

**ACHIEVING EFFECTIVE HYDROGEN SULFIDE ODOR CONTROL AT MINIMAL COST –
PILOT TESTING CONVENTIONAL AND EMERGENT TECHNOLOGIES AT A CENTRAL FLORIDA
WATER TREATMENT FACILITY**

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INTRODUCTION

The City of Oviedo (City) provides potable water to roughly 23,000 residents in central Florida. The City required an effective treatment method for removing sulfides at their new 10 million gallon per day water treatment facility. Forced-draft aeration (FDA) was identified as an effective and economic way to remove sulfides from the City's groundwater. However, it was recognized that the resulting hydrogen sulfide (H₂S) laden FDA off-gas would need to be treated prior to atmospheric release because of concerns regarding operator safety, corrosion of exposed metal surfaces and odor complaints from the surrounding community.

The authors performed engineering evaluations to develop an environmentally friendly water treatment facility that produced high quality water without releasing offensive odors to the neighboring community. While packed tower scrubbers (PTSs) are widely used to treat these off-gases, they require rigorous operation and maintenance, not to mention chemical handling and waste stream disposal requirements (Boyle 1995). Faced with a number of emergent alternative odor reduction technologies, a pilot test program was implemented to evaluate cost and performance data for both conventional PTS and non-conventional technologies.

Existing Raw Water Supply

The City has historically relied on groundwater pumped from the Floridan Aquifer. Raw water is treated at two conventional groundwater treatment facilities, each comprising cascade tray aeration, chlorine addition for primary disinfection, ammonia addition to form chloramines for residual disinfection and phosphate-based chemical injection for corrosion control.

Each of the City's wells exhibits some degree of hydrogen sulfide with concentrations ranging from 2 to 3 mg/L as S.

Sulfide is a naturally occurring mineral in some soil and rock formations that contain groundwater, particularly at higher depths where anaerobic conditions prevail. If left untreated, sulfides impact finished water quality. These impacts may include changes in corrosivity, undesirable taste and odor, and visible turbidity and color as a result of colloidal (elemental) sulfur formation, some of which the City has experienced over the years (Duranceau et al., 1999).

The City's existing water treatment facilities (WTFs) release hydrogen sulfide directly to the atmosphere, which generates offensive odor complaints from residents in the surrounding community. Consequently, developing an effective odor control strategy was a primary project goal.

The City Action Plan

In response to the aforementioned issues and increasing consumer demand, the City initiated a program to expand and improve treatment for its customers. The program encompasses construction of a new water treatment, storage and distribution facility. A planning and study phase included pilot testing select water treatment and odor control options. Water quality enhancements were evaluated using FDA and membrane softening. The new WTF will be designed initially to remove sulfide using FDA. Membrane softening was evaluated to support WTF master planning relative to future implementation for disinfection by-product precursor and salinity control.

While a number of alternative odor reduction technologies have emerged in recent years, only limited independently collected performance and cost information is available for many of these systems. The first component of this project involved a conceptual odor control treatability evaluation (Boyle, 2000), from which three alternatives to conventional packed tower scrubbers were identified:

- Catalyzed/adsorptive carbon (Calgon Phoenix)
- Granular reactive media (SulfaTreat)
- Inorganic-based media biofiltration (Biorem)

In the interest of generating site-specific data, four odor control technologies were evaluated. Performance capabilities, process selection and identification of operating conditions for full-scale implementation are presented herein.

METHODS AND MATERIALS

Odoriferous off-gas, produced by a 50 gallon per minute FDA pilot unit, was ducted to each odor reduction system. Carbon dioxide was used to adjust raw water pH and shift the equilibrium of the sulfide species in favor of hydrogen sulfide gas (H₂S), which is readily removed from water when exposed to air. When left in the dissolved HS⁻ and S²⁻ state, aeration is limited to only

partial removal. Figure 1 depicts the general arrangement of aeration and odor-control equipment.

