Non-Buoyant Oxygen Infusion Treatment

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EXECUTIVE SUMMARY

PROJECT GOAL

Oxygen is universally used to support the biological treatment of wastewater in support of the biological oxidation of organics and nitrogen compounds. The oxygen needed to support these aerobic processes is conventionally provided via energy intensive mechanical systems that can account for roughly 60% of a wastewater facility's energy demand. This emerging technology (ET) project evaluates the treatment efficiency impacts of applying a non-buoyant oxygen infusion treatment technology in a municipal wastewater system, first in the sewer and then in a side stream treatment process at the wastewater treatment facility. The technology is an alternative means of infusing oxygen into water in a more physically optimized and energy efficient manner to achieve a broad range of treatment objectives.

TECHNOLOGY DESCRIPTION

The non-buoyant oxygen infusion treatment technology provides a novel approach to oxidize dissolved sulfide, ammonia and biochemical oxygen demand (BOD) in wastewater with a lower energy threshold than conventional oxidation methods. The technology purifies ambient air to form pure oxygen which is pressurized and emulsified into a stream of water and discharged at high velocity through capillary tubes submerged in water. The process creates an ultra-fine diffusion of molecular oxygen in the form of nano-bubbles, which collapse upon being discharged into the water, and is hypothesized to generate radical hydroxyl ions of oxygen. This results in a non-buoyant fluid saturated with highly charged ion radicals of oxygen which remain suspended in water and achieve significantly higher levels of Standard Oxygen Transfer Efficiency (SOTE) than conventional fine or coarse bubble aeration methods, reducing the need for both mechanical and chemical treatments.

PROJECT FINDINGS

This technology was deployed in a two-phase effort at the San Luis Obispo Water Resource Recovery Facility (WRRF) for preliminary treatment of wastewater in the sewer and an in-plant high-strength side stream. Process performance and energy demand, both locally and throughout the facility, were monitored for periods of time prior to, during, and following the pilot effort. To establish an accurate baseline for this project, an evaluation was conducted of the process and energy performance of the secondary treatment process in-situ oxidation technology at the WRRF.

Phase 1 of the study, evaluating the technology in the collection system, was ended prematurely due to site based technical issues related to equipment clogging and noise complaints.

Phase 2 of the study evaluated the technology applied to a high-strength side stream discharge from the dewatering system to the Supernatant Lagoon (SNL), which was then recirculated back to the secondary treatment system. Ammonia levels entering and exiting the side stream were measured to determine technology treatment effectiveness. Phase 2 was staged to test the technology under different operating strategies, loading conditions and varying outputs common to the industry to identify optimal energy and process performance parameters.

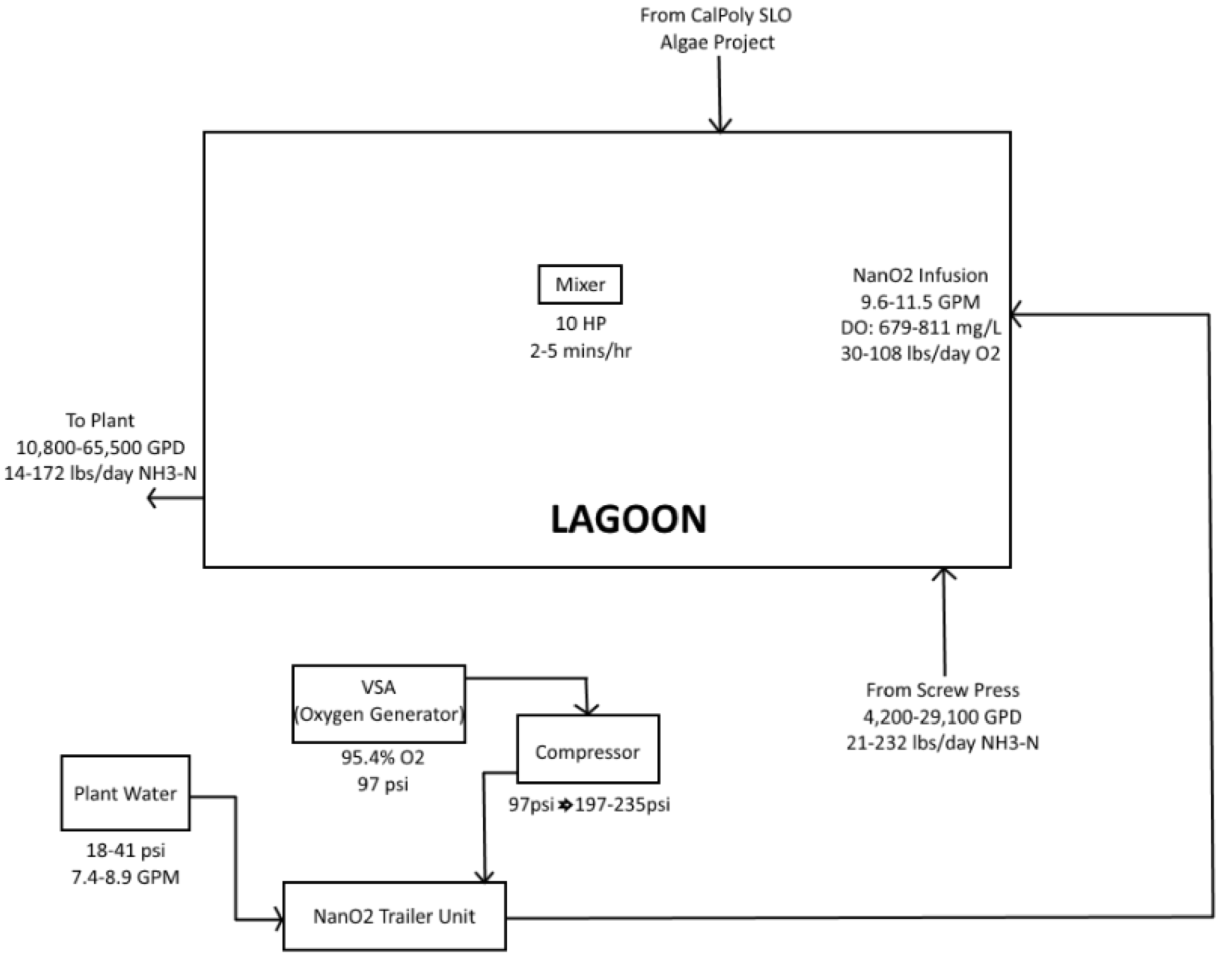

FIGURE 1 SIMPLIFIED SINGLE LINE DIAGRAM OF THE PHASE 2 EFFORT

Over the course of Phase 2, measured data indicated that the non-buoyant oxygen infusion treatment technology achieved an oxidation rate of 1.41 lbs of oxygen per lb of ammonia destroyed on average, compared to the industry standard rate of 4.5 lbs of oxygen per lb of ammonia destroyed. The variability of the oxidation efficiency of the infusion technology is attributed to the various iterations of operation implemented throughout the pilot, including timing and system pressures.

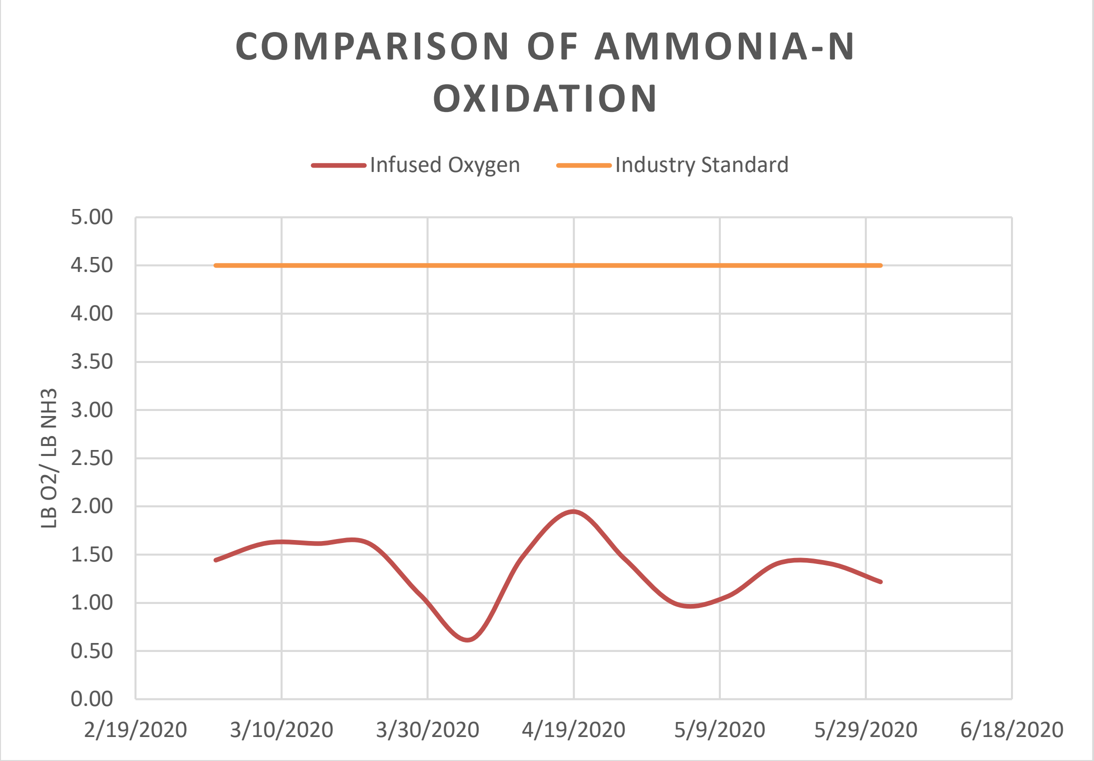

Figure 2 Comparison of Ammonia-N Oxidation Savings to In-Situ Conditions

While the demonstration unit was not sized to treat the entirety of the side steam load, it reduced the applied energy specific to the rate of oxidation of Ammonia-N (ammonia as nitrogen) by an average of 21% over baseline methods. This is represented in Table 1 below as “New Technology – Measured Side Stream Savings”. During 2019, the activated sludge system at SLO operated at an average removal efficiency of 2.80 kWh per lb Ammonia-N, while the infusion technology was able to achieve the same metric at an efficiency of 1.62 kWh per lb of Ammonia-N. In a properly sized and operationally optimized condition, an expected efficiency of 0.80 kWh per lb of Ammonia-N is expected. As all Ammonia-N loading to the treatment facility would require oxidation at the activated sludge system, this presented the opportunity to more energy-efficiently provide treatment using the infusion technology.

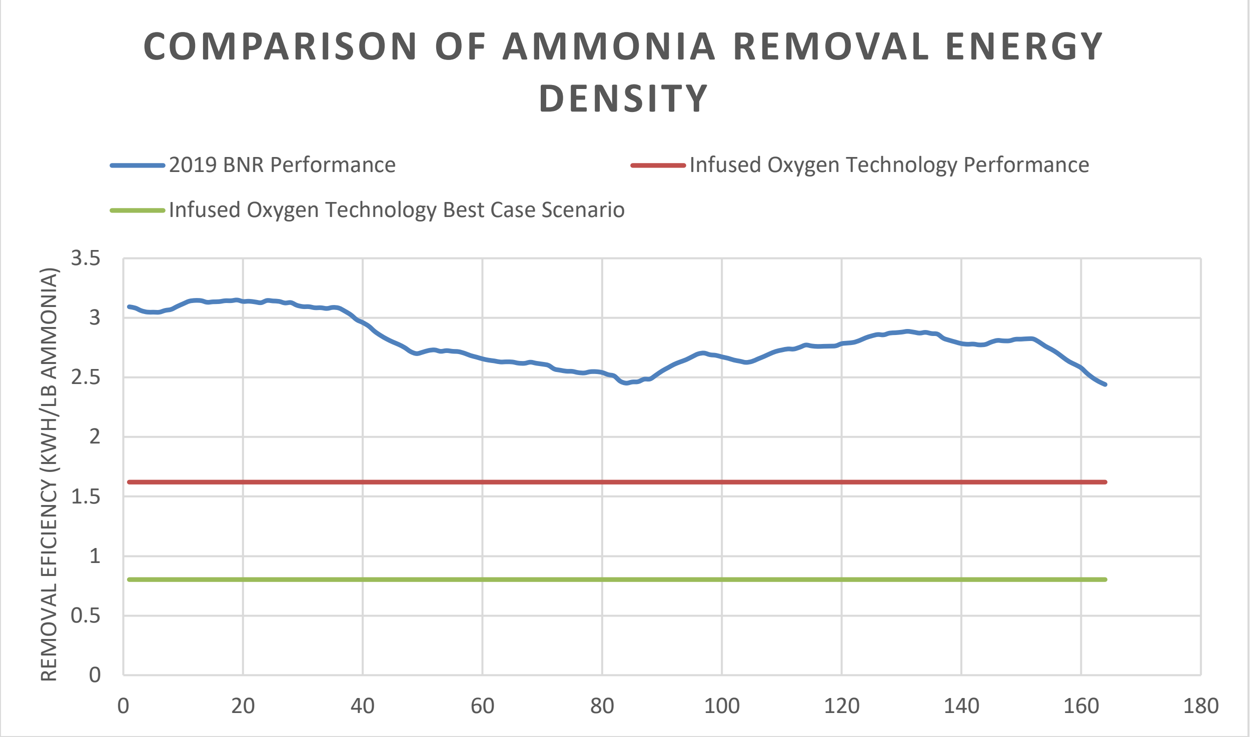

FIGURE 3 COMPARISON OF ENERGY DENSITY TO THE IN-SITU CONDITIONS

Applying the same average treatment efficiency, the team calculated that if the unit had been sized to treat the entire load entering the SNL, it would have reduced the applied energy specific to the rate of oxidation of Ammonia-N by ~69% over the baseline conditions. This is represented in Table 1 (page VI) as “New Technology – Potential Side Stream Savings”.

Finally, the team calculated the potential savings if the unit had been sized to treat the entire side stream load, and the unit had been operated continuously at the optimal operating conditions discovered during the various test stages, which achieved a best case treatment efficiency of 0.7 lbs per lb of oxygen destroyed. In this scenario, the unit would have reduced the applied energy by 84% over the baseline conditions. This is represented in Table 1 as “New Technology –Optimized Potential Side Stream Savings”.

It is likely that efficiency improvements beyond the 0.7 lbs per lb of oxygen could be achieved by utilizing higher pressure gas delivery of 300 psi as designed, which is possible in a stationary unit configuration with properly sized external oxygen generation and pressurization systems.

The table below provides an overview of the energy savings potential for this technology in comparison to incumbent technologies. Table 1 presents the baseline of savings within the capacity limits of the non-buoyant oxygen infusion treatment Demonstration Unit (NDU) as it functioned during the limited time of the project and with the constraints of the rented oxygen supply and compressor system.

TABLE 1 SUMMARY OF ENERGY SAVINGS AND DEMAND REDUCTION

	LB OF O_2 PER LB OF AMMONIA REMOVED	ANNUAL ENERGY CONSUMPTION (KWH/YR)	ANNUAL ENERGY SAVINGS (KWH/YR)	PEAK DEMAND (KW)	DEMAND REDUCTION (KW)	SAVINGS OVER BASELINE (%)
Industry Baseline	4.5	173,234	-	23	-	(%)
New Technology – Measured Side Stream Savings	1.41	136,525	36,709	17	6	21%
New Technology – Potential Side Stream Savings	1.41	53,703	119,531	5	18	69%
New Technology – Potential Optimized Side Stream Savings	0.7	26,946	146,288	5	18	84%

In addition to energy benefits, several non-energy process benefits were measured including the destruction of hydrogen sulfide in the sewer and volatile fatty acids (measured as soluble BOD), enhanced settling and clarification, prevention of algae growth, and reduced chemical demand for pH control via pass through of total alkalinity, all of which lead to potentially significant cost savings benefits for treatment plant operations.

Table 2 describes the cost effectiveness of the three evaluated installation scenarios. Energy cost savings are based on a blended average cost per kWh over a 12-month period, from January through December of 2019, averaging $0.14/kWh. Incentives are estimated at $0.12/kWh and $150/kW. A permanent configuration would entail the installation of an IN-15 unit, estimated by the manufacturer at a cost range between $315,000 and $350,000 depending on site specific characteristics. An average cost of $330,000 was used for the cost-benefit analysis. Although the simple payback period (SPP) exceeds the estimated useful life of the equipment of 15 years, the annual cost savings attributable to non-energy process benefits in the form of operations and maintenance (O&M), chemical usage, and process reliability have not been quantified or included. Further quantification of these metrics would improve the cost effectiveness of this measure.

TABLE 2 COST-BENEFIT ANALYSIS

	ANNUAL ENERGY SAVINGS (KWH/YR)	DEMAND REDUCTION (KW)	ENERGY COST SAVINGS ($/YR)	INCENTIVE ($)	INSTALLED COST ($)	SIMPLE PAYBACK PERIOD (YRS)
New Technology – Measured Side Stream Savings	36,709	6	$5,139	-	-	-
New Technology – Potential Side Stream Savings	118,823	19	$16,635	$17,109	$330,000	18.8
New Technology – Potential Optimized Side Stream Savings	146,286	19	$20,480	$20,404	$330,000	15.1

PROJECT RECOMMENDATIONS

The non-buoyant oxygen infusion treatment technology has the potential to provide energy and performance improvements to sewage treatment systems in a variety of applications, and to deliver energy efficiency and demand response benefits through utility programs. Based on the findings of this preliminary study, which focused on treating a portion of a side stream, the technology significantly improved the SOTE and treatment efficiency which, when applied to broader treatment loads, could have a major impact on system-wide energy loads including aeration, pumping, and UV disinfection.

Additional studies are needed to expand on these findings and evaluate the energy and process impacts on broader wastewater applications including in the primary treatment, secondary treatment, solids handling, and tertiary treatment/disinfection systems. This may include larger scale implementations, and targeted Utility program support to mitigate market barriers of low product awareness, low customer priority, and capital costs of the technology integration through incentives for early adoption. For the technology to gain market traction and adoption, plant managers and operators will need to be aware of, and open to, advances in treatment approaches that challenge business-as-usual paradigms.

The evaluated technology manufacturer reports that enhancements to the NDU are underway to improve system pressure, control and reliability. This could further expand the electro-chemical impacts of the system and increase on-board energy efficiency of the test unit. These improvements will be incorporated progressively as the NDU is tested for other applications at other sites.

Once additional test sites are selected, it will be important to develop a robust sampling and monitoring plan to fully characterize the holistic impact of the non-buoyant oxygen infusion electro-chemical treatment benefits (the unanticipated but observed creation of radical hydroxyl ions of oxygen), versus normally expected biological conditions. In addition, it will be critical to use chemical analytical procedures to define the electro-chemical pathways within the oxygen emulsion process to determine appropriate energy demand to support optimum energy consumption relative to constituent treatment and removal.

