at $2000 per diffuser)
Electrical	ls		1	$ 61,000	(Estimate at $15,000 + $200 per hp required)
Installation	ls		1	$ 192,000	(Rough estimate based on number/size of diffusers, ~$150/$ft^2$)
Shipping/Transportation	ls		1	$ 12,000	(Estimate based on size/weight and assumed number of shipments)
Total Capital Cost				**$ 1,210,000**	
Annual O&M					
Power	kWh	$ 0.02	348703	$ 7,000	(Calculated based on typical G.C. energy costs)
Diffuser Repair/Repl/Cleaning	ls		1	$ 38,000	(Estimate at 15% of diffuser cost annually)
Compressor Repair/Repl/Service	ls		1	$ 29,000	(Estimate at 15% of compressor costs)
Additional Labor	hrs	$ 70	200	$ 14,000	(Estimate)
Total Annual O&M				**$ 88,000**	

Note: These are preliminary cost estimates based on the listed assumptions and minimal quotes from vendors.

* ls = lump sum

Preliminary Performance Analysis

Diffuser Treatment of Gas Supersaturation

Case No. 2 - Assumed Worst Case, 100% Contingency on Performance

Grand Coulee, WA		Units	Source	Alamosa Field Test *	Units	Source
Design Parameters						
Design Flow Rate	210,000	cfs	(Grand Coulee (G.C.) - 7 day/10 year statute)			
River Depth	50	ft	(Estimated from G.C. documents, conservative, fluctuates by ~30')	4	ft	(Actual)
Useable Width	200	ft	(Estimated from G.C. documents)	15	ft	(Actual)
Avg. Flow Rate	109,000	cfs	(G.C.)	12.4	cfs	(Actual)
Max. TDG	120	%	(Historical data, assumed maximum w/o regulatory exemptions)	126	%	(Actual)
Target TDG Concentration	110	%	(Regulatory requirement)	119.4	%	(Actual)
Diffuser System						
Diffuser Width	4	ft		0.27	ft	(Actual)
Diffuser Length	8	ft		2.29	ft	(Actual)
Diffuser Surface Area	32	ft^2	(Calculated)	0.62	ft^2	(Actual)
Diffuser weight/ft^2	6.4	lb/ft^2	(4.4 lbs for ceramic, 2 lbs for frame/housing)			
Diffuser weight	204.8	lbs	(Calculated)			
** Treatment Effectiveness	164.82	cfs/ft^2	(Cfs treated per square foot of diffuser, calculated from flow, depth, etc.)	19.98	cfs/ft^2	(Calculated)
*** Contingency	100	%	(Added due to uncertainty in treatment effectiveness, see notes)			
Total Diffuser Area	2548.16	ft^2	(Calculated)	9.93	ft^2	(Calculated)
Number of Diffusers	80		(Calculated)	16		(Actual)
Gas	O_2		(Assume 90%+ oxygen)	O_2		
Operating Pressure	51.7	psi	(Calculated)	30	psi	(Actual)
Boyle's Law Correction	-		(To be added later, expected to be minimal)	-		
Gas Flow Rate/Area	5.14	scfh/ft^2	(Actual from field tests)	5.14	scfh/ft^2	(Calculated)
Gas Flow Rate	13087	scfh	(Calculated)	51	scfh	(Actual)
"	218	scfm	(Calculated)	0.85	scfm	(Calculated)
Gas Density	0.0828	lb/scf	(Standard tables)	0.0828	lb/scf	
Mass Flow Rate	1084	lb/h	(Calculated)	4	lb/h	
Power Factor for O_2	25.00		(Estimated power multiplier to produce 90%+ oxygen, very conservative)	25.00		
Fluid Horsepower	102.3	hp	(Calculated)	0.23	hp	
Efficiency	22	%	(Estimated from typical compressor efficiency values)	22	%	
Actual Horsepower	465	hp	(Calculated)	1.05	hp	
Annual Hours of Operation	2000	hrs	(Estimated average)			
Annual Energy Usage	697406	kWh	(Calculated, confirmed using 3.5 kWh/ft^3 of oxygen produced)			

* The Alamosa field test data was collected in August 2001 and is representative of similar conditions in the Columbia River.

** 'Treatment Effectiveness' is an estimated formula based on current knowledge of the process. This formula will be refined to further consider turbulence, bubble bouyancy, and other parameters as the project proceeds.

*** Contingency added to total diffuser area based on current uncertainty. Will be revised as additional testing proceeds.

Preliminary Cost Analysis

Diffuser Treatment of Gas Supersaturation

Case No. 2 - Assumed Worst Case, 100% Contingency on Performance

Grand Coulee, WA

	Unit	Unit Cost	Quantity	Total	Source/Assumptions
Capital Cost					
Treated Diffusers	ft^2	$ 200	2560	$ 512,000	(Calculated based on assumed cost/ft^2)
Oxygen-Enriching System/Compressors	ls*		1	$ 393,000	(Estimate based on $30 per scfh at full pressure, conservative)
High Pressure Tank	ls		1	$ 65,000	(Rough estimate, $5 per scfh required)
Control System	ls		1	$ 10,000	(Estimate)
Mounting Structure	ls		1	$ 764,000	(Rough estimate, $300 per ft^2 of diffuser)
Piping/Valves/Hoses	ls		1	$ 160,000	(Estimate at $2000 per diffuser)
Electrical	ls		1	$ 108,000	(Estimate at $15,000 + $200 per hp required)
Installation	ls		1	$ 384,000	(Rough estimate based on number/size of diffusers, ~$150/$ft^2$)
Shipping/Transportation	ls		1	$ 12,000	(Estimate based on size/weight and assumed number of shipments)
Total Capital Cost				**$ 2,396,000**	
Annual O&M					
Power	kWh	$ 0.02	697406	$ 14,000	(Calculated based on typical G.C. energy costs)
Diffuser Repair/Repl/Cleaning	ls		1	$ 77,000	(Estimate at 15% of diffuser cost annually)
Compressor Repair/Repl/Service	ls		1	$ 59,000	(Estimate at 15% of compressor costs)
Additional Labor	hrs	$ 70	200	$ 14,000	(Estimate)
Total Annual O&M				**$ 164,000**	

Note: These are preliminary cost estimates based on the listed assumptions and minimal quotes from vendors.

* ls = lump sum

Appendix F

Unit Conversions

Unit Conversion Factors

Multiply	By	To Obtain
cfs	7.4805 1699 0.64632	gallons/sec liters/min MGD
in	2.54	cm
ft	0.3048	meters
ft^2	0.09290304	m^2
lbs (mass)	0.45359237	kilograms
lbs (force)	4.448222	newtons
kWh	3412	BTU
micron	0.001 $1x10^{-6}$ 3.93×10^{-5}	millimeters meters inches
mg/L	1 6.2428×10^{-5}	ppm lb/ft^3
scfh	7.481	gallons/hr
°F	°C = (°F-32°)/1.8	°C