Odor control system operating periods spanned 1 to 2 months with each process configured in a manner representative of anticipated full-scale conditions. Inlet H_2S concentrations were normally 25 to 35 ppm_v. Short-term tests were also conducted to evaluate performance under a projected worst-case 90 ppm_v concentration.

Odor Control Processes

Table 1 provides a general overview of each odor control system. Operational principles are treated in more detail in the following sections.

Packed Tower Scrubber. The packed tower scrubber system consisted of two 10-foot tall towers connected in series (two-stage). Centrifugal pumps recirculated chemical scrubbing solutions continuously with the suction line submerged below the chemical solution surface in the sump for each respective stage. The first stage handled the bulk of the inlet H_2S , while the second stage polished the off-gas to achieve high removal efficiency.

Odoriferous off-gas from the FDA was forced upward through the tower of first-stage, contained by a piping system and sent to the bottom of the second stage. The off-gas was further treated through the second stage and finally dispersed to the atmosphere from the top of the second stage. Both the first and second-stage towers were filled with Jaeger Tri-Pack media, which, in the same manner as in the FDA tower, provide intimate contact to allow sulfide transfer from the off-gas to the chemical treatment solution.

Sample lines located at the inlet and outlet to stage two were used to evaluate the level of hydrogen sulfide in the inlet and exhaust.

Granular Reactive Media (SulfaTreat). The SulfaTreat pilot unit comprised an engineered vessel filled with a static reactive media bed. Vessel dimensions were 6'x4'x6' (LxWxH). A 43-inch bed depth provided an approximate 20 to 30-second empty bed residence time, depending on flow rate. Four sample lines were installed at various depths throughout the media to test the level of hydrogen sulfide through the media.

Catalyzed/Adsorptive Carbon (Phoenix). A carbon odor reduction process, trade name Phoenix Carbon, was tested. H_2S removal was accomplished by directing odoriferous air through a single 35 pound canister filled with Centaur HPTM granular activated carbon. H_2S transfer occurred as the odoriferous air stream passed through the radially-designed carbon canister in an outside-in mode. Treated off-gas was routed through the open end of a center collection pipe sealed and separated from the incoming off-gas. According to the manufacturer, sulfuric acid is formed rather than elemental sulfur due to the catalytic nature of the activated carbon. This results in gaseous H_2S conversion to loosely adsorbed sulfuric acid, which can be removed during a water rinse cycle, thereby restoring the carbon's affinity for H_2S .

Based on anticipated hydrogen sulfide loading, anticipated canister regeneration frequency was once every four to five days. Regenerations were performed by shutting down the system and filling the canister chamber with potable water and rinsing at a rate of 3-gpm for 1½ hours.

Biofiltration. A biological filtration system by Biorem Technologies was tested. The biofilter consisted of a media filled bed where odorous compounds were biologically degraded by microbes living within the media to non-odorous compounds such as carbon dioxide, water and inorganic salts.

The biofiltration system consisted of a covered vessel containing Biosorbens™ media, preceded by a humidification chamber, and equipped with an irrigation system and outlet drain. The humidification system was intended to maintain relative humidity to greater than 98-percent and avoid drying out the media. The irrigation system was also used to keep the media moist and provide a high wetted surface area or liquid film on the media for microbes to proliferate.

The biofilter was operated in an upflow mode with the inlet air stream entering the bottom of the vessel, flowing through the media and exiting out the top. Dimensions for the high-density polypropylene (HDPE) tank were 64-inch diameter by 6-feet tall, containing 28-inches of Bisorben media. The HDPE tank was equipped with two layers of perforated irrigation hose, media thermometer, and pressure gauge.

RESULTS

Packed Tower Scrubbing

The PTS was capable of a wide range of treatment and operated with a great deal of flexibility by adjusting chemical and make-up water feed rates to the first or second stage. Experiments were conducted to enable characterization of PTS operation as a single and two stage process. Performance was evaluated as a function of stage 1 pH, stage 1 make-up water feed rate, stage 2 pH, stage 2 oxidation reduction potential (ORP), H₂S loading, and carbon dioxide loading.