ABBREVIATIONS AND ACRONYMS

AOP	Advanced oxidation processes (AOPs) - a set of chemical treatment procedures designed to remove organic and sometimes inorganic materials in water and wastewater by oxidation through reactions with hydroxyl radicals (·OH).
BNR	Biological Nutrient Removal (BNR) - a process to remove nitrogen and phosphorus from wastewater before it is discharged into surface or ground water.
BOD	Biochemical Oxygen Demand (BOD) - a measure of the amount of oxygen required to remove waste organic matter from water in the process of decomposition by aerobic bacteria (those bacteria that live only in an environment containing oxygen)
CBOD	Carbonaceous Biochemical Oxygen Demand (CBOD) - the BOD from organic (carbon-containing) compounds as well as the oxidation of inorganic compounds such as ferrous iron and sulfide.
DO	Dissolved Oxygen - molecular oxygen dissolved in water
GHG	Greenhouse Gas Emissions
H_2S	Hydrogen Sulfide in air
HS^-	Sulfide - gaseous sulfide in water
MGD	Million gallons per day
Mg/L	Milligrams per liter
Micro	Extremely small, usually measured in micrometers
NDU	Non-buoyant oxygen infusion treatment Demonstration Unit
N_2	Nitrogen gas
N_2O	Nitrous oxide
NO	Nitric oxide
NH_3-N or NH_4-N	Ammonia in water. The terms NH3-N or NH4-N are interchangeable, commonly used in scientific publications to depict Ammonia in water and not the measure of its quantity.
NO3-N	Nitrate-nitrogen
NO2-N	Nitrite-nitrogen
PLC	Programmable Logic Controller
SLO	San Luis Obispo
SOTE	Standard Oxygen Transfer Efficiency
SMP	Sampling and Monitoring Plan
SNL	Supernatant Lagoon
TKN	Total Kjeldahl Nitrogen - a measure of all inorganic nitrogen compounds plus organic nitrogen
TVA	Total Volatile Acids
VSA	Vacuum Swing Absorption unit - used to separate oxygen from atmospheric air to create pure oxygen for compression in the NDU
WRRF	Water Resource Recovery Facility

CONTENTS

EXECUTIVE SUMMARY ____ II

Project Goal ii

Technology Description ii

Project Findings ii

Project Recommendations vi

ABBREVIATIONS AND ACRONYMS ____ VIII

INTRODUCTION ____ 1

The Problem with Air in Conventional Biological Oxidation of Ammonia 1

Market Segments 3

EMERGING TECHNOLOGY BACKGROUND ____ 10

Existing Installations 10

Manufacturing and Field Support 12

Scientific Principle of Technology 12

Purification 14
Emulsification 14
Infusion 14

Incumbent Technologies & Practices 15

Sewage Collection Systems 15
Side-Stream Treatment 16
Primary Treatment Systems 17
Secondary Treatment Systems 17

ASSESSMENT OBJECTIVES ____ 20

Phase I – Preliminary Treatment of Raw Sewage 20

Phase II – Treatment of Side Stream Supernatant 21

TECHNICAL APPROACH & TEST METHODOLOGY ____ 22

Host Site Description 22

San Luis Obispo Water Resource Recovery Facility 22
San Luis Obispo Wastewater Collection System 24

Pilot Test Chronology 24

Phase I – Calle Joaquin Pump Station 24
Phase II – WRRF Supernatant Lagoon 26

M&V Plan 29

Phase I – Preliminary Treatment of Raw Sewage 29
Phase II – Treatment of Side Stream Supernatant 31

RESULTS 34

Phase I – Calle Joaquin Pump Station 34

Phase II – SNL Application 34

Stage 1 – Baseline Analysis – January 30 through February 15, 2020 35

Stage 2 – Initiation of Nano-bubble infusion Oxygen Emulsion for DO Control – February 15 through March 28, 2020 36

Stage 3 – Sludge Blanket Characterization and Bio-Augmentation for Denitrification – March 29 through May 23, 2020 39

Stage 4 – Cease Cycling of Non-Buoyant Oxygen infusion Feed and Characterize Sludge Blanket 42

Stage 5 – Cessation of Non-Buoyant Oxygen Infusion Operation and Return to Conventional Treatment – May 31 through June 10, 2020 43

Phase II Summary 44

DISCUSSION 45

Results of the Assessment 45

Phase I 46

Phase II 46

Performance of Non-Buoyant Oxygen Infusion Treatment Demonstration Unit 48

Energy Impact 49

Barriers 49

Tools for Measurement 50

Non-Energy Benefits 50

Market Barriers 51

RECOMMENDATIONS 51

Management Considerations 51

Technical Recommendations 51

Data and Analysis Recommendations 52

APPENDICES 53

Calculation Methodology 56

REFERENCES, OPTIONAL 60

GLOSSARY 61

FIGURES

Figure 1 Simplified Single Line Diagram of the Phase 2 Effort iii
Figure 2 Comparison of Ammonia-N Oxidation Savings to In-Situ Conditions iv
Figure 3 Comparison of Energy Density to the In-Situ Conditions v
Figure 4 Composition and Content of Dry Air by Percentage 2
Figure 5 Overview of system prior to Non-Buoyant Oxygen infusion integration 11
Figure 6 Non-Buoyant Oxygen Infusion Installation 11
Figure 7 Upper left pond 125 days after system commissioning........ 11
Figure 8 Relation of Bubble Size to Transfer Efficiency 13
Figure 9 Non-Buoyant Oxygen Infusion Technology Schematic......... 14
Figure 10 Infusion of Supersaturated Oxygen Emulsion........ 15
Figure 11 Schematic of Side stream Pre-Treatment 17
Figure 12 Schematic of Side stream Equalization........ 17
Figure 13 Simplified Overview of the WRRF operations........ 22
Figure 14 Overview of Lagoon System and Highlight of Non-Buoyant Oxygen Infusion Technology 23
Figure 15 Elevation Drawing of the Existing Lagoon System........ 24
Figure 16 Collection Systems Map 24
Figure 17 Calle Joaquin Pump Station 25
Figure 18 Called Joaquin Sewer Pump Station Power Supply Switchgear 25
Figure 19 Calle Joaquin pump Station Proximity to Local Hotels 26
Figure 20 Staff Obtaining Grab Sample of Sludge 28
Figure 21 Basic Schematic of Monitoring Locations and Non-Buoyant Oxygen Infusion Technology Integration........ 31
Figure 22 Sampling Log Used by Site for Phase II of the Pilot Test.... 33
Figure 23 Hach AS950 Sampler........ 33
Figure 24 Emulsification Oxygen Flow in to Supernatant Lagoon at SLO WRRF........ 37
Figure 25 Diurnal observations of ORP and DO measurements......... 47
Figure 26 Comparison of Ammonia-N Oxidation of Industry Standard and Emerging Technology........ 53
Figure 27 Comparison of Ammonia-N Energy Density Between SLO BNR System and Emerging Technology 54
Figure 28 Historical Ammonia-N Loading from SNL 56
Figure 29 2019 BNR Oxygen Energy Density........ 57

TABLES

Table 1 Summary of Energy Savings and Demand Reduction vi
Table 2 Cost-Benefit Analysis vi
Table 3 Collection System Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 6
Table 4 Side-Stream Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 7
Table 5 Primary Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 7
Table 6 Secondary Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 8
Table 7 Solids Handling Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 8
Table 8 Tertiary Treatment Objectives and Benefits of Non-Buoyant Oxygen Infusion 9
Table 9 Aeration Equipment and Standard Aeration Efficiency (SAE) . 18
Table 10 Phase I Sampling and Monitoring Plan 29
Table 11 Phase II Sampling and Monitoring Plan 32
Table 12 SNL Conditions During Initial Startup 36
Table 13 Stage 2 SNL Conditions 38
Table 14 Stage 2 Analysis of Nano-bubble infusion Oxidation of NH4-N 38
Table 15 Stage 3 Sludge Analysis 40
Table 16 Stage 3 SNL Conditions 41
Table 17 Stage 3 Analysis of Nano-bubble infusion Oxidation of NH4-N 41
Table 18 Re-evaluation of Stage 2 Nano-bubble infusion Oxidation of NH4-N 42
Table 19 Stage 4 SNL Conditions 43
Table 20 Stage 4 Analysis of Nano-bubble infusion Oxidation of NH4-N 43
Table 21 Stage 5 SNL Conditions 44
Table 22 Overview of the baseline scenario energy and demand usage 44
Table 23 Overview of the Proposed Scenario Energy and Demand Usage 45
Table 24 Overview of pilot energy and demand savings 45
Table 25 Theoretical Energy and demand savings.......................... 45
Table 26 Summary of Energy Savings 49

Table 27 Overview of Baseline and Proposed Scenario Energy Savings.......... 55

Table 28 Overview of the Potential Energy Savings for the Average Case Scenario.......... 55

Table 29 Overview of the Potential Energy Savings for the Best Case Scenario with Denitrification 56

INTRODUCTION

California has a network of more than 2,100 wastewater treatment plants, municipal water agencies, special districts, public utilities, municipal water companies, and county districts. Water and wastewater facilities account for nearly 40% of a municipality's energy consumption and in times of austerity can be an increasingly lucrative opportunity for energy cost saving investments. Additionally, recent changes in the chemistry of raw sewage due to elevated temperatures, as well as decreased flow rates resulting from droughts, has increased the process energy demand in many facilities by well over 20% in the past five years.

According to a 2008 analysis of SCE's public sector sewage treatment plants (STPs) conducted by SCE's Design and Engineering Services group, there were 1,728 plants with capacity flow greater than 1 million gallons per day (MGD), with a total annual electric impact of 407,000 MWh/yr. Typically, the energy used to mechanically introduce oxygen in the treatment process accounts for roughly 60% of a facility's usage, equaling roughly 244,200 MWh/yr of energy consumed to oxidize wastewater in these facilities in SCE's territory alone.

This study explores the energy and cost savings, process optimization potential, potential applications within the water and wastewater sector, and the technical opportunity of a non-buoyant oxygen infusion treatment technology in the wastewater sector. The non-buoyant oxygen infusion treatment technology uses an electro-chemical mechanism to rapidly oxidize dissolved sulfide, ammonia, and biochemical oxygen demand (BOD) with a low threshold of energy consumption. This technology was deployed in a two-phase effort at the San Luis Obispo Water Resource Recovery Facility (WRRF) for preliminary treatment of raw sewage (Phase I) and an in-plant high-strength side stream (Phase II) to quantify the opportunity to infiltrate the market and potential barriers.

This study was performed by AESC on behalf of SCE's Emerging Products (EP) group. In part, the EP program strives to increase the exposure and success of emerging and underutilized energy efficiency (EE) and Demand-Side Management (DSM) technologies in California.

THE PROBLEM WITH AIR IN CONVENTIONAL BIOLOGICAL OXIDATION OF AMMONIA

In wastewater treatment, oxygen is used to biologically convert and remove carbonaceous and nitrogenous materials. The development and enhancement of aeration technologies for biological wastewater treatment have been relatively stagnant and standardized for decades, with the exception of attempting to create finer bubbles, more efficient blowers and refined durability and Programmable Logic Controller (PLC) control of sensors and dissolved oxygen (DO) control. These enhancements have provided only nominal, incremental improvement in energy profiles.

In conventional aeration, mildly compressed air is used to mix oxygen with bacteria in wastewater treatment systems to support metabolism for uptake of carbon and nitrogen inherent in sewage. Energy is used to push air (surrogate for oxygen) through blowers into water through submerged diffusers.

Air is an inherently inefficient means of transferring oxygen to water. Because Oxygen comprises only 21% of a volume of air, about 79% of the energy used to move air is wasted moving non-useful gases, CO2 and N2, which provide no measurable treatment value, except mixing; the bacteria do not use much of the carbon dioxide (CO2) and none of the nitrogen (N2) inherent in air.

Figure 1 describes the composition and content of dry air. The oxygen in the supplied air must be sufficient to support full biological treatment of the organics and nitrogen. No artificial chemistry is used other than to maintain proper pH for the biological metabolism.

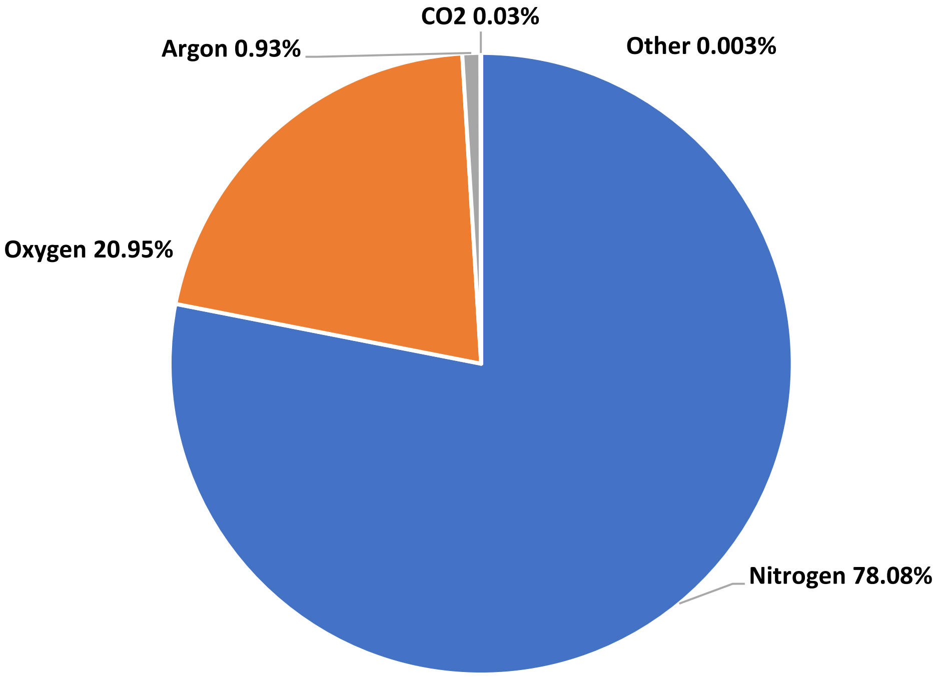

FIGURE 4 COMPOSITION AND CONTENT OF DRY AIR BY PERCENTAGE

Because air bubbles are buoyant, air needs to be mechanically pressurized and introduced at the bottom of the tank by a diffusion system, typically at a water depth of 14-19' of submergence. This depth is necessary to allow time for the oxygen bubbles to come into contact with the water as they rise, in order to provide transfer of some of the oxygen into the water. Submerged diffusers are not mounted directly on the tank floor, nor directly adjacent to each other, leaving voids and reducing mixing energy and effective tank volume at the base by typically 10%.

Standard Oxygen Transfer Efficiency (SOTE) is a ratio of the amount of oxygen that dissolves into water to the total amount of oxygen pumped into the water. Higher SOTE is associated with aeration at greater depth, but at the cost of increased energy of pressurization. The normal range of SOTE in conventional aeration is 8-18%. Entrained, non-soluble nitrogen maintains buoyancy and progressively reduces SOTE via molecular crowding while the bubbles rise. As bubbles rise, they also expand and coalesce into larger bubbles, further reducing SOTE relative to surface/volume, depth, time and distance of rise. Small bubbles increase SOTE, but do not provide robust mixing.

As only dissolved oxygen (DO) is available for treatment, a SOTE of 8-18% translates into 82-92% of the oxygen in conventional aeration being wasted when it rises and is released at the surface of the water. Some of the blower energy used to introduce oxygen to the treatment process also is designed to provide mixing force for the wastewater. The normal range of SOTE is 8-18% transfer of oxygen into water for biological uptake. This means that 82-92% of the oxygen remains in the bubble by the time it is released at the surface of the tank; by then, unusable and wasted.

MARKET SEGMENTS

Many industries use aeration/bubble technologies for biological oxidation in their physical, physical/chemical and biological processes. The following industries use these technologies both in their production processes and to treat waste generated in the production process:

- Water & Wastewater Treatment (Municipal and Industrial)
- Oil & Gas Production and Processing
- Pulp & Paper
- Food Processing and Beverage Production
- Dairy Production and Processing
- Power Generation
- Limestone Wet Flue Gas Desulfurization (WFGD)
- Shore & Onboard Based Marine
- Fermentation
- Bio-fuels Production (Enzymes)
- Yeast Production & Control
- Pharmaceutical Production
- Aquaculture

This study focuses on the application of non-buoyant oxygen infusion treatment technology to the wastewater sector. At this point of development, there appear to be four principle applications in wastewater treatment with various interconnected elements: (1) sewage collection systems, (2) side stream processes, and (3) primary and (4) secondary treatment processes. Additional benefits may be realized in tertiary treatment, solids handling, and in water treatment, but these benefits need further evaluation.

- Sewage Collection Systems – Emulsified oxygen may be used in sewer mains to prevent the formation of and destroy hydrogen sulfide, destroy ammonia and reduce BOD prior to the treatment plant. This reduces corrosion potential and decreases energy associated with oxygen demand in the treatment plant.
- Side-stream Treatment – Various side streams in wastewater treatment plants, such as digested sludge filtrate or dewatering centrate/pressate, create problematic, energy intensive loads within the plants. Application of emulsified oxygen can effectively treat these low-flow, high-concentration streams and reduce the energy demand on main-stream processes, such as energy intensive biological nutrient removal systems.

- Primary and Secondary Treatment Systems – Emulsified oxygen has two effects – physical and bio-chemical. In primary treatment, emulsified ionized oxygen functions as a coagulant that improves particle removal and sedimentation. Enhanced primary sedimentation reduces the energy demand imposed on secondary treatment by reducing the pass-through of particulate BOD, which must otherwise be treated with aerobic biological consortia. The enhanced sedimentation transfers organic mass to anaerobic digesters which produce recoverable methane for energy production and greenhouse gas (GHG) emission reduction. In secondary biological treatment, emulsified oxygen provides non-buoyant, molecular oxygen that enhances biological uptake and conversion of remaining BOD and ammonia. This can be used to enhance existing, energy-intensive aeration systems, or, coupled with a robust mixing system, as a singular replacement of that technology at a much-reduced capital and operating cost.

Other applications within water and wastewater treatment plants include but may not be limited to the following: inhibition of algal growth, improved coagulation and settling, enhanced biosolids dewatering, more effective operation of trickling filters, improved tertiary filter performance, enhanced UV disinfection, improved ozone saturation and potential recovery of hydrogen gas:

- Inhibition of Algal Growth – The introduction of oxygen to reservoirs, lagoons, ponds and tanks can change the physical chemistry of the water, providing DO that limits the ability of algae to grow. There are a variety of energy and non-energy benefits to removing algae from water treatment systems, such as reduced pumping energy and avoided addition of coagulants.
- Improved Coagulation and Settling – Providing coagulation in primary and secondary sedimentation tanks without alternative chemicals reduces particulate organic load to secondary systems and improves settling and compaction in secondary clarifiers with more concentrated sludge, reducing sludge pumping and recirculation rates.
- Enhance Biosolids Dewatering – Applying nano-bubble oxidation to anaerobically digested sludge prior to dewatering provides several significant benefits. It enhances dewatering via aerobic charge neutralization of the sludge particles, which overcomes electro-chemical properties of sludge in anaerobic conditions. Further, the additional chemical oxidation via the radical hydroxyl ions reacts with soluble phosphorus to form particulate phosphate (such as calcium phosphate) bound in the sludge. This prevents subsequent reaction with magnesium, ammonium and iron to that form struvite and vivianite after the dewatering process. This protects the dewatering system and downstream piping and pumps from chemical plating, especially problematic with systems incorporating high-phosphorus sludge, such as BNR activated sludge. Progressive scaling of pumps and pipe works reduces operating efficiencies and increases energy demand.
- Optimized Trickling Filter Operations – As generally the upper one-third of trickling filter media is not physically consuming particulate BOD, providing oxygen to the media can increase their effective oxidative capacity, reducing the required surface area and energy associated with surface wetting, recirculation and vent air.
- Improved Tertiary Filter Performance – Inclusion of superoxide and singlet oxygen enhances tertiary filter performance by formation of neutral charged particles. Unlike conventional coagulants, it provides not only coagulation but also destruction of short-chained organics that cause biological growth in the

filter media. This can enhance filter runs and reduce energy associated with frequent backwash cycles. Further, oxygen ions in excess of demands, before and in the filters, is available as a super-oxidant to further aid disinfection, reducing energy for ultraviolet (UV) application, as well as reduce chlorine demand for conventional chemical disinfection.

- Enhanced UV Disinfection – Cleaner secondary effluent improves the ultraviolet transmissivity (UVT) of wastewater destined for UV treatment. Further, the UV disinfection process is more efficient due to the radical oxygen ions in the Advanced Oxidation Process that are excited by UV irradiation. This electro-chemical reaction allows each oxygen ion in the UV chamber to provide more disinfection per unit of energy.
- Improved Ozone Saturation – Provides a non-buoyant ozone emulsion that stays in solution for hours or days instead of off-gassing within minutes. This increases the transfer efficiency related to retention time from an industry standard 15% to greater than 90%, significantly reducing energy demand associated with oxygen and ozone generation. Just as with SOTE, the transfer efficiency (TE) of ozone is measured by bubble size, temperature, gas to liquid ratio, concentration of ozone related to the ozone generation unit, and water chemistry. A more efficient (and smaller) ozone infusion system would dramatically improve TE. The non-buoyant oxygen infusion treatment technology is gas agnostic, Oxygen or Ozone can be infused in solution.
- Potential Recovery of Hydrogen Gas – Singlet oxygen and other oxygen radicals created in the non-buoyant oxygen infusion process react with ammonia to cleave the hydrogen from the nitrogen. Both gases become directly buoyant and rise to be potentially captured in a low-pressure vessel and refined via vacuum swing absorption as separate sources of nitrogen and hydrogen. The hydrogen can be blended with methane and digester gas to enhance the BTU value of the final product.

The current study selected the boundaries of the Phase I (Collection System) and Phase II (Side stream treatment) projects due to the small size of the demonstration unit, and the potential non-energy benefits that could be realized through these applications. It was necessary to select a site for both phases that could notice a measurable impact from the relatively low level of oxygen infusion that the demonstration unit can produce. Moreover, the inherent challenges associated with high-strength side-stream waste, and the odor and corrosion of sewer systems caused by high levels of H2S are both problems that justifiably receive a very high level of attention by facility operators and across the industry.

The following tables (Table 3 through Table 8) describe the proposed treatment objectives, energy benefits, and non-energy benefits of the non-buoyant oxygen infusion technology in wastewater treatment applications. Benefits that were measured or observed in this pilot study are marked with an Asterix, while other benefits would need to be demonstrated under different conditions in future study, as described in the recommendations.