Single Stage PTS Evaluations

Stage 1 pH. Performance impacts related to variable stage 1 pH were examined by varying the feed rate of sodium hydroxide (NaOH) into the stage 1 sump chamber. Inlet H₂S concentrations for these tests were fairly constant ranging from 32 to 35 ppm_v. The profile provided in Figure 2 indicates Stage 1 performance improved with increasing scrubbing solution pH. At pHs less than 9.5, minimal treatment was achieved. Substantial H₂S removal was not achieved until the pH was increased to the 10.2 to 10.8 range, which lead to respective H₂S capture rates of 90 to 96-percent. Corresponding outlet concentrations were 1.5 to 3.5 ppm_v, respectively. Greater than 99-percent H₂S removal was achieved by increasing the pH to ~11.5.

While 99-percent removal can be achieved in the first stage, this level of treatment must be weighed against the amount of chemical needed to achieve this level of treatment. For instance, dose rates of 212, 560 and 1,484 mg/L NaOH were required to maintain respective pHs of ~9.5, ~10.5 and ~11.5. Based on this data, a target Stage 1 pH range of 10.2 to 10.8 was identified for subsequent tests.

Stage 1 Make-up Water Feed Rate. Make-up water was required at a rate sufficient to discharge reacted chemical and sulfide and account for water loss to evaporation and air entrainment. Make-up water feed rates were varied to identify a target operating condition, one that simultaneously minimized chemical dilution and/or supersaturated conditions in the chemical sump, both of which are undesired due to impacts related to NaOH consumption, diminished performance capability, and chemical precipitation. Operating conditions included make-up water feed rates of 10 to 33 gal/hr. Good pH was provided varying from 10.2 to 10.8 standard units.

Average Stage 1 outlet H₂S concentration is shown in Figure 3 for three ranges of make-up water flow rate, 10-15 gph, 16-24 gph and 26-33 gph. In general, the average outlet concentration from the odor reduction scrubber increased as the make-up water feed rate was increased. With an average outlet H₂S concentration of 2 ppm_v, the highest level of performance occurred at make-up water feed rates between 10-15 gph. Increasing the make-up water flow rate to 16-24 gph and 26-33 gph lead to diminished performance with average outlet H₂S concentrations of 3.8 and 5.2 ppm_v, respectively.

While the make-up water feed rate impacted Stage 1 performance, the impact of the Stage 1 pH was comparatively greater. The selected operational set-point was 15 gph and targeted for remaining tests. The 15 gph value was chosen in lieu of 10 gph to minimize sodium and sulfate concentrations in the first stage chemical waste stream and reduce the potential of sulfate salt precipitation. For scale-up purposes, a normalized make-up water flow rate of 1.8 gpd/cfm was derived (make-up water feed rate of 15 gph divided by a 200 cfm airflow).

Dual Stage PTS Evaluations

To achieve higher overall H₂S removal, additional tests were performed to utilize the first stage for primary H₂S removal (~90-percent) followed by a second stage treatment. Sodium hypochlorite (NaOCl) and NaOH comprised the chemical additives used to polish the first stage off-gas. In the following sections, impacts related to Stage 2 oxidation reduction potential (ORP) and pH is discussed. Additional results include performance results at increased H₂S and CO₂ loading.

Stage 2 ORP. The relative impact of NaOCl addition was monitored by ORP, which provides a direct measure of chlorine available for oxidation of H₂S to elemental sulfur (S₀). All other variables were held constant, as best as possible, to isolate the effect of ORP on performance, particularly pH. Precise control of Stage 2 pH was somewhat complicated by sodium hypochlorite addition which is an alkaline chemical that also influenced pH. Still, pH was controlled with the range of 8.9 to 9.2 for these tests.

Stage 2 outlet H₂S concentrations are plotted versus ORP in Figure 4. The inlet H₂S concentration during these tests was relatively stable averaging 2.75 ppm_v. In general, the outlet H₂S concentration decreased with increasing ORP. At an ORP of approximately 210 mV, H₂S exiting the second stage measured 1.0 ppm_v. Further reductions to 0.5 to 0.6 ppm_v or less were realized when the ORP was increased in excess of 650 mV, resulting in 78- to 82-percent

removal by the second stage. Using an average inlet H₂S concentration of 31.5 ppm_v, overall PTS H₂S removals of 98-percent were achieved at ORPs greater than 450 mV.

Stage 2 pH. Separate tests characterized the impact of variable pH on Stage 2 performance. Corresponding Stage 2 inlet H₂S concentration measured 14 ppm_v. The other process variables recorded during this test were: ORP of 276 to 455 mV, Stage 1 pH of 9.9 to 10.1 and make-up water feed rate of 15 gph.

Starting at a Stage 2 pH of 9.2, Figure 5 shows the outlet H₂S concentration measured 6 ppm_v. Increases in pH were carried out up to pH 9.8. Only marginal improvement was realized by increasing the pH above 9.6. At pH 9.5 to 9.6, the outlet H₂S concentration ranged from 2.8 to 2 ppm_v corresponding to 91 and 93 percent removal by Stage 2. Consequently, operation between pH 9.5 to 9.6 was recommended to maximize removal and avoid excessive sodium hydroxide consumption.

When compared to the performance impact of ORP, pH appeared to have a greater overall effect, though both sodium hydroxide and sodium hypochlorite were required to achieve enhanced performance.

Increased Off-gas Hydrogen Sulfide and Carbon Dioxide Loading. Two additional tests included PTS operation at separate evaluations at elevated H₂S and carbon dioxide loading. The PTS inlet H₂S concentration was increased to 85 to 100 ppm_v. Identified by scenarios A through E, Table 2 presents a summary of performance by test condition for these tests along with reference to baseline conditions identified previously.

Scenario A corresponds to operations at elevated H₂S loading. Comparing scenarios A and B quantifies differences from prior operation at lower inlet H₂S concentrations of 25 to 35 ppm_v. With an outlet H₂S concentration of 0.75 ppm_v, the PTS was fully capable of providing greater than 99-percent removal of H₂S at *high* loading. However, sharp increases in chemical feed rates were required at increased loading. More specifically, pH in Stage 1 and 2 had to be increased to 11.7 and 10.4, respectively, or a seven-fold increase in NaOH consumption and a two-fold increase in NaOCl demand.

As mentioned previously, carbonic acid was used to suppress pH ahead of the forced-draft aerator. For the tests described previously, raw water pH was reduced to approximately 6.5. While lower FDA feed water enhances H₂S removal from water, a secondary impact related to PTS NaOH demand was recognized. Higher NaOH demand is the result of higher CO₂ levels in the FDA off-gas, which along with H₂S is stripped from the acidified raw water during aeration. Shown as test scenario C in Table 9, the raw water pH was lowered from the previously established pH of 6.5 to 6.0. While this represents a seemingly minor adjustment in pH, this significantly increased the amount of sodium hydroxide consumed in each stage. Sodium hydroxide dosages were 1,407 and 317 mg/L for the first and second stages, respectively; amounting to a 225-percent increase from the baseline condition at FDA feed pH 6.5. This result clearly demonstrates the connection between carbonic acid addition for sulfur removal from groundwater and subsequent chemical demand. Consequently, when using carbonic acid to

enhance H₂S removal from water, feed water pH should be balanced against impacts to PTS chemical demand.