TABLE 3 COLLECTION SYSTEM TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Collection System			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Prevent formation of hydrogen sulfide Destroy hydrogen sulfide	Chemical mitigation (Ferric, Mag Hydroxide, etc.) or bio-augmentation (non-pathogenic microbial solutions) with mechanical odor control (e.g. wet scrubber, dry scrubber, exhaust and ventilation fans)	Reduced energy demand from mechanical odor control (e.g. wet scrubber, dry scrubber, exhaust and ventilation fans).	*Reduced odor (chemical and other mitigation techniques) Deferred capital expenditures for corrosion mitigation (pipeline rehabilitation, lining, treatment). *Prevention of hydrogen sulfide and inhibition of nitrification in the secondary treatment process. Mitigate human health hazards associated with hydrogen sulfide.
Destroy ammonia	Aeration blower in activated sludge system (High-Speed Turbo Blower, Multi-stage Centrifugal Blower, etc.) with diffused aeration (coarse, medium, or fine bubble) and/or mechanical mixing.	Reduced aeration demand through higher Standard Oxygen Transfer Efficiency (SOTE) and improved electro-chemical conversion of NH3-N that reduces load on aeration blowers.	Increase treatment capacity in secondary treatment system.
Reduce Biochemical Oxygen Demand (BOD) load to secondary treatment process	Chemical mitigation (Ferric, Mag Hydroxide, etc.) or bio-augmentation (non-pathogenic microbial solutions)	Delay the breakdown of particulate BOD in collection system for settling in primary clarifiers and transfer to digester for enhanced biogas production. Avoids breakdown of particulates that pass through to secondary treatment and require excess load on aeration blowers.	Increase treatment capacity in secondary treatment system

TABLE 4 SIDE-STREAM TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Side-Stream Treatment			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Oxidation of targeted constituents to achieve outcomes such as nitrification-denitrification, nitritation-denitritation, and partial nitritation-anaerobic ammonium oxidation (de-ammonification). Suspected electro-chemical and biological oxidation of ammonia to N2 and NO2 prior to biological oxidation.	Sidestream pretreatment or sidestream equalization with oxidation energy demand (aeration blower and diffusers) and surface mixing to keep solids suspended within the equalization basin. Often pretreatment includes bioaugmentation (non-pathogenic microbial solutions).	*Reduced energy demand on primary and secondary treatment processes (sludge pumps, aeration blowers, mixing energy).	Reduced or avoided release of orthophosphate and ammonium during solids digestion decreases the accumulation of struvite or vivianite in pipelines.

TABLE 5 PRIMARY TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Primary Treatment			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Application of emulsified ionized oxygen to coagulate solids and improve particle removal and sedimentation.	Application of polymers or other coagulants, such as iron salts.	Reduced secondary treatment aeration demand on blowers from a reduction of pass-through particulate BOD in primary treatment. Reduced sludge pumping energy and transfer pump efficiency improvements. Increased organic mass transfer and conversion to methane in the digester as biogas.	Reduced chemical coagulant (e.g., polymers, iron salts) costs. Reduced sludge hauling and removal costs related to inefficient solids handling. Optimize capacity in digesters Reduce digester cleaning costs

TABLE 6 SECONDARY TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Secondary Treatment			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Application of emulsified pure oxygen to provide non-buoyant, molecular oxygen to enhance biological uptake and conversion of remaining BOD and ammonia.	Aeration blowers provide oxygen in atmospheric air to encourage biological uptake and conversion of BOD and ammonia.	*Reduce aeration energy demand on blowers.	Increased secondary system capacity due and avoidance of future expansion due to improved Standard Oxygen Transfer Efficiency (SOTE) and improved removal efficiency.
Application of oxygen to the trickling filter (TF) media to increase effective capacity, as generally the upper one-third of trickling filter media is not physically consuming particulate BOD. Oxidized molecules activate TF media.	Use of channel mixing with aeration blower to increase oxygen in Trickling Filter (TF) media. Increase trickling filter recirculation rates.	Reduced Trickling Filter (TF) pumping and recirculation energy.	Increased trickling filter capacity Extended useful life of pumps and motors. Improved BOD removal in trickling filter.

TABLE 7 SOLIDS HANDLING TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Solids Handling			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Oxidize fugitive sludge	Dredge, de-water, and haul	*Eliminate Volatile acids and sulfides in sludge, reducing aeration load in secondary clarifier.	Avoiding hauling costs
Super oxidizing nanobubbles react with soluble phosphorus to form particulate phosphate bound in the sludge, preventing a subsequent reaction with magnesium, ammonium and iron to form struvite and vivianite.	Application of hydrogen peroxide and other chemical inhibitors.	Improved efficiency of dewatering sludge and side-stream pumps as a result of lower levels of iron salt build up in pipes.	Reduced maintenance costs of removing iron salts and clearing pipelines. Extend equipment life of pipes, pumps, and motors due to reduced iron salt build up.

TABLE 8 TERTIARY TREATMENT OBJECTIVES AND BENEFITS OF NON-BUOYANT OXYGEN INFUSION

Tertiary Treatment/Disinfection			
Treatment Objective	**Industry Standard Practice (ISP)**	**Energy Benefits**	**Non-Energy Benefits**
Application of superoxide and singlet oxygen to enhance filtration. Forms neutral charged particles for coagulation and destroys short-chained organics which cause biological growth in the filter media.	Application of chemical and polymer coagulants to reduce biological growth in filter media.	Reduces energy related to frequent backwash cycles to improve filter operation. Excess oxygen ions are available to aid disinfection, reducing energy for ultraviolet (UV) application.	Reduced chlorine costs used in conventional chemical disinfection.
Application of nano bubbles to improve ultraviolet transmissivity (UVT)	Improved filter performance and secondary treatment removal efficiency	Reduced energy demand to achieve treatment in UV disinfection process	Extends bulb life of UV system
Radical oxygen ions in the Advanced Oxidation Process (AOP) are excited by UV irradiation	No ISP	Reduced energy demand to achieve treatment in UV disinfection process	Extends bulb life of UV system

EMERGING TECHNOLOGY BACKGROUND

The non-buoyant oxygen infusion treatment technology was initially developed in the medical field to oxygenate blood during heart transplants. The inventor, a cardiac surgeon, collaborated with a professional in the wastewater industry to scale up the concept for commercial applications in water and wastewater treatment. The system concept was patented to include a pressurization and saturation system to provide a high-pressure, high-velocity saturated solution of oxygen in water induced into a treatment stream via specialized capillary nozzles.

EXISTING INSTALLATIONS

To date, the non-buoyant oxygen infusion treatment technology has had limited application in the municipal wastewater industry. Initial tests of the technology were performed on private food and animal waste systems while the system configuration was first being developed and refined for commercial use. Two systems have been installed in rural municipal wastewater settings. One is in a sewage collection system in North Liberty, Illinois. The second is in a pond treatment plant in Mediapolis, Iowa. While both systems have been in service for over two years, they are sparse on operating data to quantify the energy and treatment benefits. Focused efforts are needed to provide a detailed understanding and quantification of the benefits and efficiency of the systems.

Only one commercial installation has been completed in a municipal wastewater treatment plant. A non-buoyant oxygen infusion treatment system was installed in the rural town of Mediapolis, Iowa, located 1.0 mile east-northeast of downtown, during the fall of 2018 and began operations on December 14, 2018. The City's treatment system consisted of six ponds fitted with conventional mechanical surface aerators. As shown by the photographs below (Figure 5), prior to the installation of the non-buoyant oxygen infusion treatment systems, Mediapolis's wastewater treatment ponds, run by the City, were in poor condition and were violating discharge standards with low dissolved oxygen and a considerable amount of suspended solids and algal growth, indicating high levels of nitrogen and minimal oxidation. Consequently, the City tested a mobile NDU, then purchased and installed a larger non-buoyant oxygen infusion treatment system capable of providing about 430 lbs per day of oxygen in emulsified form for $399,000 (Figure 6). As shown in Figure 7, below, by April 2019 the ponds had been restored to original condition.

Whole facility

Closeup of upper left pond

Figure 5 Overview of system prior to Non-Buoyant Oxygen infusion integration

Incoming supply purification tank, control panel, pressurization & saturation tank

Pressurization & saturation tank, incoming supply holding tank

Power supply control, 480 volts

Outbound emulsion manifold

Status panel, PCI's DOCS 200 oxygen concentrator

Figure 6 Non-Buoyant Oxygen Infusion Installation

Figure 7 Upper left pond 125 days after system commissioning

MANUFACTURING AND FIELD SUPPORT

Kadance Resources, one manufacturer of a non-buoyant oxygen infusion treatment technology has contracted with Gas Turbine Efficiency (GTE) of Orlando, Florida to build the pressurization and infuser systems. GTE is a contract manufacturer and systems integrator supplying customers in variety of industries. Its pressurization products are installed in over 500 plants around the world and the company has designed and built equipment for notable companies including Siemens, Mitsubishi, GE, Caterpillar, Pratt & Whitney, Lockheed Martin, Duke Energy and the U.S. Department of Defense.

GTE is a business unit of EthosEnergy, headquartered in Houston, Texas and Aberdeen, Scotland. EthosEnergy is a joint venture of John Wood Group PLC and Siemens AG consisting of the Maintenance and Power Solutions businesses of Wood Group GTS and Siemens' TurboCare business unit. The company was formed on May 6, 2014 and has over 4,500 employees serving customers in more than 100 countries. It is an independent service provider for rotating equipment in the power generation, oil & gas, and industrial markets.

GTE provides field support for startup, commissioning, and general service support of their non-buoyant oxygen infusion treatment system for Kadance Resources. Their support was provided for the demonstration project at the San Luis Obispo WRRF.

SCIENTIFIC PRINCIPLE OF TECHNOLOGY

The non-buoyant oxygen infusion process provides infused, non-buoyant, and ionically charged and dissolved molecular oxygen. This assures maximum transfer efficiency and long-term residency of oxygen in solution. Based on Henry's Law, gas solubility is a function of pressure and temperature. If at a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid. As the process pressure increases, the number of gas molecules that are retained in the fluid increases. The pressurized solution that is developed can become a supersaturated emulsion of the two.

The gas quality, size distribution and retention time of the bubbles are the three most important factors in the treatment process. The size and content of the bubble has a direct impact on the effectiveness of aeration. Larger bubbles have a greater buoyancy factor and rise rapidly through a water column, requiring a greater depth for tanks and lagoons to ensure adequate bubble contact time to achieve basic oxygen transfer, as described in Figure 8, below. Inclusion of non-beneficial gases, such as nitrogen and carbon dioxide, maintains buoyancy, which is counter-productive to oxygen transfer.

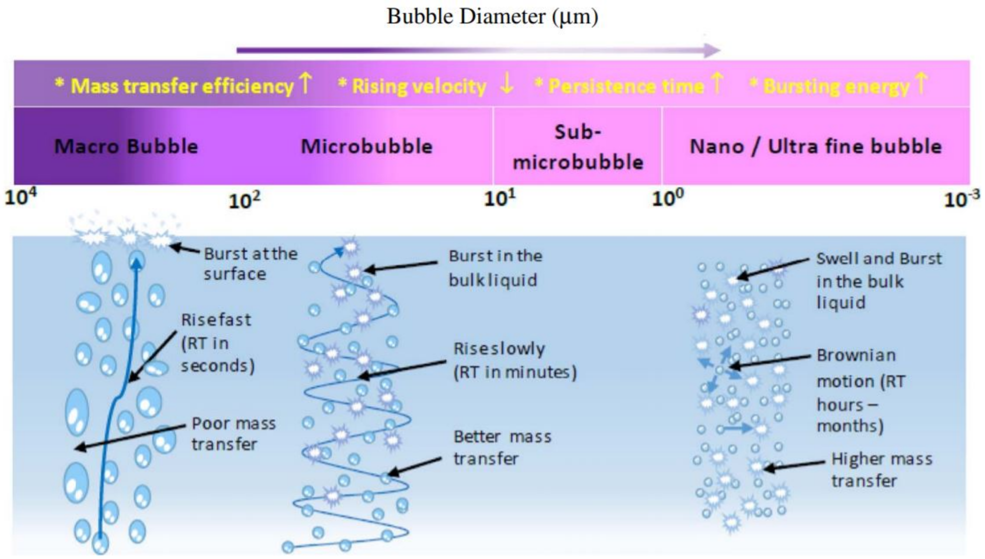

FIGURE 8 RELATION OF BUBBLE SIZE TO TRANSFER EFFICIENCY

The non-buoyant oxygen infusion process begins with oxygen being pressurized, then atomized and passed through a concentrated gas zone within the non-buoyant oxygen infusion process vessel, and then discharged and rapidly depressurized into either potable or wastewater. This forms the nano-bubbles in the high-density two-phase solution that is discharged as determined by the process control strategy. The process can deliver a solution with dissolved oxygen content up to 40 times that of conventional aeration. Figure 9 is a schematic of the non-buoyant oxygen infusion treatment technology.

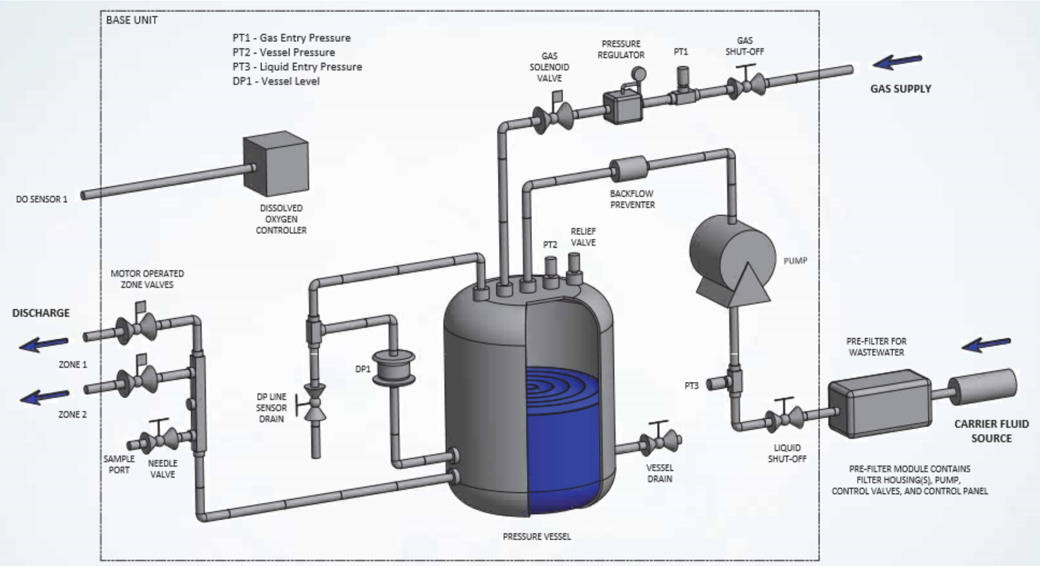

FIGURE 9 NON-BUOYANT OXYGEN INFUSION TECHNOLOGY SCHEMATIC

PURIFICATION

The first critical step in the non-buoyant oxygen infusion technology is the purification of gas, wherein the non-beneficial gases are removed, leaving oxygen in near-pure form (90-93% pure oxygen). This removes the interference in oxygen transfer at the gas-water interface and removes the antagonistic buoyancy of the insoluble nitrogen.

EMULSIFICATION

Then the purified oxygen gas is emulsified. The emulsified oxygen is in the form of "micro nano-bubbles." The non-buoyant, micro nano-bubbles in the system oxygen-water emulsions range from a few nanometers to just a few microns in diameter, resulting in a reduced rate of rise, and minimizing losses to off-gassing. By several orders of magnitude, this increases the time that dissolved oxygen is available for biological processes, chemical treatment and environmental remediation. The effect of non-buoyancy and extended contact time is the second main feature that dramatically increases SOTE. It increases contact time from a normal baseline of just a few minutes to several hours.

INFUSION

The non-buoyant oxygen infusion process delivers the two-phase, high-pressure emulsion through High Velocity Nozzles (HVN) creating a rapidly expanding cloud of micro nano-bubbles, depicted in Figure 7, below.

The supersaturated solution is discharged hydraulically through the zone valve manifold via tubing or piping to the specialized engineered nozzles. The nozzles are submerged at the point of treatment allowing for oxygen transfer and delivery where it is deemed most effective.

FIGURE 10 INFUSION OF SUPERSATURATED OXYGEN EMULSION

The non-buoyant oxygen infusion nozzles create a high velocity liquid discharge to deliver the high concentrations of dissolved gases without the formation of larger buoyant bubbles, thus improving aeration. More available oxygen can increase biological activity, enhance organic sludge reduction, oxidize contaminants, and improve odor management.

INCUMBENT TECHNOLOGIES & PRACTICES

An assessment of the incumbent technologies and practices with the principle applications in wastewater treatment defined above was performed to compare the non-buoyant oxygen infusion treatment technology to industry standard practices.

SEWAGE COLLECTION SYSTEMS

Addressing the biological conditions within a collection system is currently a non-mechanical process and requires continuous usage of microbial or chemical solutions to maintain the desired environment.

Sewage collection systems are composed of gravity pipes, manholes, tanks, lift stations, control structures, and force mains that gather used water from residential and nonresidential customers and convey the flow to the wastewater treatment plant. Proper maintenance of a collection system provides for the safe conveyance of wastewater to the treatment plant and mitigation of H2S gases. Maintenance also preserves system flow performance with the design service capacity.

Sewage collection system conditions are changing. As hydraulic flows have declined over the years, and are expected to continue to decline, sewage quality is continuously changing. This presents a challenge on original wastewater treatment designs, and infrastructure. This higher strength sewage more rapidly degrades infrastructure and leads to costly system-wide failures. Additionally, at the treatment plants, capacity is being lost and conventional designs are failing. Historically, BOD was mostly particulate and minor soluble, whereas now BOD is breaking down within the collection systems and forming sulfide, ammonia, and volatile acids. Higher sulfide levels are not only hazardous, but toxic to aerobic biology in treatment plants. Additionally, some forms of volatile acids are inhibitory or toxic to nitrogen removal biology, and excessive ammonia creates chemical imbalances and significantly increases aeration energy in secondary treatment. Historical conventional designs are stressed by changing conditions, equipment is strained under a new paradigm, and there is an increase in pressure in planning for future challenges.

One mediation is engineered bioaugmentation treatment, where high concentrations of naturally occurring, non-pathogenic microbial solutions are dispensed through the collection system network. Non-buoyant oxygen is needed to support the biology in this application. In one case study, the influent loads, e.g., biochemical oxygen demand (BOD5), total suspended solids (TSS), and total Kjeldahl nitrogen (TKN) to the WWTP decreased by approximately 13%, 13%, and 5%, respectively. Additionally, the WWTP operating costs associated with aeration energy and sludge disposal was reduced due to the reduction of the oxygen requirement (15-20%) and sludge production (~10%). The effluent water quality improved with a reduction of BOD5 (~17%), TSS (~30%) and TKN (~13%)[1]

SIDE-STREAM TREATMENT

The separation of water from primary, secondary, combined, or digested sludges during solids processing generates a liquid stream, which has characteristics that prevent direct discharge of the stream with the wastewater treatment plant final effluent. At facilities that thicken primary and secondary waste sludges before aerobic or anaerobic digestion and dewater the digested solids, multiple recycle streams are generated, each with a different composition, flowrate, and impact on the treatment plant. Because anaerobic and aerobic digestion result in the release of soluble organic nitrogen-containing compounds, ammonium and orthophosphate into the bulk liquid, the post-digestion recycle stream generated by the dewatering of the digested solids will have elevated nutrient concentrations resulting in an increased nutrient loading relative to the primary and secondary treatment processes.

The release of orthophosphate and ammonium during solids digestion often results in the formation of insoluble inorganic compounds such as magnesium ammonium phosphate, also known as struvite, which can cause operational and maintenance problems and increased energy demand in mechanical dewatering equipment and pipes that convey the recycle stream. Current practice at most wastewater treatment plants is to recycle these side-streams to the head of the plant or directly to the secondary process for treatment. However, because these side-streams can significantly impact the performance of the secondary treatment process, many treatment plants now treat these streams separately.

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[1] Sewer Collection System Bioaugmentation Reduces Influent Load and Improves Plant Performance (2012)

For treatment plants with stringent nutrient removal requirements, pretreatment of the nutrient-rich side-streams, similar to the one shown in Figure 11, prior to return to the mainstream process is employed using physiochemical and biological treatment options. This is either done through bioaugmentation to the selected stream or an additional energy intensive process to oxidize the targeted constituents to achieve outcomes such as nitrification-denitrification, nitritation-denitritation, and partial nitritation-anaerobic ammonium oxidation (de-ammonification).