Granular Reactive Media (SulfaTreat)

The SulfaTreat media was tested for approximately 1,000 hours. Inlet and outlet concentrations are shown in Figure 6. Over the course of testing, the SulfaTreat media consistently provided a high level of treatment with H₂S levels at or below the 0.25 ppm_v method detection level of the Interscan analyzer. This applied to measurements from each sample location, even at three inches depth from the interface between untreated off-gas and media. Measurements taken at 6- and 18-inch bed depths were not statistically different from measurements at 3-inches.

The slight variations at start-up may be the result of changes in media compaction or moisture content over the first day of testing. The remaining values exceeding 0.25 ppm_v are minimal and appear to occur randomly suggesting analytical error or occasional short-circuiting.

Empty Bed Residence Time. For the first 1,000 hours of testing, the flow rate averaged 190 cfm. Taking the media volume into account, this corresponds to an empty-bed residence time (EBRT) of 28 seconds. A reduced EBRT of 19 seconds was evaluated by increasing the FDA off gas flow rate to 270 cfm. Comparative data is presented in Figure 7, which shows the impact was insignificant despite having less time to react with and capture H₂S, i.e., increased superficial velocity through the bed. Over the 4-day test period, outlet concentrations, measured within the first 3-inches of media depth were <0.25 ppm_v. Even though performance was not diminished at lower EBRT, it is intuitive that premature breakthrough is one potential long-term impact. In order to achieve a thorough characterization performance changes with EBRT under conditions representative of full-scale operation, it is believed that a test interval approaching one year would have been required, a period beyond the scope of this evaluation.

Increased Hydrogen Sulfide Loading. The impact of a spike increase in inlet H₂S concentration was assessed. This test was performed over a 15-minute period to determine the media's capacity to perform under stressed conditions. Baseline conditions measured prior to testing were inlet and outlet H₂S levels of 31 and <0.25 ppm_v, respectively, and 194 cfm airflow rate (26 second EBRT). Following an increase in inlet H₂S concentration to 90 to 100 ppm_v, the H₂S concentration profile within the media remained unchanged indicating the SulfaTreat media was able to provide consistent treatment during a sudden and significant increase in H₂S loading.

Catalyzed/Adsorptive Carbon

Catalyzed/adsorptive carbon testing was conducted over a one-month period. Operation was intermittent and hampered by operational difficulties limiting total operational time to 365 hours. Following an initial carbon activation/water regeneration step (90-minute potable water flush at 3 gpm), the unit was immediately placed into operation. Inlet and outlet H₂S profiles are shown in Figure 8. Vertical bars are also provided to delineate when periodic regeneration cycles were performed and canisters replaced. As a result of moisture variations in the canister, operation at 200 cfm target airflow was not satisfactorily achieved, particularly within 24-hours of water regeneration. Maximum air flow rates following period water regeneration were typically at or

below 100 cfm making precise control of inlet airflow in a manual operation mode virtually impossible.

Initially, 83-percent H₂S removal was achieved with an outlet concentration of 5 ppm_v. The rate of removal increased and stabilized to 98-percent (outlet concentration of 0.75 ppm_v) over the next 45 hours, then dropping to 95- to 96-percent removal after 100-hours of testing. The lower percent removals observed initially were attributed to moisture remaining after water regeneration. As the FDA off gas stream dried the carbon, performance improved significantly. However, as the reaction sites within the carbon become saturated, performance gradually degraded. Following discussions with the manufacturer, the outlet concentration profile observed in the first test is typical for this technology, although the manufacturer projected high removal than that observed.

A water regeneration cycle was performed after 128-hours, which is consistent with the manufacturer's recommended 5-day regeneration frequency (based on an inlet H₂S concentration of ~35 ppm_v). A similar response profile was observed during the second test interval. Here again, as the canister dried, improved performance, increased airflow and reduced pressure drop were observed. Even though performance improved, the minimum outlet concentration of 2 ppm_v H₂S was more than doubled that observed during the first test interval.

A significant decrease in removal efficiency was observed during the third test interval where removals did not exceed 30-percent. At this time, the manufacturer was informed of the less than desired removal efficiency and a replacement canister along with a demister device was supplied. The demister was installed to remove mist carried over from the FDA tower.

The carbon canister was replaced at hour 300. Unfortunately, the system modifications did not improve performance. In fact, the performance deteriorated. These peculiarities led to shutdown followed by a thorough inspection of the system. A fractured canister housing was determined to be the cause of poor performance during the fourth and final test. While the canister appeared to be intact upon arrival and installation, a fine crack was discovered along the welded joint connecting the outer porous polypropylene wall and canister end-cap/pilot cover. A third and final canister was requested from the manufacturer, but was not received in time to perform additional tests.

Biofiltration

The biofiltration system was evaluated for approximately 61 days. Overall, the system performed reliably and required minimal operator attention beyond routine monitoring and data collection. The operation profile for inlet and outlet H₂S concentration is shown in Figure 9. Overall, H₂S capture efficiency averaged 98-percent. It was anticipated that lower percent removals would occur initially until the system became acclimated. Biological acclimation was evidenced, but not initially. The only sign of acclimation occurred after 174 hours when the outlet H₂S concentration increased to 1 ppm_v. Based on the observed response pattern during the first 112 hours, the media appears to possess both biological and adsorptive H₂S removal capability, with adsorption providing the bulk of treatment initially until the biological component became sufficiently acclimated or established.

Empty Bed Residence Time. For an average airflow of 210 cfm, the biofilter was initially operated at an average 29-second EBRT. The level of treatment provided under this condition was stable and of high quality. The airflow rate was increased after 1,127 hours to measure the effect of reduced EBRT on treatment performance. Figure 9 shows that the 21-second EBRT had virtually no effect on performance over the next 75 hours of testing; supporting the conclusion that biofilter performance was not adversely impacted by reduced EBRT.

Increased Hydrogen Sulfide Loading. The final test conducted with the biofilter involved a shock loading of H₂S to the system by increasing the inlet H₂S concentration to approximately 100 ppm_v. The system was monitored for the next 30-minutes of operation, during which the outlet concentration increased from 0.4 to 1.0 ppm_v. A longer run time was desired but was not possible due to operational constraints. Based on discussions with the vendor representative and performance capability citations in the literature, the biofilter may not be able to handle projected worst-case hydrogen sulfide loadings over an extended period of time creating the need for H₂S reduction ahead of the biofilter to maintain relatively constant inlet concentrations.

Biofilter Media Analysis. Filter media was randomly sampled from the biofilter after 794 hours of testing. The media was sampled by digging down into the media and taking samples at depth. Analysis included total microbial counts, pH, moisture content, and nutrient content, each of which serve as critical indicators to overall biofilter health. Summarized in Table 3, this data suggested the media was in suitable condition for sustained hydrogen sulfide removal. Only minor changes in the media were noted visually. Visual observations included media discoloration, particularly within the first 6-inches of the bed bottom where a distinct white coating had developed.

CONCLUSIONS

The findings demonstrate that conventional packed tower scrubbers and non-conventional granular reactive media and inorganic biofiltration technologies can be used to effectively reduce H₂S odor produced by WTFs. Consequently, water purveyors should include these newer processes when evaluating odor control needs. In addition to cost, preliminary and final selection should take into account H₂S loading rate, desired odor reduction capability, waste disposal impacts, land requirements, and ease of operation. Additional testing or product development is needed to resolve factors contributing to the treatment and operational difficulties associated with the catalyzed/adsorptive carbon process.

RECOMMENDATIONS

Based on the performance data collected and considering constructability, operational and ancillary factors, the odor reduction process recommended for implementation consisted of a single stage packed tower scrubber followed by a biofilter. An odor reduction system configured in this manner provides odor reduction with optimal flexibility, system redundancy, and minimal media replacement frequency. The packed tower scrubber was not selected for stand-alone treatment because of excessive operational and maintenance costs associated with chemical consumption. Biofiltration was not desired as a stand-alone system because of possible increases in H₂S loading that may result from groundwater degradation over time. Coupling these two complementary processes mitigated issues surrounding their individual use.