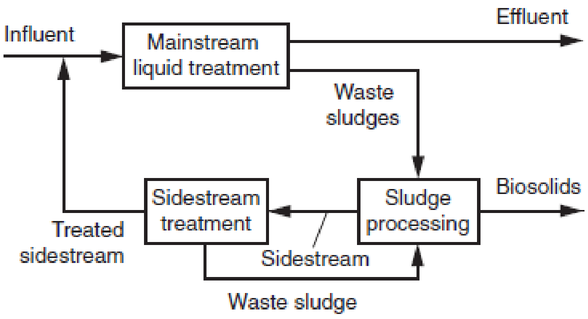


FIGURE 11 SCHEMATIC OF SIDE STREAM PRE-TREATMENT

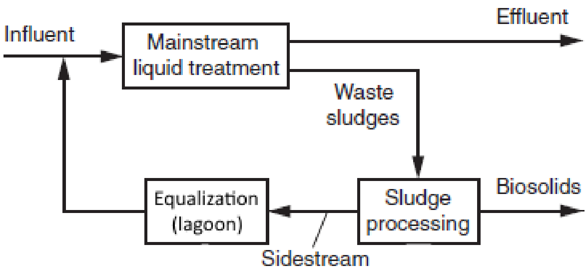


FIGURE 12 SCHEMATIC OF SIDE STREAM EQUALIZATION

Equalization of side-stream flow, as shown in Figure 12, is also commonly used to reduce the peak air demand in a biological pretreatment process, as is done at the SLO WRRF. The side-stream from the dewatering process is stored in a lined lagoon, equipped with a surface mixer to provide mixing and suspension of accumulated solids. The resident liquor is then step-fed to the WRRF at set intervals to prevent performance degradation at the main treatment process. The surface mixer does not intend to provide oxygen for biological treatment, but rather suspension of solids within the basin (lagoon). This is typically the standard practice for many facilities employing side stream equalization throughout the industry.

PRIMARY TREATMENT SYSTEMS

In primary treatment systems, coagulants are used to improve particle removal and sedimentation. Enhanced primary sedimentation reduces the energy demand imposed on secondary treatment by reducing the pass-through of particulate BOD. The typical practice within this subsection of the process is dosing with costly iron salts and polymer, a non-mechanical approach.

SECONDARY TREATMENT SYSTEMS

Conventional aeration technologies utilize atmospheric air to deliver oxygen to secondary treatment systems. In general, there are eight technologies that are used routinely in design applications and each has been generally rated by industry professionals. Their accepted efficiency ratings are described in Table 9, below. Fine-bubble diffusion has the highest delivery rating of the conventional methods of aeration at about 2.9 pounds (1.3 kg) of oxygen per kWh.

Table 9 Aeration Equipment and Standard Aeration Efficiency (SAE)

		Standard Transfer Rate	
Diffused Aeration Devices		kg O2/kW*h	lb O2/hp*h
	Fine Bubble	2.6-4.4	2.0-3.3
	Medium Bubble	2.2-3.5	1.6-2.6
	Coarse Bubble	1.3-2.6	1.0-2.0
	Tubular System or Static Tube	2.6-3.5	2.0-2.6
	Jet	2.6-5.3	2.0-4.0
	Aspirator Jet	3.3-5.5	2.5-4.0
	U-tube	2.9-5.3	2.1-4.0
Mechanical Aerators			
	Surface low-speed	3.3-4.6	2.5-3.5
	Surface low-speed with draft tube	2.6-6.2	2.0-4.6
	Surface high-speed	2.4-3.1	1.8-2.3
	Submerged turbine with draft tube	2.6-4.4	2.0-3.3
	Submerged turbine	2.4-4.6	1.8-3.5
	Submerged turbine with sparger	2.6-4.4	2.0-3.3
	Horizontal rotor	2.0-4.9	1.5-3.6

Mechanical aeration systems introduce air from the atmosphere into the wastewater by agitating the wastewater with propellers, blades, or brushes. The two typical groups of mechanical aerators are surface aerators and submerged aerators. Based on the survey results of the PG&E sponsored ISP study, design firms recommend energy efficient low-speed mechanical aerators more often, but it wasn't clear if customers actually implemented the low-speed mechanical aerators. According to the results from the plant survey, over 50% of the wastewater plants responded that vertical turbine aerators are installed in their plant. For existing facilities, vertical turbines are the common practice. For new construction projects, over 50% of the design engineers who responded to this question responded that they recommend low-speed mechanical aerators approximately 50% of the time or more. Thirty three percent (33%) of the vendors who responded to the survey said their customers purchased high-speed vertical turbine aerators more than 50% of the time. Thus, it is unclear what is considered as the industry standard practice for this technology.

Blowers are typically used in secondary and tertiary treatment processes for providing aeration to the wastewater or activated sludge. This same survey showed that the High-Speed Turbo Blowers appear to be the more widely recommended (~50% of the time) blowers although it is unclear whether plants implement them in their facility. Plant survey results show that ~26% of the plants surveyed had high speed turbo blowers installed and 19% had multi-stage centrifugal blowers installed. One design-engineering firm mentioned that recommending positive displacement blowers for small plants are typical; and recommending turbo blowers for medium to large plants are typical. Based on the survey results, it is difficult to say what is considered common practice for blowers in this industry as different operation conditions may call for different types of blowers. It appears that high speed turbo blowers and positive displacement (variable speed) blowers are trending towards becoming ISP.

Diffused aeration is a subsurface system where air is introduced into the wastewater by porous diffusers. The various types of diffusers include discs, tubes, domes, and plates. Based on market trends and market saturation survey results for diffusers, among the 3 typical options available in the market for diffused air systems, fine bubble diffusers are common technology used in wastewater treatment plants and recommended for installation. The survey shows that fine bubble diffusers are considered industry standard practice for diffused aeration systems for existing and new construction projects.

ASSESSMENT OBJECTIVES

The assessment of the Non-Buoyant Oxygen Infusion Treatment Technology was a two-phase effort, where the efficacy of the technology was to be demonstrated in two differing wastewater processes. An overview of the phases, objectives, and discussion of the iterative adaptations to the changing environments is provided in the proceeding sections.

PHASE I – PRELIMINARY TREATMENT OF RAW SEWAGE

Phase 1 aimed to implement advanced oxidation process (AOP) preliminary treatment of raw sewage in a small, isolated section of the sewage collection system to reduce the energy demand load prior to treatment at the WRRF. In Phase I, the intent was to take the initial steps to demonstrate that adding non-buoyant pure oxygen to untreated sewage can reliably create a sustainable aerobic environment in long sewers to reduce the generation of dissolved sulfide, ammonia and volatile acids to the WRRF. In this application, albeit in a small segment of the collection system, information was gathered to develop a scalable application to reduce the health, safety and environmental impacts of hydrogen sulfide, and decrease the infrastructure corrosion associated with acid formation. Further, it provided an indication of the potential to reduce the rate and magnitude of in-pipe generation of ammonia and volatile acids, which impact treatment plant capacity and energy consumption.

The following is a list of objectives established for Phase I of the assessment:

- Measure baseline conditions and determine opportunities for improvement through treatment with high-purity oxygen.
- Reduce the pass-through energy demand on the BNR system related to dissolved sulfide, ammonia and volatile fatty acids.
- Reduce health & safety impacts related to the release of H2S.
- Reduce corrosion potential and rate of release of H2S.
- Reduce the toxicity to and capacity loss in the BNR process related to generation of soluble organic acids.

The Calle Joaquin Pump Station (CJPS), where the technology was initially installed, is situated in close proximity to a hotel and numerous noise complaints were made with regards to the rented oxygen generator. Although the sound decibel level was within accordance with City statutes, two options were presented for remediation: (1) a noise enclosure system on the oxygen generator, and (2) operation of the unit during the daytime only. The logistics of obtaining the noise enclosure were deemed to be infeasible due to site constraints and delay in procurement and installation of custom enclosures. Additionally, the operation of the unit for part-time was not in line with the intent of the study and would not accurately demonstrate the efficacy of the technology. Therefore, this phase of the test was truncated early and only a small amount of data and anecdotal observations were obtained before relocating the demonstration unit to the WRRF for Phase II implementation.

PHASE II – TREATMENT OF SIDE STREAM SUPERNATANT

In Phase II, micronized oxygen was infused into a lagoon that stores ammonia-laden filtrate from dewatering of anaerobic bio-solids. The initial goal of this phase was to evaluate and measure the effect of introducing pure oxygen into this high-strength filtrate. The original premise, prior to implementation, was that the non-buoyant oxygen infusion treatment technology would provide molecular oxygen to support biological activity in controlling certain problematic contaminants, such as sulfide and ammonia, and support biology in conventional means of treating organic matter and inorganic nitrogen as Ammonia-N.

Several initial objectives for the Phase II portion were established:

- Identify all sources of organic loading resident into the lagoon, as well as the physical aspects of the system.
- Evaluate the existing secondary treatment demand and energy usage to establish a baseline case.
- Implement the Non-Buoyant Oxygen Infusion Treatment Technology within the lagoon.
- Monitor component energy and process data to compare the baseline, operating, and post-removal conditions both locally and throughout the WRRF.
- Quantify the effect of the retrofit on the process efficiency and avoided loaded to the WRRF.
- Generate an assessment report that can be used as a case study for future upgrade opportunities, and utility incentive program application.

During the initial days of the Phase II operation, the study team observed two unexpected, yet positive conditions. First, an unexpected method of treatment outside of conventional biological treatment was observed, as ammonia was being removed without the presence of significant biological population and at an oxidation and energy demand rate much lower than expected. Second, it was observed that the phosphorus and organic portion of the sludge resident in the lagoon was being reduced. These observations led to a reassessment of the study objectives to measure and characterize the unexpected benefits of this technology relative to meeting treatment objectives and further reducing demand for energy in treatment. Therefore, an additional subset of objectives was added:

- Measure percent of unexpected, direct electro-chemical oxidation of ammonia to N_2 and NO_2 prior to biological oxidation in the WRRF.
- Measure reduction in total oxygen demand of the lagoon to include reduction of phosphorus and organic mass prior to secondary treatment to improve energy demand and capacity of downstream systems.
- Characterize relative clarity and control of odor and algae production in water stored in the lagoon.
- Measure mass reduction of ammonia and volatile organics in residual sludge originally stored in lagoon.

TECHNICAL APPROACH & TEST METHODOLOGY

HOST SITE DESCRIPTION

The City of San Luis Obispo's WRRF and sewer Collection System is responsible for collecting, conveying and treating all of the wastewater (sewage) within the City, Cal Poly San Luis Obispo and the San Luis Obispo County Regional Airport. The facility treats 4.5 million gallons of wastewater daily, year-round. The plant is powered by a combination of biogas and utility energy, where typically between 20-50% of the site's demand is met through cogeneration. Figure 13 below is a basic schematic of the main plant operations.

FIGURE 13 SIMPLIFIED OVERVIEW OF THE WRRF OPERATIONS

SAN LUIS OBISPO WATER RESOURCE RECOVERY FACILITY

At the WWRF, digester pressate is produced on a daily basis in the sludge dewatering process. This liquor is high in Ammonia-N content (~1200 mg/L N) but is partially diluted by inclusion of other plant waters such as drying bed decant, plant drain water and return water from the Cal Poly Algae site. The pressate water contains relatively high Total Alkalinity (~4,500 mg/L CaCO3), dissolved sulfide (~50 HS-), and Volatile Acids (~150 mg/L). Additional flows (~5,000 gallons) also enter the lagoon but are generally devoid of ammonia and BOD. This liquor is held in a 600,000-gallon, 0.3 mm lined lagoon which is equipped with a 30 HP floating aerator, as shown in Figure 14, below. This aerator is normally operated to provide some amount of mixing and oxygen to prevent septicity and odor, but not to substantially treat the ammonia.

In recent years, excess solids from the dewatering operation have accumulated in the SNL to consume about 5' of depth volume, as shown in Figure 12, below. The volume of sludge in the SNL at the start of the pilot is approximately 45,000 cubic feet or

338,000 gallons. The top 3' of non-compacted sludge is estimated to contain 52,000 lb of volatile solids and 1,700 lb of Ammonia-N. This mass was not being treated prior to the demonstration project but was eventually identified as a major source of oxygen demand within the system. This radically impacted the apparent performance and the capacity of the NDU above that which was planned for pressate treatment.

FIGURE 14 OVERVIEW OF LAGOON SYSTEM AND HIGHLIGHT OF NON-BUOYANT OXYGEN INFUSION TECHNOLOGY

A fraction of the lagoon volume, approximately 18,000 gallons, is pumped each day to the WRRF secondary system where it blends with incoming flow. The extra Ammonia-N load from the lagoon currently (estimated at about 150 lb/day; or about 12-15% of the nitrogen load) exerts measurable demand for aeration oxygen (energy), alkalinity consumption (pH stability), as well as activated sludge stability and settling characteristics. During high-demand periods, added aeration energy must be applied in the activated sludge process and pH must be stabilized with the addition of caustic chemicals (calcium or sodium hydroxide).

FIGURE 15 ELEVATION DRAWING OF THE EXISTING LAGOON SYSTEM

SAN LUIS OBISPO WASTEWATER COLLECTION SYSTEM

The Collection System is comprised of over 138 miles of main line, nine lift stations, and various other assets. Figure 16, below, is a depiction of the collection system, with the nine lift stations identified.

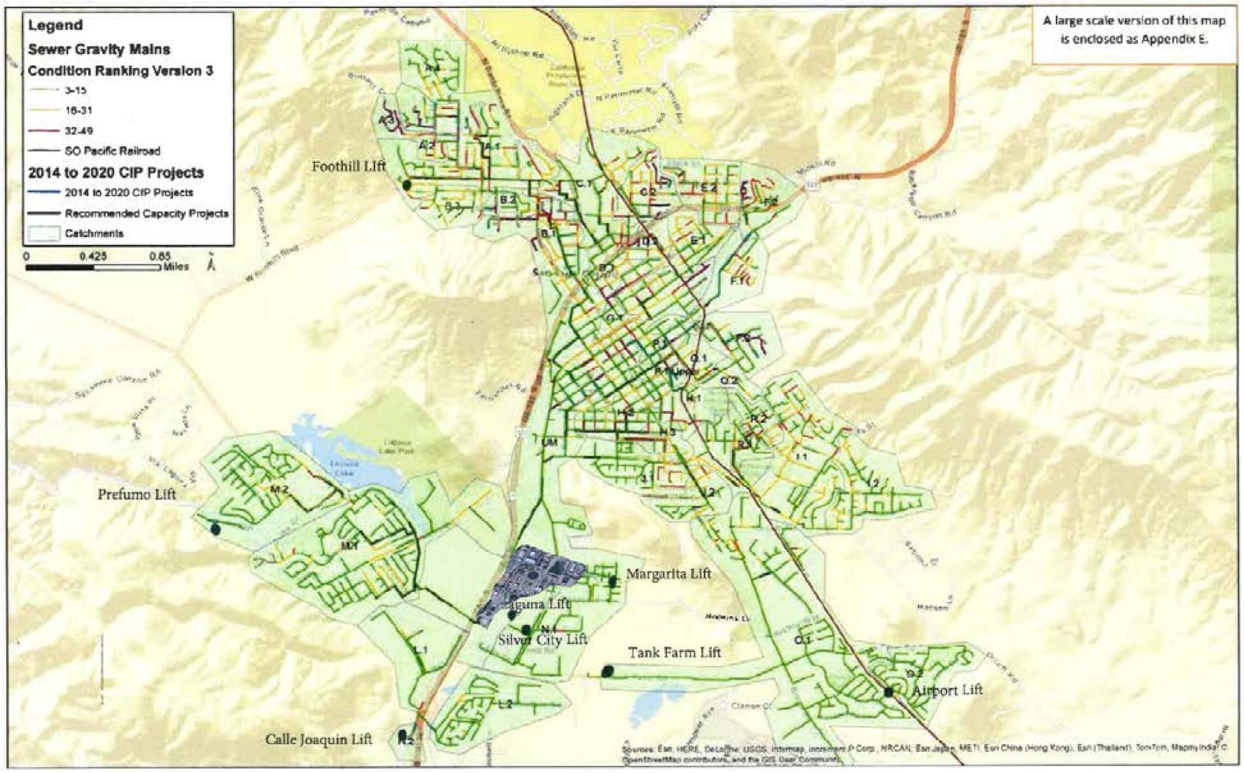


FIGURE 16 COLLECTION SYSTEMS MAP

PILOT TEST CHRONOLOGY

PHASE I – CALLE JOAQUIN PUMP STATION

The Calle Joaquin Pump Station (CJPS) is a small infrastructure in the collection system conveying less than 0.1 MGD, which is less than 3% of the total plant flow. It was selected due to convenient and secure site capacity for the demonstration trailer (shown in Figure 17), plus it had experienced severe sulfide corrosion in recent years.

FIGURE 17 CALLE JOAQUIN PUMP STATION

The choice of oxygen sources for the demonstration test was made by the City. To avoid concerns over the cost, logistics and inherent hesitation to use high-pressure bottles of pure oxygen gas, or liquid oxygen, they chose to use an on-site oxygen generator. A rental Vacuum Swing Absorption (VSA) unit was available from Pacific Consolidated Industries (PCI Gases) in Riverside, California.

- The CJPS was measured and inspected in late December to determine feasibility of installation of the demonstration unit and oxygen generator. While very constrained, the site did seem to be adequate logistically.
- Installation of the NDU and rented oxygen generator and gas compressor at the CJPS was completed on December 10th, 2019. Installation required modifications to power supply switchgear, shown below in Figure 18, as well as sewer access. System testing and troubleshooting ensued.

FIGURE 18 CALLED JOAQUIN SEWER PUMP STATION POWER SUPPLY SWITCHGEAR

- A sampling and monitoring plan (SMP) was developed and implemented on December 18, 2019. The intent was to characterize the general concentration of Ammonia-N, dissolved sulfide, BOD & COD and dissolved organics in the treated line. Sampling continued through January 16, 2020.

- Initial operation of the system was hampered by fouling of the sewage intake screen by an abundant accumulation of plastic wrappers and disposable wipes in the pump station wet well. This caused repeated shutdown of the Demonstration Unit due to loss of intake water pressure.
- Concurrently, complaints were received by the City from a nearby motel regarding continuous, low-level sound emissions from the rented oxygen generator outside of the NDU trailer. Consideration was given to providing or constructing a sound enclosure. See Figure 19 below for proximity to local hotels.

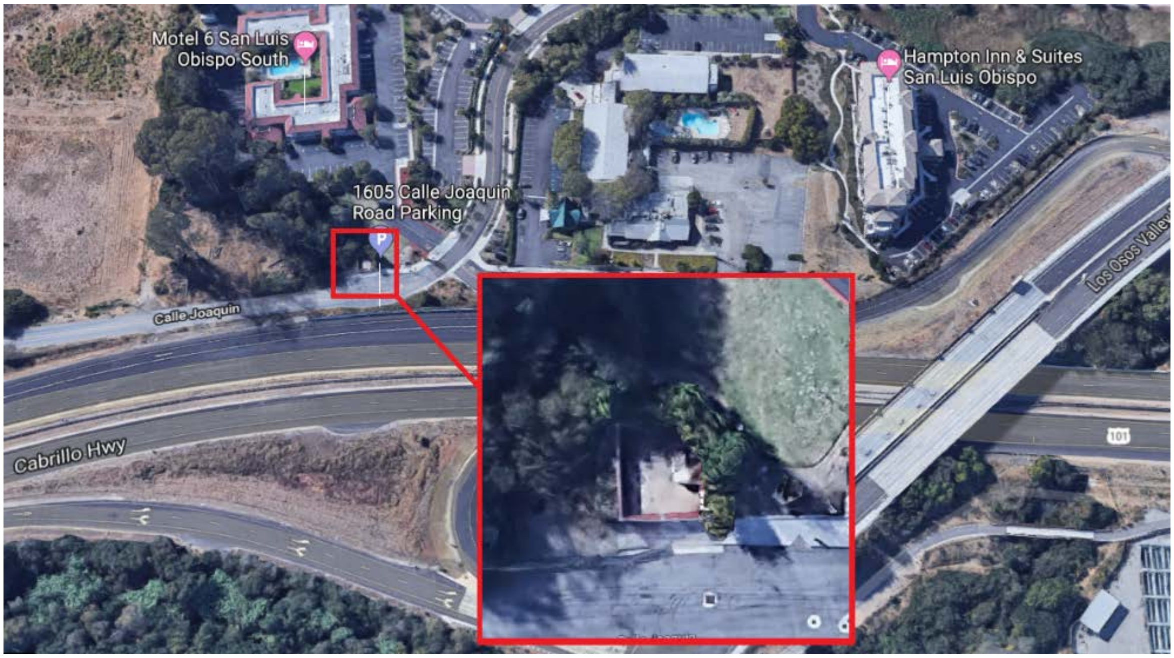


FIGURE 19 CALLE JOAQUIN PUMP STATION PROXIMITY TO LOCAL HOTELS

- On January 13, 2020 the City decided that this phase of the project should be terminated, as site constraints created difficulty in mitigating the sound and continued complaints from the motel management would impair community relations.

PHASE II – WRRF SUPERNATANT LAGOON

PHASE II – STAGE 1 – INITIAL DEPLOYMENT

- January 10-15 - Installation required modifications to power supply switchgear and access to plant water supply.
- January 17 - The NDU and oxygen generator were relocated next to the SNL.
- February 12 - A pressure regulator and screen were installed to eliminate unit shutdowns associated with loss or variation in supply water pressure.
- At that time, the SNL was full of water and residual sludge from the digester dewatering system. It was operating at a static water level of about 8’ which included an estimated sludge blanket of about 5’. Precise measurements of sludge depth were not available.

- The SNL operation included intermittent cycling of a 30 hp floating aerator, which was energized on a schedule of 20 minutes every 2 hours.
- The SNL effluent pumps were operated by timer to discharge 100 gpm for 27 minutes every 2 hours from 10AM to Midnight, unless defeated by a low-level cutoff signal, for an average discharge volume of 18,000 gallons per day.
- February 6 - A new sampling and monitoring plan was formed and initiated to define the input and output loadings of Ammonia-N, Volatile Acids (soluble BOD), Total Alkalinity, DO, ORP and other constituents of interest. The plan did not include consideration for analyzing the sludge blanket, at that time.
- February 12 - Initial, full-time operation of the unit began on February 13, 2020 with the objective of demonstrating feasibility to infuse oxygen into the water. This portion of the schedule was established solely to determine the effect and distribution of oxygen, measured as DO, through the lagoon.
- February 12 - the aeration cycle from the floating aerator was reduced to 2 minutes per hour to provide some mixing but avoid aeration.
- February 17 - the SNL top surface was becoming very clear. It became apparent that addition of microbiology for nitrification/denitrification may not be necessary. Sedimentation and clarification were occurring and initial field data indicated a significant rise in DO and reduction in Ammonia-N without the aid of biology.
- In mid-February, it became apparent that constituents in the sludge blanket were consuming oxygen and the nature and volume of the blanket was changing. This had not been previously considered as a significant issue or impact on initial objectives

PHASE II – STAGE 2 – ELECTRO-CHEMICAL OXIDATION OF AMMONIA-N TO NITRITE-N OBSERVED

- In mid-February efforts began to estimate the volume of sludge in the blanket, as it appeared to be subsiding. Samples were taken, as shown in Figure 20, below, to measure the amount of ammonia and volatile organic solids residing in the sludge, in addition to constituents being measured as input from the screw-press dewatering system.

FIGURE 20 STAFF OBTAINING GRAB SAMPLE OF SLUDGE

PHASE II – STAGE 3 – BIO-AUGMENTATION OF NITRIFICATION/DENITRIFICATION

- March 31 - Cultures of specific microbes for nitrification and denitrification were added to augment nitrification and reduce the nitrite concentration, thereby further reducing oxygen demand from the NDU.
- April 22, 2020: sludge blanket sampled and measured at 3’ of depth; a reduction of 2’ since mid-February (2 months).
- April 27 - Reduced non-buoyant oxygen infusion input time from 24/7 to 20 minutes ON and 40 minutes OFF to stimulate denitrification and biological oxygen recovery.
- May 5 - Increased non-buoyant oxygen infusion run time to 40 minutes ON and 20 minutes OFF to measure effect of denitrification.
- May 16 - Measured sludge blanket at 1.75’ thick.

PHASE II – STAGE 4 – CEASE OXYGEN CYCLING FOR DENITRIFICATION

- May 20 - Re-established non-buoyant oxygen infusion run time to full-time 24/7 operation to measure effect on NO2-N and NO3-N concentration.
- May 20 - Measured sludge blanket at 2.0’ thick; mild increase in volume.

PHASE II – STAGE 5 – CESSATION OF NON-BUOYANT OXYGEN INFUSION OPERATION AND RETURN TO CONVENTIONAL TREATMENT

- May 27, 2020: End of Phase II non-buoyant oxygen infusion operation.
- June 2020: periodic measurement of lagoon conditions and change in contaminant concentration without oxygen and bio-augmentation treatment.

M&V PLAN

A measurement and verification (M&V) plan was developed to help achieve the Assessment Objectives. The plan included data collection following IPMVP Option A (Retrofit Isolation: Key Parameter Measurement). A field study was chosen over a laboratory study, to gain insight to the actual installation process and to allow measurement of the local equipment, process parameters, as well as WRRF impacts.

PHASE I – PRELIMINARY TREATMENT OF RAW SEWAGE

The effective performance of the non-buoyant oxygen infusion treatment system was to be determined by achieving a desired change in the quality of the sewage passing into and through CJPS. Before and after metrics were expected to demonstrate the magnitude of the technology impact. The following sampling and monitoring plan was developed to demonstrate the impacts of the field test and is described in Table 10.

TABLE 10 PHASE I SAMPLING AND MONITORING PLAN

SAMPLE LOCATION	TYPE OF SAMPLE	CONSTITUENTS
CJ gravity main discharge prior to comingling with CJPS wet well	24-hour composite	• 24-hour Flow (MGD) • pH • ORP • Ammonia-N • TVA* • Acetic acid • sBOD • sCOD • dissolved sulfide (HS-)
	Grab sample, fixed time	• Headspace H2S • Wall pH (wet litmus paper) • DO
CJFM discharge	Grab sample, fixed time	• pH • ORP • Ammonia-N • TVA • Acetic acid • sBOD • sCOD • Dissolved sulfide (HS-)
Laguna PS wet well	24-hour composite	• 24-hour Flow (MGD) • pH • ORP • Ammonia-N • TVA • Acetic acid • sBOD • sCOD • Dissolved sulfide (HS-)
WRRF headworks	24-hour composite	• 24-hour Flow (MGD) • pH • ORP • Ammonia-N • TVA • Acetic acid • sBOD • sCOD • dissolved sulfide (HS-)

	Grab sample, fixed time	• DO • pH • ORP • TVA • Ammonia-N
Primary effluent	24-hour composite	• 24-hour Flow (MGD) • pH • ORP • Ammonia-N • TVA • Acetic acid • sBOD • sCOD • dissolved sulfide (HS-)
	Grab sample, fixed time	• DO • pH • ORP • TVA • Ammonia-N
Nitrified effluent	24-hour composite	• 24-hour Flow (MGD) • pH • ORP • Ammonia-N • Nitrate-N • Nitrite-N • TVA • Acetic acid • sBOD • sCOD • dissolved sulfide (HS-)
	Grab sample, fixed time	• DO • pH • ORP • TVA • Ammonia-N
NDU and Ancillary Equipment	Continuous	• Amperage • Power Factor • Voltage
WRRF Secondary Treatment Aeration System	Continuous	• True Power (kW)

The configuration of the sample points and the Phase I pilot are shown below in Figure 21.

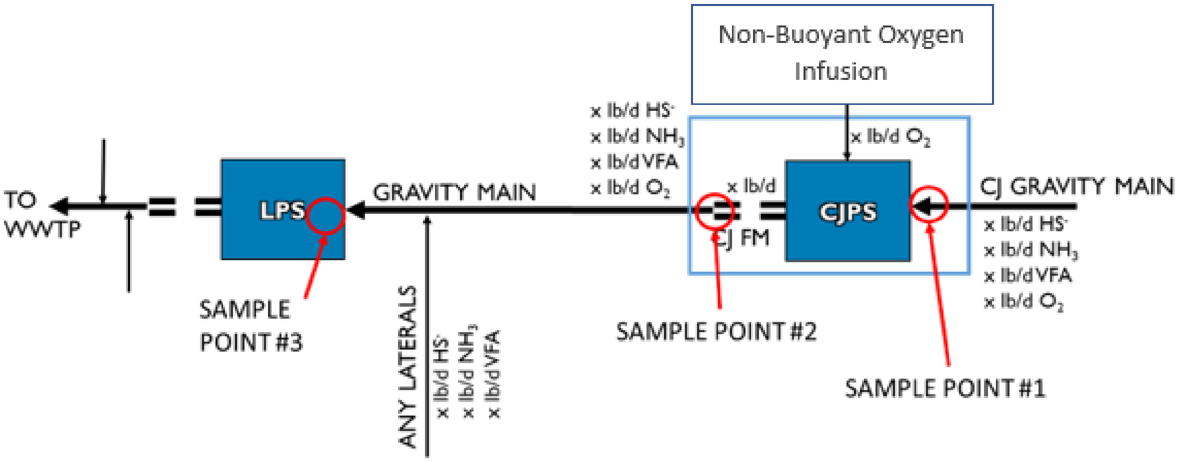


Figure 21 Basic Schematic of Monitoring Locations and Non-Buoyant Oxygen Infusion Technology Integration

The composite samples are taken by a Hach 900 MAX sampler. The grab samples are taken by dropping a rope with a plastic capped pipe and then transferred to the prospective beakers for analyzing. At the CJPS discharge, all samples are grabs. The line only contains water when CJPS is actively pumping, and high velocity fills a cup on a sampling stick.

At the Laguna Pump Station, the configuration is the same as CJPS, but a vacuum sampler is used. The grab samples of dissolved sulfide are taken from each location, usually in the afternoon.

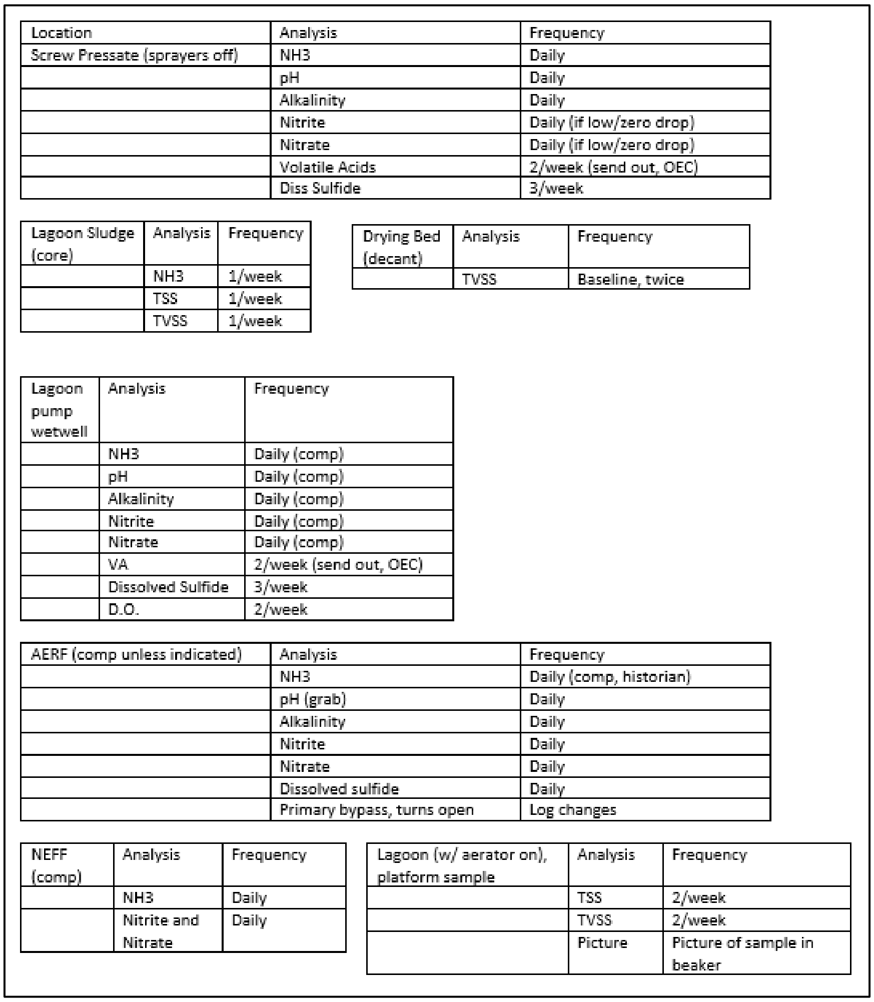
Phase II – Treatment of Side Stream Supernatant

The effective performance of the non-buoyant oxygen infusion treatment system was to be determined by achieving a desired change in the quality of the side stream passing into and through the lagoon. Before and after metrics were expected to demonstrate the magnitude of the technology impact. The following sampling and monitoring plan, shown in Table 11, below, was developed to demonstrate the impacts of the field test.

Table 11 Phase II Sampling and Monitoring Plan

Sample Location	Type of Sample	Constituents
Digester Feed	24-hour composite	• 24-hour Flow (GPM), Total solids (%)
Screw Press Dewatering System	24-hour composite	• 24-hour Inlet Flow (GPM) • Total Solids Input (%) • Total Solids Output (%) • 24-hour Discharge Flow Rate (GPM) • Ammonia-N • Alkalinity • Volatile Acids • pH • TDS • Pressate Washwater Rate (GPM) • Run Time
Lagoon System	Grab sample, fixed time	• Base Water Volume • Variable Water Volume • DisCharge Pump Schedule and Rate • Surface Mixing Aerator Operation • Sludge TSS • Sludge TVSS • Sludge Ammonia-N • Sludge Blanket Thickness
WRRF Secondary Treatment Aeration System	Continuous	• Blower True Power • pH • MLSS • MLVSS • SRT • SVI • CaOH Feed Rate • Ammonia-N • Nitrate-N • Nitrite-N
WRRF Effluent	24-hour composite	• TSS • BOD • Turbidity • pH • RAS Rate • WAS Rate
NDU and Ancillary Equipment	Continuous	• Amperage • Power Factor • Voltage • Carrier Make Up Pressure • Carrier Make Up Flow (GPM) • Carrier Process Pressure • DO • Pounds of Oxygen

Figure 22 provides an overview of the sampling sheet completed by the staff, providing additional detail on sample location, analysis, and frequency.



Location	Analysis	Frequency
Screw Pressate (sprayers off)	NH3	Daily
	pH	Daily
	Alkalinity	Daily
	Nitrite	Daily (if low/zero drop)
	Nitrate	Daily (if low/zero drop)
	Volatile Acids	2/week (send out, OEC)
	Diss Sulfide	3/week

Lagoon Sludge (core)	Analysis	Frequency
	NH3	1/week
	TSS	1/week
	TVSS	1/week

Drying Bed (decant)	Analysis	Frequency
	TVSS	Baseline, twice

Lagoon pump wetwell	Analysis	Frequency
	NH3	Daily (comp)
	pH	Daily (comp)
	Alkalinity	Daily (comp)
	Nitrite	Daily (comp)
	Nitrate	Daily (comp)
	VA	2/week (send out, OEC)
	Dissolved Sulfide	3/week
	D.O.	2/week

AERF (comp unless indicated)	Analysis	Frequency
	NH3	Daily (comp, historian)
	pH (grab)	Daily
	Alkalinity	Daily
	Nitrite	Daily
	Nitrate	Daily
	Dissolved sulfide	Daily
	Primary bypass, turns open	Log changes

NEFF (comp)	Analysis	Frequency
	NH3	Daily
	Nitrite and Nitrate	Daily

Lagoon (w/ aerator on), platform sample	Analysis	Frequency
	TSS	2/week
	TVSS	2/week
	Picture	Picture of sample in beaker

FIGURE 22 SAMPLING LOG USED BY SITE FOR PHASE II OF THE PILOT TEST

All physical, inorganic and organic testing was completed either in-house in accordance with standard laboratory procedures or through a local laboratory. Composite samples were taken using Hach AS950 samplers, depicted in the figure to the right, in Figure 23.

Local power measurements of the input power to the NDU was taken using Onset Hobo current transducers (CT) coupled with single channel loggers. The power for the WRRF secondary treatment aeration blowers is trended by the site using their local SCADA system and was provided for analysis for the pilot period, as well as the preceding year.

Power data logging was initiated in the BNR facility to track process power consumption during the project. However, major construction to upgrade the WRRF began just before the demonstration test. Major disruptions were

FIGURE 23 HACH AS950 SAMPLER

scheduled during that period. Unscheduled disruptions also occurred, which skewed much of the data logging such that it could not properly parallel the performance of the Phase II SNL test. Therefore, the team had to rely upon power data collected in the prior year, when operation was much more stable.

RESULTS

PHASE I – CALLE JOAQUIN PUMP STATION

Preliminary water quality data, including ambient H2S data, was developed before and during the short period of this phase. A small set of data was generated but indicated the potential for a reduction in energy consuming H2S, ammonia and soluble organics generated through the pump station force main. Measurements of ORP and pH, along with in-pipe generation of volatile acids and dissolved sulfide indicated significant septic biological conditions in the Calle Joaquin force main. These are significant contributors to infrastructure corrosion and energy demands for BNR treatment in the WRRF. Volatile acids increased on an average of 135-143%. They also increased to levels inhibitory and toxic to activated sludge.

The average dissolved sulfide for this period increased from 1 mg/L to over 10 mg/L. This alone increased the oxygen demand in the WRRF by over 40 mg/L, or about 1,200 pounds of oxygen per day for treatment. Separately, the gaseous H2S created upon release of the soluble sulfide from the wastewater would increase corrosion rates of equipment and infrastructure, increasing energy demand due to corrosion, and shortening life cycle replacements of critical assets.

BOD values, especially when compared to COD, indicated declining values associated with biological inhibition. This may most likely be associated with in-pipe generation of propionic acid, which has disinfection power and would suppress biological activity. This would require more oxygen in the BNR process to convert the propionic acid to a biologically treatable form.

PHASE II – SNL APPLICATION

The initial Sampling and Monitoring Plan (SMP) for Phase II was implemented on January 30, 2020. This provided a baseline indication of existing conditions prior to and during the initial start-up of the Pure oxygen non-buoyant oxygen infusion Demonstration Unit (NDU). Analytes were framed in essentially 3 groups: (1) Analytes of long-term interest relatable to process-based energy consumption, and (2) analytes of possible interest, if present in substantial concentration. Analytes in Group 1 were of specific interest and probably of most significant impact. Analytes in Group 2 were generally much more expensive or time consuming for laboratory analysis, yet of significant initial interest, if present. Group 3 Analytes were added later in Phase II and related to characterization of the sludge blanket.

- Group 1 Analytes: pH, Ammonia-N, Nitrite-N, Nitrate-N, Total Alkalinity, DO, ORP
- Group 2 Analytes: Dissolved Sulfide, Volatile Acids (Acetic Acid, Butyric Acid, Lactic Acid, Propionic Acid, Pyruvic Acid), BOD, sBOD
- Group 3 Analytes: Total Solids, Total Volatile Solids, Ammonia-N, ortho-Phosphate, and Total Phosphate.

Group 1 and 2 analyte sampling and analysis began on January 30. Group 2 analytes were evaluated through March 9, then terminated due to a lack of significance, absence of positive test results, or relative stability.

Data collected for Phase II were further grouped into chronological segments that represented different conditions in the treatment strategy. This was done to determine the effect of alternative applications of the non-buoyant oxygen infusion treatment technology and the impact of bio-augmentation on the utility of the applied oxygen. In several cases, the data went in surprising directions, which indicated that some alternate influence or condition was being seen, which was not expected. This led the team in directions that had been neither previously expected, nor planned. Limitations on staff, laboratory capacity and cost for commercial laboratory analysis limited the amount of data that could be collected for this project. These limitations have led to several of the findings and recommendations for further study in future demonstration tests by others.

Pressate is the filtered discharge from the anaerobic digester dewatering system. Some organic solids may be present, but it predominantly includes a high concentration of Ammonia-N (800-1200 mg/L) and Total Alkalinity (2,500-4,500 mg/L). Pressate is generated only when the sludge dewatering system is in operation. Typical operating times are 6 days per week from 7AM to 4PM. The total discharge volume to the SNL ranges from 13,000 to 15,000 gallons per day. Additional waters from the plant also drain to the SNL, but do not contain contaminants of concern to any significant concentration.

The SNL serves as a reservoir for the pressate. It allows the high-concentration ammonia solution to be discharged into the BNR during times when the biological reactors are best suited to convert the ammonia to nitrate and not overload the aeration system. Also, as the ammonia is nitrified, Total Alkalinity is consumed and can affect the pH of the biological process. Therefore, it is important to manage the ammonia load so as not to affect pH or require excessive addition of caustic chemicals to maintain proper pH.