ACKNOWLEDGEMENTS

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FORCED DRAFT AERATION
 WITH ODOR CONTROL

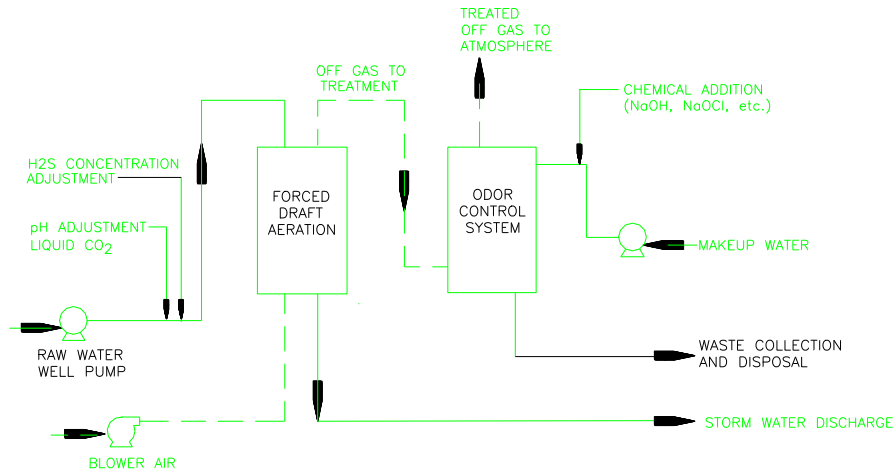


FIGURE 1 - Simplified Process Diagram- Hydrogen Sulfide Removal and Odor Reduction

TABLE 1
 Odor Reduction Equipment Summary

| Detail | Packed Tower Scrubber | Catalyzed / Adsorptive Carbon | Granular Reactive Media | Inorganic Biofiltration Media |
|----------------------------|---|-------------------------------|-------------------------|-------------------------------|
| Manufacturer | Met Pro Corp., Duall Division | Calgon Corp. | SulfaTreat Co. | Biorem Technologies Inc. |
| Manufacturer Location | Owosso, MI | Neville Island, PA | St. Louis, MO | Guelph, Canada |
| Product Trade Name | NS | Phoenix | SulfaTreat | Biosorbens |
| Configuration | 2 Stage Scrubber | Single Canister | Deep Bed – 43” Depth | Deep Bed – 34” Depth |
| Chemical Additives | 1 st Stg. – NaOH 2 nd Stg.: NaOH & NaOCl | Not Specified | Not Specified | Not Specified |
| Regeneration Capability | Continuous Sump Blow-down | Water Rinse | Not Specified | Not Specified |
| Rated Air Flow Rate (scfm) | 200 | 200 | 200-300 | 200 |