For these reasons, it is important to treat the pressate to:

- Reduce energy demand associated with aeration loading
- Maintain sufficient Total Alkalinity in the SNL discharge to minimize chemical demand for pH control

STAGE 1 – BASELINE ANALYSIS – JANUARY 30 THROUGH FEBRUARY 15, 2020

This Stage brackets the period used to characterize basic background conditions prior to and during initial start-up testing of the NDU and oxygen generator. Table 12 summarizes the key determination of SNL conditions in Stage 1.

TABLE 12 SNL CONDITIONS DURING INITIAL STARTUP

ANALYTE	ANALYTE GROUP	AVERAGE VALUE, SET OF VALUES	COMMENT
pH	1	8.1-8.15	Very stable
Ammonia-N	1	504 mg/L ave; 471-538	Variable dependent upon Pressate mass loading
Nitrite-N	1	24 mg/L ave; 14.9-35.1	Highly variable; generally increasing
Nitrate-N	1	28 mg/L ave; 17.6-39	Variable; generally declining
Total Alkalinity	1	1670-1845 mg/L	Generally stable
Dissolved Sulfide	2	0	Non-detect
Volatile Acids	2	<4 mg/L	Non-detect
BOD & sBOD	2	N/A	Not tested

The data indicates that the Ammonia-N from the pressate is diluted and accumulates in the lagoon with relatively low oxidation to Nitrite-N and Nitrate-N (less than 5%). The Total Alkalinity is relatively stable, also indicating low biological activity that would otherwise decrease and possibly deplete it and reduce the pH. The Total Alkalinity and pH values are very stable, indicating no measurable influence of biological oxidation.

Group 2 analytes were either non-detectable or not yet measured for this Stage. Except for BOD, the others were eliminated from further analysis in subsequent Stages.

The resident concentration of Ammonia-N provided a basis of expectation of potential oxygen demand in the oxidation of Ammonia-N to either Nitrite-N or Nitrate-N. Using standard biologically based design values, the following estimates for oxygen demand were formulated:

- Oxidation of Ammonia-N to Nitrite-N:(NH4-N)(3.0)=(504)(3 mg/L)=1,512 mg/L O2
- Oxidation of Nitrite-N to Nitrate-N: (NO2-N)(1.5 mg/L) = (504)(1.5 mg/L) = 706 mg/L O2
- Total Oxidation of NH4-N to NO3-N = (NH4-N)(4.5 mg/L) = 2,218 mg/L O2
- Ratio of applied O2/NH4-N = 4.5:1
- Conventional Energy Density for Nitrification at SLO WRRF: 2.85 kWh/lb NH4-N

STAGE 2 – INITIATION OF NANO-BUBBLE INFUSION OXYGEN EMULSION FOR DO CONTROL – FEBRUARY 15 THROUGH MARCH 28, 2020

On February 13, 2020, the NDU was set into fulltime operation feeding emulsified oxygen flow into the SNL. The non-buoyant and non-effervescent emulsion was immediately obvious.

FIGURE 24 EMULSIFICATION OXYGEN FLOW IN TO SUPERNATANT LAGOON AT SLO WRRF

Initially, the Ammonia-N concentration in the SNL effluent discharge appeared to increase about 2%, then progressively reduced throughout Stage 2, which ended on March 28. During this period the Ammonia-N concentration declined from 551 mg/L to 254 mg/L, or a change of about 54%.

The values for Nitrite-N and Nitrate-N varied slightly, but respectively ranged from 18-33 mg/L and 19-37 mg/L. The significance of this is that with biological oxidation the combined total of NO2-N & NO3-N should increase conservatively with the decline (oxidation) of NH4-N. Their total values should have increased 54%, or to a total of about 297 mg/L. This did not happen. Their totals remained relatively constant in a range of only 37-70 mg/L. This indicated that about 227 to 260 mg/L of the nitrogen from NH4-N was being lost to atmosphere as N2, N2O, or NO, constituents of little or no interest or impact on SNL process energy demands.

Typically, NO2-N & NO3-N produced in this type of system would have energy value in the BNR. They would provide molecular oxygen for treatment, but not require additional energy from the BNR aeration system. If they were in high concentration, say 200-250 mg/L, they would provide significant additional reduction in aeration energy. While their presence in the SNL discharge is a benefit, the actual energy offset would be difficult to calculate given their low concentration in a small return flow. The major benefit is the initial reduction in energy demand associated with NH4-N.

During this Stage, samples of the SNL biomass were taken and analyzed for the DNA of nitrifying bacteria by AsterBio of Houston, Texas. This specific biomass was found to be almost absent (less than 5% of total biomass, which was low in total). Therefore, the cause of nitrogen loss from the SNL (shown below in Table 13 and Table 14) was not due to biological activity. A different explanation was needed and was not obvious at the time.

Table 13 Stage 2 SNL Conditions

Analyte	Analyte Group	Average Value, set of values	Comment
pH	1	8.1-8.15	Very stable
Ammonia-N	1	387 mg/L avg; 254-551 mg/L	Variable dependent upon Pressate mass loading
Nitrite-N	1	27 mg/L avg; 20-33 mg/L	Highly variable; generally increasing
Nitrate-N	1	26 mg/L avg; 21-32 mg/L	Variable
Total Alkalinity	1	786-1846 mg/L	Declining, but stabilized at ~1,000 mg/L
BOD & sBOD	2	150 mg/L; 110-200 mg.L	Low and relatively stable

Table 14 Stage 2 Analysis of Nano-bubble infusion Oxidation of NH4-N

Date	Oxygen Delivered, lb/wk	O2 Utilized (lb O2/lb NH4) All data	O2 Utilized (lb O2/lb NH4) Filtered data	3-Sample average (lb O2/lb NH4)
2/16	360	3.8	3.8	
2/23	667	2.6	2.6	
3/1	651	113		3.20
3/8	560	3.6	3.6	3.10
3/15	553	3.0	3.0	3.29
3/22	295	-9.3		3.29

Two of the data points were filtered out in one column to reflect significant and probable anomalies in readings and calculations. However, all of the data is presented in the table, showing little significant influence. The most significant point is the reduced relationship of applied oxygen to the removed ammonia. The probable range of ratios is 2.6-3.6, 58-80% of normal, which is less than the ratio of 4.5:1 common to the industry. This instigated curiosity as to the fate of both the oxygen and the nitrogen. Under consideration was that some of the oxygen was being captured and held in NO2-N & NO3-N. Another possibility was that the oxygen was being used to oxidize settled organic mass. Further, it spawned the concern that the ammonia being treated was not solely from the pressate, but also being released undetected from the sludge blanket, which would skew the calculated values. This drove the decision to analyze the contents of the blanket for total mass, volatile organics and ammonia. This established the framework for Stage 3.

STAGE 3 – SLUDGE BLANKET CHARACTERIZATION AND BIO-AUGMENTATION FOR DENITRIFICATION – MARCH 29 THROUGH MAY 23, 2020

Activities in Stage 3:

- March 31 - Cultures of specific biological cultures for nitrification and denitrification were added to augment nitrification and reduce the nitrite concentration, thereby further reducing oxygen demand from the NDU.
- April 22: sludge blanket sampled and measured at 3' of depth; a reduction of 2' since mid-February (2 months)
- April 27: reduced non-buoyant oxygen infusion input time from 24/7 to 20 minutes ON and 40 minutes OFF to stimulate denitrification and biological oxygen recovery.
- May 5: Increased non-buoyant oxygen infusion run time to 40 minutes ON and 20 minutes OFF to measure effect of denitrification.
- May 16: measured sludge blanket at 1.75' thick.

Although running towards the end of the project schedule, it was determined that two additional objectives needed to be pursued: (1) characterize the potential impact of the sludge blanket on oxygen consumption via oxidation of additional, unaccounted for ammonia and organics, and (2) determine the effects of bio-augmentation with microbes combined with cycling of the oxygen injection to stimulate oxygen recovery via biological denitrification.

Microbial consortia were purchased and delivered to the site for incorporation into the lagoon system. The intent was to artificially establish a robust population of microbes that would specifically oxidize ammonia to nitrite, then denitrify it using organic carbon mass being released from the sludge blanket. The intent was to convert NO2-N & NO3-N produced by whatever mechanism was at play to oxidize ammonia, back to nitrogen gas and recover the molecularly held oxygen. Theoretically, if successful, this would provide a lower ratio of applied O2:NH4-N and also reflect a lower kWh/lb-N.

In mid to late April the sludge blanket depth was measured and sampled for TS, TVS and NH4-N. The process of blanket measurement and sampling by SLO staff was difficult and somewhat dangerous. Therefore, only a very limited set of data was generated. However, the measurements were important and enlightening.

Table 15 on the next page summarizes the characterization of the sludge blanket.

TABLE 15 STAGE 3 SLUDGE ANALYSIS

DATE	LOCATION	TSS (MG/L)	TVSS (%)	NH3-N (MG-N/L)	BLANKET THICKNESS AVG (FT)	VOL (GAL)	AMMONIA MASS (LB)
4/22/2020	Southeast	45,000	73%	870	3.0	247,573	1796
4/22/2020	Northeast	32,700	56%	846	3.0	247,573	1747
5/16/2020	North	47,866	64%	634	1.75	135,725	718
5/16/2020	South	36,778	62%	678	1.75	135,725	767
5/20/2020	North	41,160		786	2.0	157,070	1030
5/20/2020	South	49,280		764	2.0	157,070	1001
5/20/2020	Deep sludge	65,050		1032			
5/27/2020	North	42,100	62%	728			
5/27/2020	South	42,500	68%	732			
5/27/2020	Deep sludge	64,370	58%	893			

First, it is important to note that the sludge blanket depth had reduced by 2’ in just six weeks since the initiation of the project. This represented a significant and rapid reduction in organic and nitrogenous mass. The mass of organics and nitrogen had only one place to go – into the supernatant being treated by the non-buoyant oxygen infusion emulsion.

Second, the concentration of ammonia in the upper layer of the blanket was very high, averaging nearly 800 mg/L. This would have a significant influence on oxygen demand, and skew the calculation for applied oxygen:nitrogen, as the source of nitrogen from the blanket was not being recognized by the monitoring plan initially. It’s contribution alone was adding approximately 27 lb/day on average, or nearly 25% of the flow-through load from the pressate.

Early in Stage 3 the concentrations of NO2-N & NO3-N were steadily rising. This gave the appearance of increasing O2:NH4-N ratios due to the oxygen being captured by the nitrogen and forming nitrite and nitrate. Once the denitrification cycle was initiated on April 27, the respective concentrations of NO2-N & NO3-N were reduced by nearly 50%, which greatly reduced the calculated O2:NH4-N ratios.

Table 16 Stage 3 SNL Conditions

Analyte	Analyte Group	Average Value, set of values	Comment
pH	1	7.7-8.2	Very stable
Ammonia-N	1	379 mg/l ave; 282-455	Variable due to variations in applied oxygen rate
Nitrite-N	1	42 mg/L ave; 24-57 mg/l	Generally increasing from 24 – 70 mg/L until denite cycle initiated; reduced average to mid-40s.
Nitrate-N	1	23 mg/L ave; 21-25 mg/L	Very stable; declined slightly with denite
Total Alkalinity	1	1188 mg/L ave; 715-1568 mg/L	Declined initially with biological nitrification; rebounded with denite.
BOD & sBOD	2	N/A	Not tested

Analysis of nano-bubble infusion oxidation of NH4-N during Stage 3 are shown below in Table 17.

Table 17 Stage 3 Analysis of Nano-bubble infusion Oxidation of NH4-N

Date	Oxygen Delivered, lb/wk	O2 Utilized (lb O2/lb NH4) All data	O2 Utilized (lb O2/lb NH4) Filtered data	3-Sample average
3/29/20	277	0.6	0.6	1.08
4/5/20	550	3		0.62
4/12/20	683	2.3	2.3	1.48
4/19/20	652	1.6	1.6	1.95
4/26/20	246	0.5	0.5	1.45
5/3/20	360	0.9	0.9	0.99
5/10/20	420	1.8	1.8	1.06
5/17/20	533	1.5	1.5	1.41

During early Stage 3 period, with addition of nitrifying microbes, the NO2-N production increased, which also increased the calculated value for O2:NH4-N. However, including the mass of ammonia determined to be coming from the sludge blanket, the values during Stage 3 appear to be much lower than those shown above in Stage 2. Once the mass of ammonia coming from the blanket was included in the mass load calculation, the apparent O2:NH4-N relationship dropped dramatically. When the nitrite values are lowest, as in after implementing biological denitrification, the ratio dropped even more to 0.5-0.9 O2:NH4-N. Not correcting for possible outliers, the average values are still below 2:1, which is only 44% of the 4.5:1 expected value.

Re-evaluating the data set for Stage 2, but including the ammonia load exuding from the blanket, the O2:NH4-N values closely parallel those determined directly in Stage 3, as is seen below in Table 18.

TABLE 18 RE-EVALUATION OF STAGE 2 NANO-BUBBLE INFUSION OXIDATION OF NH4-N

DATE	OXYGEN DELIVERED, LB/WK	O2 UTILIZED (LB O2/LB NH4) ALL DATA	O2 UTILIZED (LB O2/LB NH4) FILTERED DATA	3-SAMPLE AVERAGE
2/16	360	1.3	1.3	
2/23	667	1.6	1.6	
3/1	651	4		1.44
3/8	560	1.7	1.7	1.62
3/15	553	1.5	1.5	1.61
3/22	295	2.1		1.61

Through this phase of the test, the lowest values of Ammonia-N in the SNL appeared to be about 250 mg/L. This may reflect the limits of oxygen delivery capacity of the NDU. The combination of reduced pressure and throughput of the rented oxygen generator and compressor limited the output of the NDUs to about 108-130 pounds per day. With pure oxygen from bottles, the pressure may have been increased from roughly 200 psi to above 300 psi and the throughput could have increased from 108 pounds per day to over 200 pounds per day. Future configurations should consider providing higher pressure from the compressor to overcome this apparent capacity limit for this size of nano-bubble infuser.

STAGE 4 – CEASE CYCLING OF NON-BUOYANT OXYGEN INFUSION FEED AND CHARACTERIZE SLUDGE BLANKET

This period is defined by cessation of cycling of the oxygen from the NDU and returning to full time operation. The reason for this was to observe subsequent change in conditions that would stop the denitrification process, even with the presence of the appropriate bacteria. By this means, it could be determined how dependent and sensitive the system function was to oxygen, relative to removal of oxidized nitrogen.

This required maintaining a constant high-level DO, with the intention to interfere with the denitrification cycle. On the last day of sampling, the NDU had been shut down and oxygen was no longer being applied.

At the same time, during this period, observation of the sludge blanket continued. It was noted that the blanket level had risen slightly to about 2’ deep, still down from an initial level of about 5’. It is difficult to determine why the sludge blanket increased slightly during this period, the team speculates that it is related to a general shift in sludge location as the density changed. While it appeared that organic mass and ammonia continued to be drawn from the blanket, adding to the oxygen demand applied to the non-buoyant oxygen infusion system, the character of the blanket was changing and becoming more voluminous and less dense. This may have been due more to concentrated biological activity and less to densifying physics.

Only a sparse amount of analytical data was generated during this period, as the project was nearing completion and impacts of the COVID restrictions upon the site staff were greater.

TABLE 19 STAGE 4 SNL CONDITIONS

ANALYTE	ANALYTE GROUP	AVERAGE VALUE, SET OF VALUES	COMMENT
pH	1	7.95-8.05	Very stable
Ammonia-N	1	410 mg/l ave; 382-459 mg/L	Variable due to variations in applied oxygen rate
Nitrite-N	1	59 mg/L ave; 49.5-73 mg/l	Rapidly increase due to cessation of denitrification
Nitrate-N	1	21 mg/L ave; 18.5-24 mg/L	Generally declined due to shift in increased NO2 values
Total Alkalinity	1	1203 mg/L ave; 990-2184 mg/L	Generally stable
BOD & sBOD	2	N/A	Not tested

The ammonia concentration was relatively stable. However, as was expected, the nitrite concentration quickly elevated with lack of denitrification. The nitrate concentration remained relatively stable as a latent source of nitrite in the sludge zone.

TABLE 20 STAGE 4 ANALYSIS OF NANO-BUBBLE INFUSION OXIDATION OF NH4-N

DATE	OXYGEN DELIVERED, LB/WK	O2 UTILIZED (LB O2/LB NH4) ALL DATA	O2 UTILIZED (LB O2/LB NH4) FILTERED DATA	3-SAMPLE AVERAGE (LB O2/LB NH4)
5/17/20	533	1.5	1.5	1.41
5/24/20	326	0.9	0.9	1.41
5/31/20	0	0	0	1.22

STAGE 5 – CESSATION OF NON-BUOYANT OXYGEN INFUSION OPERATION AND RETURN TO CONVENTIONAL TREATMENT – MAY 31 THROUGH JUNE 10, 2020

At the end of the schedule demonstration test, the NDU was shut down and decommissioned. However, it was decided to continue monitoring conditions in the SNL to see if, how much, and how quickly it might begin returning to the original state prior to Stage 1.

Activities of Stage 5:

- May 27: End of Phase II non-buoyant oxygen infusion operation
- June: periodic measurement of lagoon conditions and change in contaminant concentration without auxiliary oxygen and bio-augmentation treatment

TABLE 21 STAGE 5 SNL CONDITIONS

ANALYTE	ANALYTE GROUP	AVERAGE VALUE, SET OF VALUES	COMMENT
pH	1	8.15-8.21	Very stable
Ammonia-N	1	558 mg/l ave; 416-790 mg/L	Generally increasing due to lack of oxygen
Nitrite-N	1	44 mg/L ave; 25-61 mg/l	Decreasing due to lack of oxygen
Nitrate-N	1	18 mg/L ave; 13.3-27 mg/L	Generally declined due to lack of oxygen
Total Alkalinity	1	1559 mg/L ave; 1271-1686 mg/L	Generally stable but increasing due to lack of nitrification

Data and calculations of oxygen relative to ammonia were not performed, as the NDU had been shut down and very little air was being provided to the SNL, except via the floating aerator that had been returned to service.

PHASE II SUMMARY

To determine the energy and demand savings of this technology, an assessment of the in-situ WRRF conditions for the preceding year along with the pilot data was completed. Historically, the lagoon provided an average Ammonia-N loading to the WRRF of approximately 149 lbs/day, extrapolated to 54,221 lbs/yr. using the industry standard approximation of 4.5 lbs O_2/ lb Ammonia-N required in the aerobic treatment process, which equates to approximately 668 lb O_2/day, extrapolated to 243,994 lbs O_2/yr. During the preceding year, the BNR system operated at an average efficiency of 0.71 kWh/ lb O_2 with the following assumptions:

- Standard Oxygen Transfer Efficiency (SOTE): 12%
- Losses due to distribution: 15%
- Lb O_2 / lb air: 19%

Thus, the following energy metrics were developed for the baseline scenario:

TABLE 22 OVERVIEW OF THE BASELINE SCENARIO ENERGY AND DEMAND USAGE

	ANNUAL ENERGY CONSUMPTION (KWH/YR)	PEAK DEMAND (KW)
BNR System Treatment	**173,234**	**23**

During the pilot effort, the loading from the lagoon was reduced to 85 lbs/day on average, extrapolated to 30,898 lbs/yr. This load was sent to the BNR system, operating at the efficiency determined above of 0.71 kWh/lb O_2. The remainder of the Ammonia-N load was treated via the non-buoyant oxygen infusion system, estimated to be 64 lbs/day, extrapolated to 23,323 lbs/yr. Through analysis of process and energy data, the NDU operating efficiencies were determined to be 1.41 lbs O_2/ lb Ammonia-N and 1.15 kWh/ lb O_2. The following metrics were calculated for the proposed scenario and are shown in Table 23.

TABLE 23 OVERVIEW OF THE PROPOSED SCENARIO ENERGY AND DEMAND USAGE

	ANNUAL ENERGY CONSUMPTION (KWH/YR)	PEAK DEMAND (KW)
BNR System Treatment	98,718	13
Non-Buoyant Oxygen Infusion System Treatment	37,806	4
Total Proposed Scenario	**136,525**	**17**

The savings during the pilot period are described in Table 24, below:

TABLE 24 OVERVIEW OF PILOT ENERGY AND DEMAND SAVINGS

	ANNUAL ENERGY CONSUMPTION (KWH/YR)	ANNUAL ENERGY SAVINGS (KWH/YR)	PEAK DEMAND (KW)	PEAK DEMAND REDUCTION (KW)
Baseline	173,234	-	23	-
New Technology	136,525	36,709	17	6

As seen in the pilot effort, during the weeks of 4/26 and 5/3, when the nitrite values are lowest, after implementing biological denitrification by reducing the O2 supplied to the SNL, the treatment ratio dropped even more to 0.5-0.9 O2:NH4-N. Theoretically, if the non-buoyant oxygen infusion unit was sized to treat the entire NH4-N loading from the lagoon and the load was completely reduced using the non-buoyant oxgen infusion in the denitrification mode, the load to the BNR could be reduced to zero. In this case, using the average ratio of 0.7 O2:NH4-N, the non-buoyant oxygen infusion system could potentially treat the avoided 243,994 lbs O_2/yr with only 37,955 lbs $O_{2/yr}$. This equates to 206,040 less lbs O_2/yr required in the BNR system with an energy savings of 146,288 kWh/yr, as shown in Table 25.

TABLE 25 THEORETICAL ENERGY AND DEMAND SAVINGS

	ANNUAL ENERGY CONSUMPTION (KWH/YR)	ANNUAL ENERGY SAVINGS (KWH/YR)	PEAK DEMAND (KW)	PEAK DEMAND REDUCTION (KW)
Baseline	173,234	-	23	-
New Technology	26,946	146,288	5	18

DISCUSSION

RESULTS OF THE ASSESSMENT

Wastewater treatment plants are dynamic and complex environments to experiment with emerging products and technologies. The non-buoyant oxygen infusion treatment pilot at the SLO Collection System and WWRF provided multiple benefits including energy savings compared to conventional BNR operation.

PHASE I

Although with limited data, it appears that the Phase I deployment in the Collection System resulted in a decrease of H2S generated in the collection system. This would lead to treatment plant energy savings in terms of odor control cost savings as well as aeration energy reduction. Higher levels of H2S also leads to pipeline corrosion and accelerated wear and tear on mechanical equipment. The NDU demonstrated that emulsified oxygen may be used in sewer mains to prevent the formation of and destroy hydrogen sulfide, destroy ammonia, and reduce BOD prior to the treatment plant. Lower levels of H2S generation should be evaluated and findings confirmed in future studies.

Further studies should evaluate effect of non-buoyant oxygen infusion on BOD values, especially when compared to COD. This should include measurement of the presence of propionic acid, which has disinfection power and suppresses biological activity. Production of propionic acid in the sewer requires more oxygen in the BNR process to convert the propionic acid to a biologically treatable form. A reduction in propionic acid created in the sewer would result in energy savings but needs to be verified in future studies.

PHASE II

Phase II demonstrated that the NDU would treat ammonia and BOD in the supernatant lagoon before the return flow would deliver an energy demand to the BNR system. During the beginning stages of this phase, the Ammonia-N concentration in the lagoon declined from 551 mg/L to 254 mg/L; a decrease of approximately 54%. During the initial months of the assessment, data indicated a reduced relationship of applied oxygen to the removed ammonia. The probable range of ratios is 2.6-3.6, 58-80% of normal, which is less than the ratio of 4.5:1 common to the industry. The team suspected that some of the oxygen was being captured and held in NO2-N & NO3-N, or that the oxygen was being used to oxidize settled organic mass in the sludge layer of the lagoon. It appeared that the ammonia being treated was not solely from the pressate, as originally expected, but also being released undetected from the sludge blanket, which skewed the calculated values.

In what the team describes as Stage three of the Phase II assessment, the sludge blanket depth had reduced by 2’ in six weeks since the initiation of the project. This represented a significant and rapid reduction in organic and nitrogenous mass. The mass of organics and nitrogen had only one place to go – into the supernatant being treated by the non-buoyant oxygen infusion emulsion. By the end of the study, organic mass and ammonia continued to be drawn from the blanket, adding to the oxygen demand applied to the non-buoyant oxygen infusion system. The character of the blanket was changing and becoming more voluminous and less dense. This may have been due to more to concentrated biological activity and less to densifying physics. Samples of the SNL biomass were analyzed to characterize the nitrifying bacteria. This specific biomass was found to be less than 5% of total biomass, which was low in total, indicating that the cause of nitrogen loss from the SNL was not due to biological activity.

Sensors for DO and ORP were deployed in the SNL to record changes during loading and treatment. Oxygen was typically applied 24/7. Loading from the screw press occurred between 7 AM and 4 PM. Diurnal swings in ORP and DO measurements were noted and are represented on Figure 25, below.

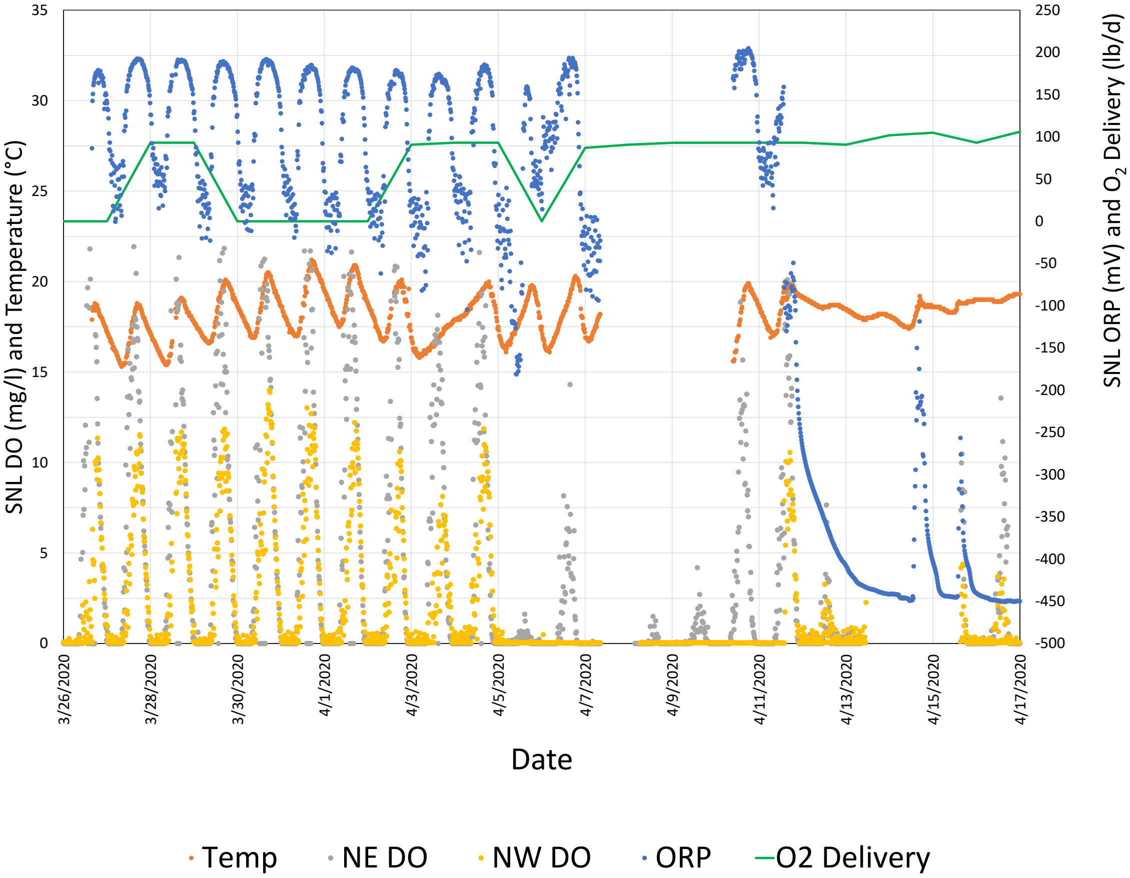


FIGURE 25 DIURNAL OBSERVATIONS OF ORP AND DO MEASUREMENTS

The timing of the diurnal swings appears to be inverse to the loading periods and congruent with solar radiation. The lagoon was sampled for algal and bacteriological content. Biomass was determined to be very low and insufficient to cause the DO to increase at all, especially to the magnitude represented by the readings.

Also, the ORP values lead and lag the swings in DO readings. This indicates that the oxidation potential superseded the DO, which seems counter intuitive to what is normally observed in biological processes, suggesting a photo-chemical reaction process. Further, the low DO readings at night indicate that the oxygen was in the lagoon in some form other than molecular oxygen. These patterns lead the investigators to pursue other concepts for oxidation of ammonia and organics residing in the lagoon.

Microbial consortia were used to artificially establish a robust population of microbes that would specifically oxidize ammonia to nitrite, then denitrify it using organic carbon mass being released from the sludge blanket. This would convert NO2-N and NO3-N produced by whatever mechanism was at play to oxidize ammonia, back to nitrogen gas and recover the molecularly held oxygen. Once the mass of ammonia coming from the blanket was included in the mass load calculation, the apparent O2:NH4-N relationship dropped dramatically to 1.41lb O2:NH4-N. When the nitrite values are lowest, as in after implementing biological denitrification, the ratio dropped even more to 0.5-0.9

O2:NH4-N. Not correcting for possible outliers, the average values are still below 2:1, which is only 44% of the common 4.5 value. Conversely, the energy density to oxidize the NH4-N was determined to be 1.62 kWh:lb NH4-N within the lagoon system.

In summary, the NDU delivering oxygen to the SNL, representing approximately 9% of the WRRF total flow, resulted in avoided NH3-N load to the BNR of 64 lbs/day during the pilot period. This avoided NH3-N load would consume energy if sent to the BNR at an estimated annual value of 36,709 kWh/yr. These savings occurred while removing approximately 3’of sludge from the lagoon with its own additional energy demand in the BNR system.

PERFORMANCE OF NON-BUOYANT OXYGEN INFUSION TREATMENT DEMONSTRATION UNIT

There were problems with the rented vacuum swing absorption unit (VSA) and gas compressor, as described earlier. The equipment choices of the ancillary units used to produce and pressurize the oxygen supply limited the throughput of oxygen for which the demonstration unit was built by about 50%. Also, outside of the NDU these compressors generated noise complaints from the public, as well as lower than expected oxygen generation that will be corrected for subsequent pilots.

Initial operation of the system at CJPS was hampered by fouling of the sewage intake screen by an abundant accumulation of plastic wrappers and disposable wipes. This caused repeated shutdown of the NDU due to loss of water pressure. A pressure regulator and intake water screen were installed to address concerns of losing pressure in Phase II.

During the Phase II study, the NDU failed to operate consistently for long periods of time. Periodically the carrier water feed pressure would drop, causing the NDU to shut down unexpectedly. The restart procedures following these periodic issues include manual activity and could not be remotely addressed. Additionally, the site experienced problems with pressure control of the treatment plant supply water, causing a differential pressure alarm and system shutdown.

To address the issue, the team had to manually remote into the NDU system to see the details of each alarm. Site staff operators were not aware of the alarms until they made their daily rounds to take measurements or make observations. The strainer clogging issue was addressed and mitigated by regular cleaning. The remote notification of an alarm/shutdown continues to be a problem with the NDU. Future iterations of the product should address these issues.

Despite these challenges, well within one month of Phase II commissioning, the SNL top surface was observed becoming clear. Sedimentation and clarification was occurring and initial field data indicated a significant rise in DO and reduction in Ammonia-N without the aid of biology. The normal baseline DO of <0.5 mg/L rose to 5 mg/L, with daily diurnal peaks of 25 mg/L. This was far above what was expected.

The electro-chemistry of the non-buoyant oxygen infusion emulsion was oxidizing Ammonia-N at rates of 0.7-2.0:1, well below the industry standard of 4.5:1, for an apparent reduction in oxygen demand of 56-89%, depending upon residual nitrite & nitrate values. Translated as aeration energy savings to the BNR system, this could reflect a potential reduction of 146,288 kWh/yr. Table 26, below, describes the energy efficiency findings and potential of the system in the current application.

TABLE 26 SUMMARY OF ENERGY SAVINGS

	LBS. OF O_2 PER LB OF AMMONIA REMOVED	ANNUAL ENERGY CONSUMPTION (KWH/YR)	ANNUAL ENERGY SAVINGS (KWH/YR)	PEAK DEMAND (KW)	PEAK DEMAND REDUCTION (KW)	SAVINGS OVER BASELINE (%)
Industry Baseline	4.5	173,234	-	23	-	-
New Technology – Measured Side Stream Savings	1.41	136,525	36,709	17	6	21%
New Technology – Potential Side Stream Savings	1.41	54,411	118,823	4	19	69%
New Technology – Potential Optimized Side Stream Savings	0.7	26,946	146,286	4	19	84%

** The oxidation rate is 1.41 lb O2/lb NH4-N but there was only partial treatment of the total NH4-N load during the pilot study

ENERGY IMPACT

The NDU delivering oxygen to the SNL, representing approximately 9% of the WRRF total flow, resulted in avoided NH3-N load to the BNR of 64 lbs/day during the pilot period. This avoided NH3-N load would consume energy if sent to the BNR at an estimated annual value of 36,709 kWh/yr. The oxygen generator rented for this pilot (VSA unit) was later understood to be oversized for the side stream treatment application and was therefore cycling on and off constantly through the pilot phases. Further, as described earlier, an unanticipated and significant percentage of the oxygen demand was consumed by the destruction and transfer of organic material from the sludge layer. Therefore, the energy savings described are indicative of a proof of concept application and are anticipated to be significantly increased in full scale deployment.

In conventional wastewater treatment, oxygen is used to biologically convert and remove carbonaceous and nitrogenous materials. Oxygen is typically conveyed in normal atmospheric air as an industry standard practice. The development and enhancement of aeration technologies for biological wastewater treatment have been relatively stagnant and standardized for decades, with the exception of attempting to create finer bubbles, more efficient blowers and refined durability and PLC control of sensors and DO control. This has provided only nominal, incremental improvement in energy profiles.

BARRIERS

Wastewater systems are dynamic and complex environments of different types and concentrations of contaminants. Testing and sampling for effective re-operation of BNR processes with tools such as the non-buoyant oxygen infusion treatment system can be difficult and costly. The electro-chemical concepts of the non-buoyant oxygen infusion treatment technology is far outside normal industry concepts of biological aeration and oxidation. A new industry-level understanding of physical chemistry that often far exceeds the normal expertise of wastewater operators and biological process specialists is needed to understand how the various improvements can be recognized, understood, valued, and ultimately optimized. High level education is needed to gain industry acceptance of this entirely new technology, yet the potential magnitude of its impact is profound.

A notable barrier for this study was the emergence of the Coronavirus pandemic and the related strain on staff time at the WRRF. Further, due to stay at home orders and social distancing requirements related to the pandemic, the project team was limited in our ability to participate in site activities during the second half of the pilot study. Sampling activities were also compromised due to limited staff availability and the cost for analyses by commercial laboratories. Finally, flow patterns shifted dramatically as Cal Poly SLO students left campus for the remainder of the semester starting in April. The change in flow patterns added a layer of complexity to the energy models the project team developed for the study.

The NDU was designed to provide oxygen into water and wastewater systems for the purpose of visualizing oxygen emulsion and measuring impacts on treatment functions. It was not designed or optimized specifically for energy management, per se. The oxygen generator and gas compressor were selected by availability, not energy efficiency and provided only 66% (200 psi versus 300 psi) of the desired pressure normally provided by pressurized, gaseous oxygen bottles. Yet, the energy consumption of those units was included in the study calculations. This reflected a reasonable maximum energy consumption by a non-optimized system. Even so, this reflected a significant reduction in comparison to industry standards.

To overcome these barriers, demonstration of the electro-chemical, physical chemical, and biological benefits of nano-bubble technology should be broadly disseminated and discussed at industry events, such as trade shows and academic/professional conferences. Further pilots, and documentation of results, will generate confidence and understanding in and of this novel technology. Ultimately, permanent installations of non-buoyant oxygen infusion technology will offer the opportunity to refine the energy associated with gas production (the rented vacuum swing absorption unit (VSA), in this case) ahead of the non-buoyant oxygen infusion treatment system.

TOOLS FOR MEASUREMENT

All physical, inorganic and organic testing was completed either in-house or by a local commercial laboratory in accordance with standard laboratory procedures. Composite samples were taken using Hach AS950 samplers.

Local power measurements of the input power to the NDU was taken using Onset Hobo current transducers (CT) coupled with single channel loggers. The power for the WRRF secondary treatment aeration blowers is trended by the site using their local SCADA system and was provided for analysis for the pilot period, as well as the preceding year.

NON-ENERGY BENEFITS

The reduced energy demand on the aeration blowers in the BNR will result in reduced wear and tear on existing blowers and should result in extending their effective useful life and deferring maintenance and capital expenditures.

The destruction and removal of sludge from supernatant lagoon provides a significant non-energy benefit to the WRRF, as draining and removing the sludge from a lagoon of that size represents a significant labor and cost outlay for dredging, thickening and disposal.

Finally, and potentially most importantly, the reduced odor and corrosion in sewer pipelines and collection system pump stations can extend the useful life of assets by decades and can eliminate community and customer complaints. The improved health and safety benefits should be studied in future investigations but were not quantified for this study.

MARKET BARRIERS

Many of the sanitary engineer design firms do not fully understand the physics, chemistry and electro-chemical technology described in this study or demonstrated in this pilot. It will take a couple of years for this technology to be progressively accepted beyond the most progressive and innovative water and wastewater utilities. Wastewater operators, specifically, are risk-averse by nature and are driven by mission critical performance objectives, primarily. Energy management is not a top priority for wastewater plant operators, engineers, and managers. Because fine bubble diffuser technology is the driving paradigm in activated sludge systems, it will take demonstration and data-rich evaluations to convince wastewater plants to change treatment processes to take advantage of this technological innovation.

Further, traditional aeration equipment has a multi-decadal EUL, and agencies will be hesitant to abandon oversized equipment to realize the energy efficiency benefits of this technology. Finally, in collection system management, chemical vendors will resist the wave of more efficient management strategies.

RECOMMENDATIONS

MANAGEMENT CONSIDERATIONS

- Identify wastewater decision makers who will pursue and support technologies that take a radically different approach to treatment and reduce the demand for energy and chemicals and are counter-intuitive to existing industry standards.
- Prepare and provide educational and informational pathways to begin establishing a knowledge-based culture for technological changes, such as that offered by the non-buoyant oxygen infusion treatment technology.
- Establish an ISO-based project management approach to project definition and management for efficacy determination of energy reduction and performance improvements via alternative technologies.

TECHNICAL RECOMMENDATIONS

- Design and install appropriate oxygen supply, generation and pressurization systems to fully support the non-buoyant oxygen infusion system.
- Prequalify application sites to suit local environmental, commercial and public impact conditions and requirements (i.e. noise threshold levels).
- Identify potential test sites for application in raw sewage conveyance systems with issues of low flow, high strength sewage generating elevated H2S, ammonia and soluble BOD which create excessive energy demands in BNR and oxidation processes.

- Identify potential test sites for side-stream treatment of flows containing high concentration of Ammonia-N, phosphorus, volatile acids and dissolved sulfide which impact secondary treatment aeration energy demands.
- Identify treatment systems utilizing trickling filters for secondary treatment which are organically overloaded and exceed the aeration capacity needed for oxidation.
- Identify conveyance and treatment facilities utilizing high-energy scrubbing and chemical treatment systems for odor and corrosion control related to hydrogen sulfide, mercaptans, amines and ammonia.

DATA AND ANALYSIS RECOMMENDATIONS

- Improve characterization of baseline conditions for point of application.
- Provide a more robust sampling and monitoring plan to better characterize holistic impact of the non-buoyant oxygen infusion electro-chemistry, versus normally expected biological conditions.
- Define and use chemical analytical procedures to define the electro-chemical pathways within the oxygen emulsion process to determine appropriate energy demand to support optimum energy consumption relative to constituent treatment and removal.

APPENDICES

As discussed in the report, the NDU achieved a more efficient oxidation rate of Ammonia-N as compared to the baseline throughout the pilot study. For standard nitrification, 4.6 pounds of oxygen are required per pound of Ammonia-N. On average the NDU exhibited an average nitrification rate of 1.41 pounds of oxygen per pound of Ammonia-N. Depending on the iteration of runtime and varying oxidation demand the profile of oxidation varied as depicted in Figure 26 below.

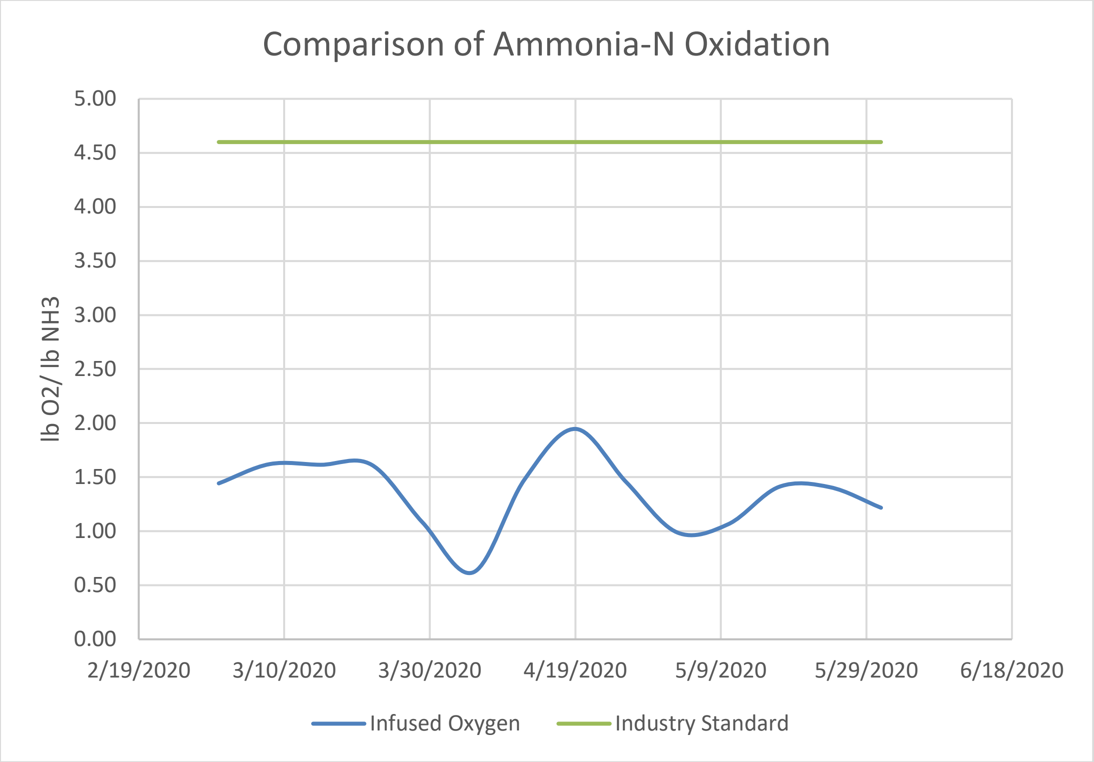


FIGURE 26 COMPARISON OF AMMONIA-N OXIDATION OF INDUSTRY STANDARD AND EMERGING TECHNOLOGY

To estimate the energy savings, the total avoided load was determined using the methodologies described in this report. Without the integration of the emerging technology, this load would have been treated by the existing BNR system. Therefore, a comparison of the in-situ BNR energy density to the emerging technology was determined and is provided in Figure 27 below.

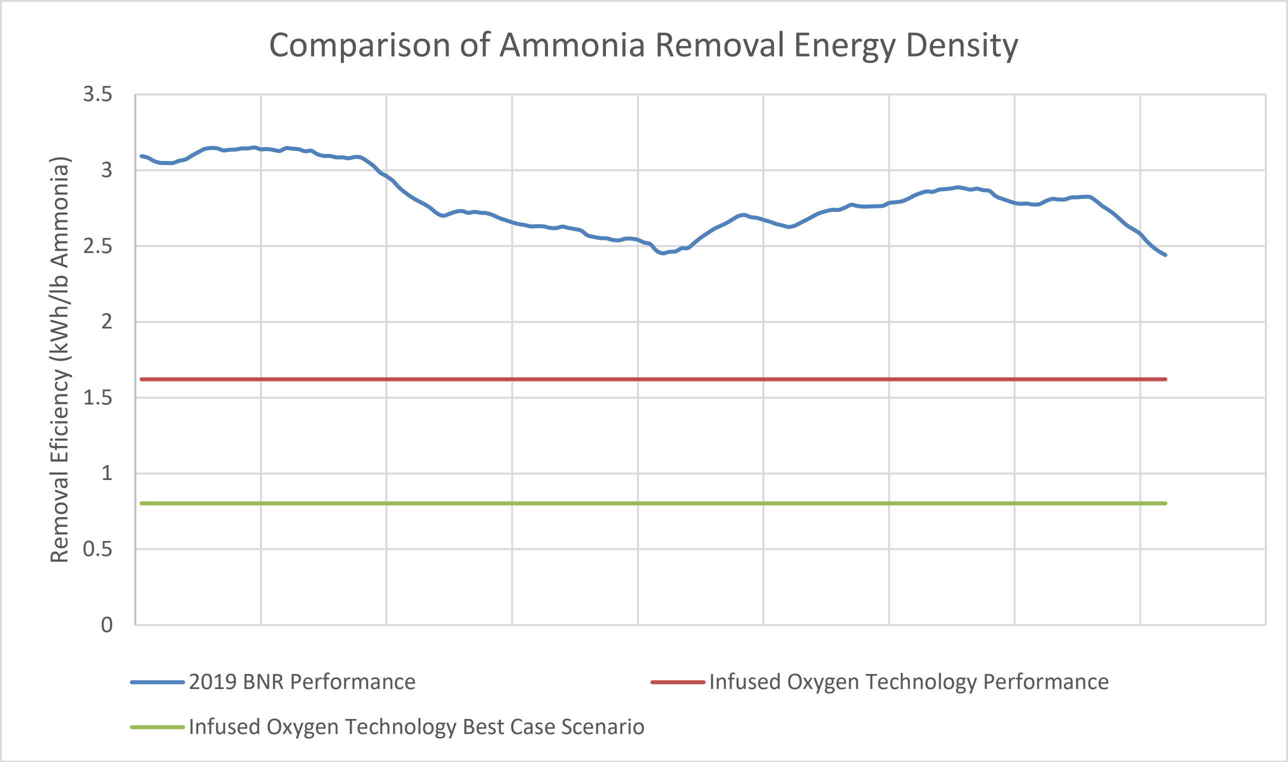


FIGURE 27 COMPARISON OF AMMONIA-N ENERGY DENSITY BETWEEN SLO BNR SYSTEM AND EMERGING TECHNOLOGY

An overview of the energy savings baseline and proposed case scenarios was determined using the avoided load to the existing treatment plant, as shown in the table below. The avoided load was determined in lbs of O2 per year reduction, less the increased power demand of the infused oxygen technology.

TABLE 27 OVERVIEW OF BASELINE AND PROPOSED SCENARIO ENERGY SAVINGS

	Baseline
668	lbs of O2 per day used in BNR to treat historical load @4.5 lbs O2/lb NH3-N
243,994	lbs of O2 per year used in BNR
0.71	BNR kWh/lb O2
173,234	kWh/yr
23	kW
	Proposed
381	lbs of O2 per day used in BNR to treat new load @4.5 lbs O2/lb NH3-N
139,042	lbs of O2 per year used in BNR
0.71	BNR kWh/lb O2
98,718	kWh/yr
13	kW
37,806	Non-buoyant Oxygen Infusion Treatment System Annual Energy Consumption (kWh/yr)
4	Non-buoyant Oxygen Infusion Treatment System Demand (kW)
136,525	Total Proposed Energy Usage (kWh/yr)
17	Total Proposed Demand (kW)
36,709	**Energy Savings (kWh/yr)**
6	**Demand Savings (kW)**

A similar analysis was done for the scenario in which the system was sized to treat the entirety of the SNL load at the measured metrics (Average Case Scenario), as well as a situation of optimized sizing and operation (Best Case Scenario with Denitrification). Both of these scenarios treat the entirety of the load; however the latter optimizes the system operation to cycle, creating aerobic and anaerobic conditions for denitrification. An overview of each potential scenario is provided in the tables below, respectively.

TABLE 28 OVERVIEW OF THE POTENTIAL ENERGY SAVINGS FOR THE AVERAGE CASE SCENARIO

668	lbs of O2 per day used in BNR to treat historical load @4.5 lbs O2/lb NH3-N
243,994	lbs of O2 per year used in BNR
76,636	lbs of O2 per year used by Non-buoyant Oxygen Infusion Treatment System Using 1.41 lbO2/lbNH3-N
167,358	lbs of O2 avoided by Non-buoyant Oxygen Infusion Treatment System
118,823	**Energy Savings (kWh/yr)**

TABLE 29 OVERVIEW OF THE POTENTIAL ENERGY SAVINGS FOR THE BEST CASE SCENARIO WITH DENITRIFICATION

668	lbs of O2 per day used in BNR to treat historical load @4.5 lbs O2/lb NH3-N
243,994	lbs O2 per year avoided in BNR
37,955	lbs O2 per year used by Non-buoyant Oxygen Infusion Treatment System Using 0.7 lbO2/lbNH3-N
206,040	lbs O2 avoided by Non-buoyant Oxygen Infusion Treatment System
146,286	**Energy Savings (kWh/yr)**

CALCULATION METHODOLOGY

Baseline Determination

To determine the baseline scenario, historical data from the previous three years for Ammonia-N loading from the supernatant lagoon (SNL) was evaluated. Data for flow rates (MGD) and Ammonia-N concentration was provided by the site and the load was calculated using the following equation:

$$\frac{lbs}{day} = flow\ rate\ (MGD) * concentration\ \left(\frac{mg}{L}\right) * 8.34$$

During this time period the site was not implementing any pre-treatment processes; therefore, the entirety of this load was being treated in the existing biological nutrient recovery (BNR) secondary treatment process. On average, the load from the lagoon was approximately 149 pounds per day of Ammonia-N. An overview of the historical load is provided in the chart below.

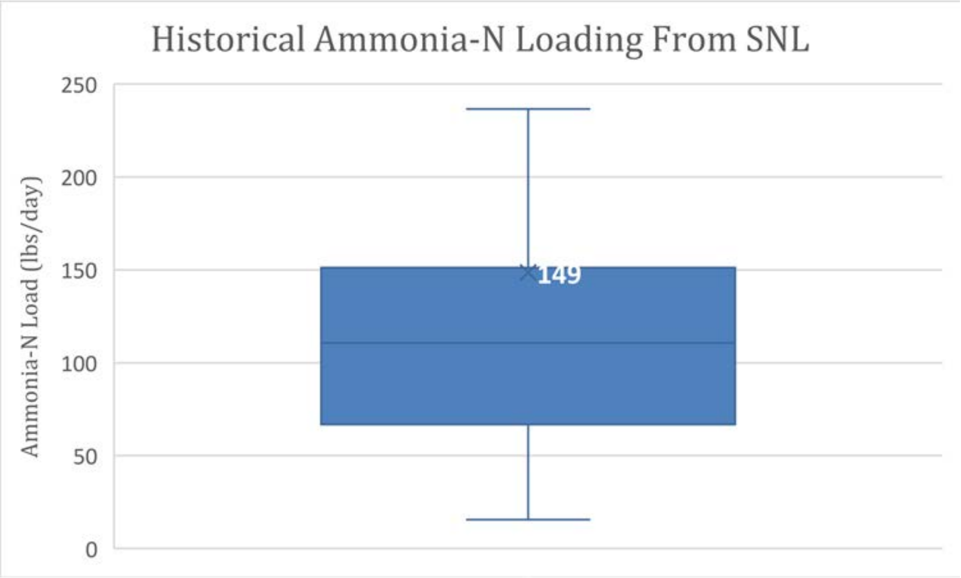


FIGURE 28 HISTORICAL AMMONIA-N LOADING FROM SNL

To oxidize Ammonia-N in the BNR system, 4.5 pounds of O2 are needed per pound of Ammonia-N. Therefore, on average 668 pounds of O2 were required to treat the influent load from SNL in the BNR system.

$$\frac{lbs\ O_2}{day} = SNL\ Loading\ to\ BNR\ \left(149\ \frac{lbs\ Ammonia - N}{day}\right) * 4.5\frac{lbs\ O_2}{lb\ Ammonia - N} = 668\ \frac{lbs\ O_2}{day}$$

Extrapolating to an annual basis, this equated to 243,994 pounds of O2 per year to treat this load. To determine the energy impact of this, the site provided data for blower flow rate (SCFM) and Ammonia-N removal (lbs/day). This was used to determine the BNR removal efficiency of 0.71 kWh per pound of O2 produced by the blower system. This is demonstrated in the figure below.

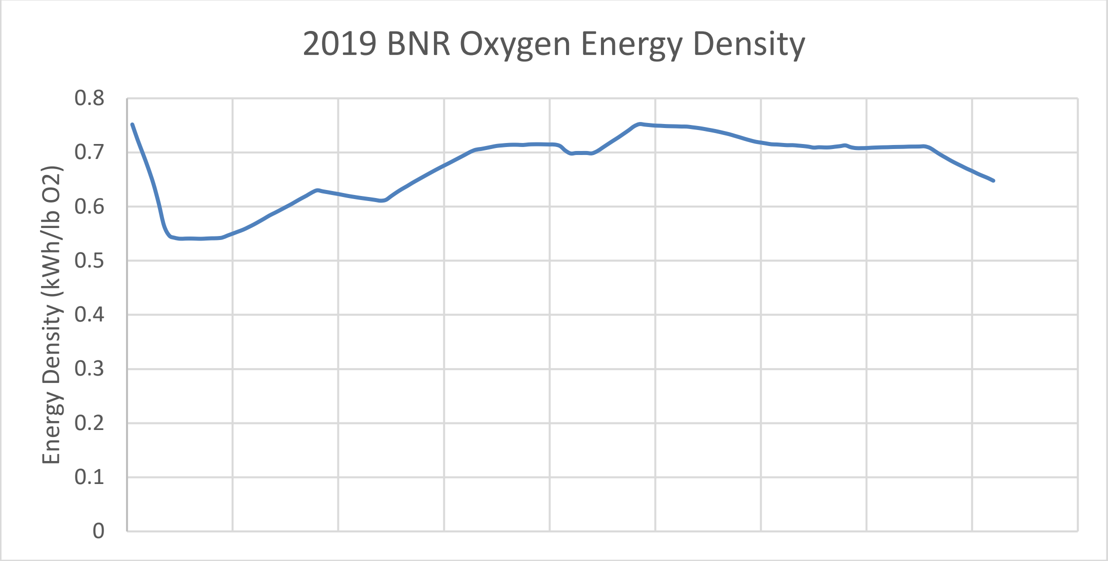


FIGURE 29 2019 BNR OXYGEN ENERGY DENSITY

Therefore, the following metrics were developed for the baseline scenario:

$$Annual\ Usage = 243{,}994\ \frac{lbs\ O_2}{yr} * 0.71\frac{kWh}{lb\ O_2} = 173{,}234\ kWh/yr$$

The peak demand associated with this load was determined by evaluating the blower power during weekdays from 4 PM to 9 PM, and the portion of the total load attributable to the SNL loading yielding 23 kW.

Scenario 1: Measured Data

In this scenario, the pilot unit was deployed to pre-treat the SNL load prior to flowing to the BNR system. During the pilot period, the SNL loading was reduced from 149 to 85 pounds of Ammonia-N per day on average, a reduction of 64 pounds per day. Using the equations above, this equaled an estimated 381 pounds of O2 load on the existing system, a reduction of 287 from 668 pounds per day or 104,953 pounds per year. At the same BNR operating efficiency of 0.71 kWh per pound of

Ammonia-N, the new scenario required only 98,718 kWh/yr and 13 kW, a savings of 74,516 kWh/yr and 10 kW.

The emerging technology utilizes a vacuum swing absorption unit (VSA), compressor, and ancillary controls to infuse the pure oxygen into the lagoon system. This system amperage was monitored throughout the study to determine the energy impact. The resulting usage was calculated as 37,806 kWh/yr and 4 kW.

The savings for scenario 1 were calculated as follows:

$$\begin{aligned} &Annual\ Energy\ Savings \\ &\quad = Baseline\ Usage\ \left(\frac{kWh}{yr}\right) - Proposed\ BNR\ Usage\left(\frac{kWh}{yr}\right) \\ &\quad - ET\ System\ Usage\ \left(\frac{kWh}{yr}\right) = 36{,}709\ kWh/yr \end{aligned}$$

$$\begin{aligned} &Demand\ Savings \\ &\quad = Baseline\ Demand\ (kW) - Proposed\ BNR\ Demand (kW) \\ &\quad - ET\ System\ Demand\ (kW) = 6\ kW \end{aligned}$$

Scenario 2: Properly Sized System

As the mobile demonstration unit was not properly sized for the application, only a portion of the SNL load could be treated prior to flowing to the BNR system. In a permanent configuration, the technology would be sized appropriately to provide adequate O2 to completely oxidize all of the Ammonia-N load within the lagoon. This would entail treating all 149 pounds of Ammonia-N, and removing the need of 243,994 pounds of O2 per year from the BNR system. On average, throughout the study the emerging technology demonstrated an efficiency of 1.41 pounds of O2 per pound of Ammonia-N. The O2 requirement of the emerging technology was calculated as:

$$\frac{lbs\ O_2}{yr} = 149\frac{lbs\ Ammonia - N}{day} * 365\frac{days}{yr} * 1.41\ \frac{lbs\ O_2}{lb\ Ammonia - N} = 76{,}636\frac{lbs\ O_2}{yr}$$

The technology exhibited an average of 1.15 kWh per pound of O2 produced, therefore the proposed system would have the following energy impact:

$$Annual\ Usage = 1.15\frac{kWh}{lb\ O_2} * 76{,}636\ \frac{lbs\ O_2}{yr} = 87{,}892\frac{kWh}{yr}$$

$$Demand = .04\frac{kW}{lb\ O_2} * 210\ lbs\ O_2 = 8\ kW$$

The savings for scenario 2 were calculated as follows:

$$Annual\ Energy\ Savings = Baseline\ Usage\ \left(\frac{kWh}{yr}\right) - ET\ System\ Usage\ \left(\frac{kWh}{yr}\right) = 85{,}342\ kWh/yr$$

$$Demand\ Savings = Baseline\ Demand\ (kW) - ET\ System\ Demand\ (kW) = 15\ kW$$

Scenario 3: Properly Sized System and Optimized Operation for Simultaneous Nitrification – Denitrification

This scenario is similar to Scenario 2, however in this configuration the unit would be cycled to create oxic and anoxic conditions to stimulate Simultaneous Nitrification – Denitrification (SNdN). This was accomplished as one of the iterations of the pilot, by cycling the units operation on and off in 30 minute increments. By doing this, a much more efficient oxidation of 0.7 pounds of O2 per pound of Ammonia-N was achieved. The O2 requirement of the emerging technology was calculated as:

$$\frac{lbs\ O_2}{yr} = 149\,\frac{lbs\ Ammonia - N}{day} * 365\,\frac{days}{yr} * 0.7\ \frac{lbs\ O_2}{lb\ Ammonia - N} = 37{,}955\,\frac{lbs\ O_2}{yr}$$

The technology exhibited an average of 1.15 kWh per pound of O2 produced, therefore the proposed system would have the following energy impact:

$$Annual\ Usage = 1.15\,\frac{kWh}{lb\ O_2} * 37{,}955\ \frac{lbs\ O_2}{yr} = 43{,}529\,\frac{kWh}{yr}$$

$$Demand = .04\,\frac{kW}{lb\ O_2} * 104\ lbs\ O_2 = 4\ kW$$

The savings for scenario 3 were calculated as follows:

$$Annual\ Energy\ Savings = Baseline\ Usage\ \left(\frac{kWh}{yr}\right) - ET\ System\ Usage\ \left(\frac{kWh}{yr}\right) = 129{,}705\ kWh/yr$$

$$Demand\ Savings = Baseline\ Demand\ (kW) - ET\ System\ Demand\ (kW) = 19\ kW$$

REFERENCES, OPTIONAL

1. BASE Energy, Inc. & Pacific Gas & Electric Company (2016), A Study on Technology Options and Energy Efficiency Standard Practices for Municipal Wastewater Treatment Plants. San Francisco, CA: Pacific Gas & Electric Company.

2. Water Environment Federation (2017), Liquid Stream Fundamentals: Aeration Design. Alexandria, VA: Water Environment Federation.

3. Temesgen, T, TT Bui, M Han, T Kim, H Park (2017), Micro and nanobubble technologies as a new horizon for water-treatment techniques: A review. *Advances in Colloid and Interface Science,* 246:40-51.

GLOSSARY

Collection System	Wastewater collection systems collect and dispose of household wastewater generated from toilet use, bathing, laundry, and kitchen and cleaning activities. Centralized systems are public sewer systems that serve established towns and cities and transport wastewater to a central location for treatment.
Emulsion	A fine dispersion or suspension of minute droplets of one liquid in another in which it is not soluble or miscible.
Infusion	The process of introducing a new element or quality.
Ion	An atom or molecule with a net electric charge due to the loss or gain of one or more electrons.
Micro nano-Bubble	Bubbles of gas that measure less than a micron in diameter (< µ).
Nitrogenous	Containing nitrogen in chemical combination.
Non-buoyant	Tending neither to sink nor rise in a liquid or in air. Of comparatively equal or greater physical weight or density.
Pressate	The drain water from the belt press or screw press used to dewater sludge.
Secondary Treatment	Removal of dissolved and suspended organic compounds through biological digestion.