FIGURE 2
Stage 1 Outlet H₂S Concentration Versus pH

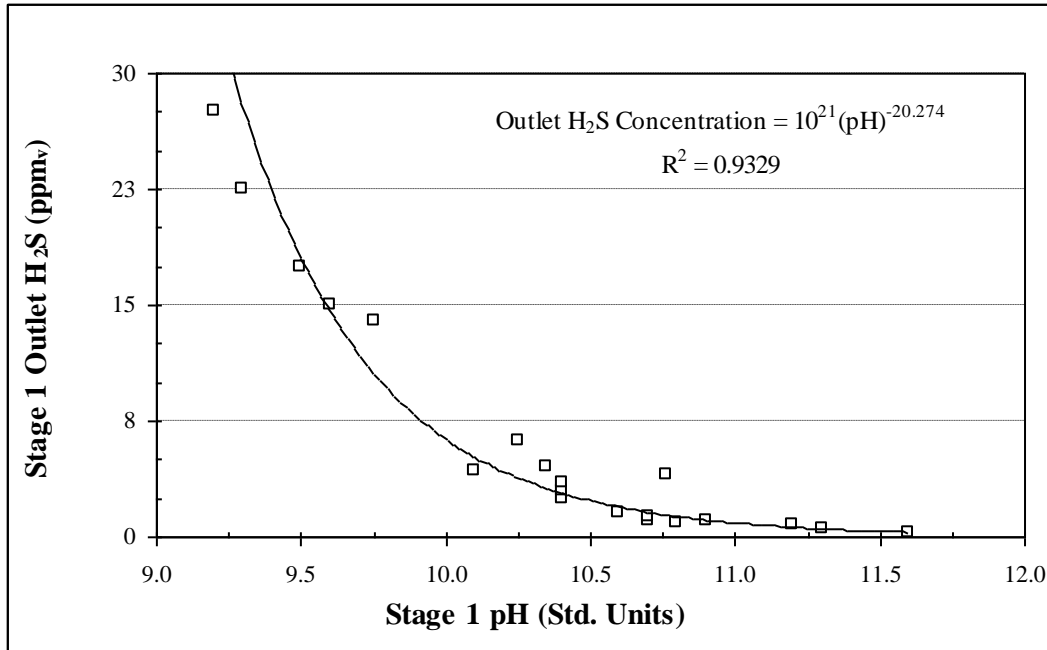
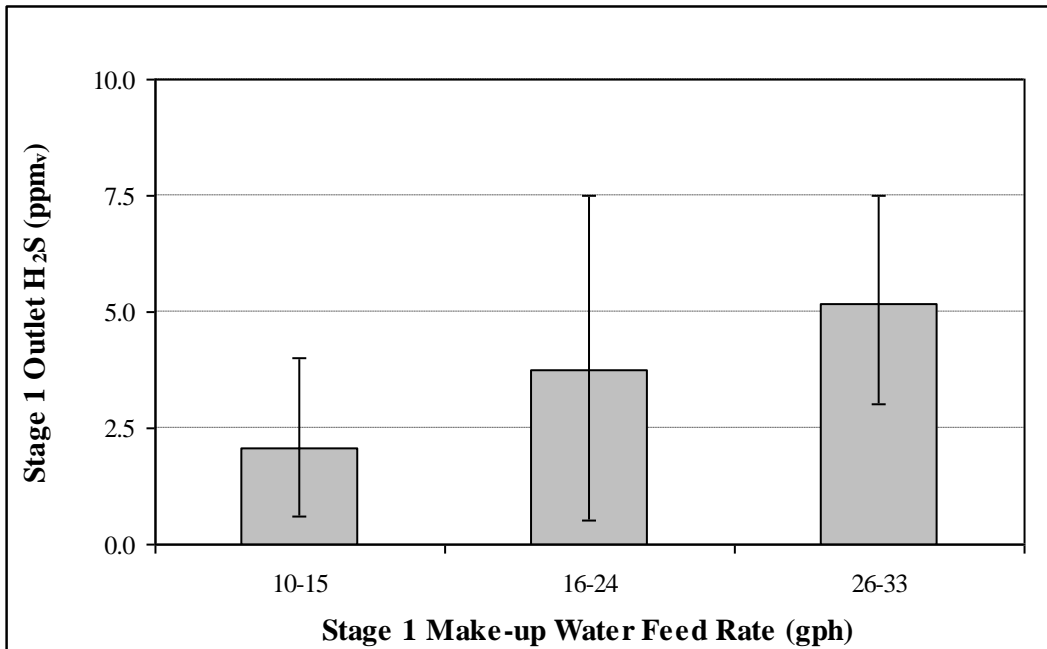


FIGURE 3
Stage 1 Average Outlet H₂S Concentration Versus Make-up Water Feed Rate



* Corresponding pH range of 10.2 to 10.8.

FIGURE 4
Stage 2 Outlet H₂S Concentration Versus ORP

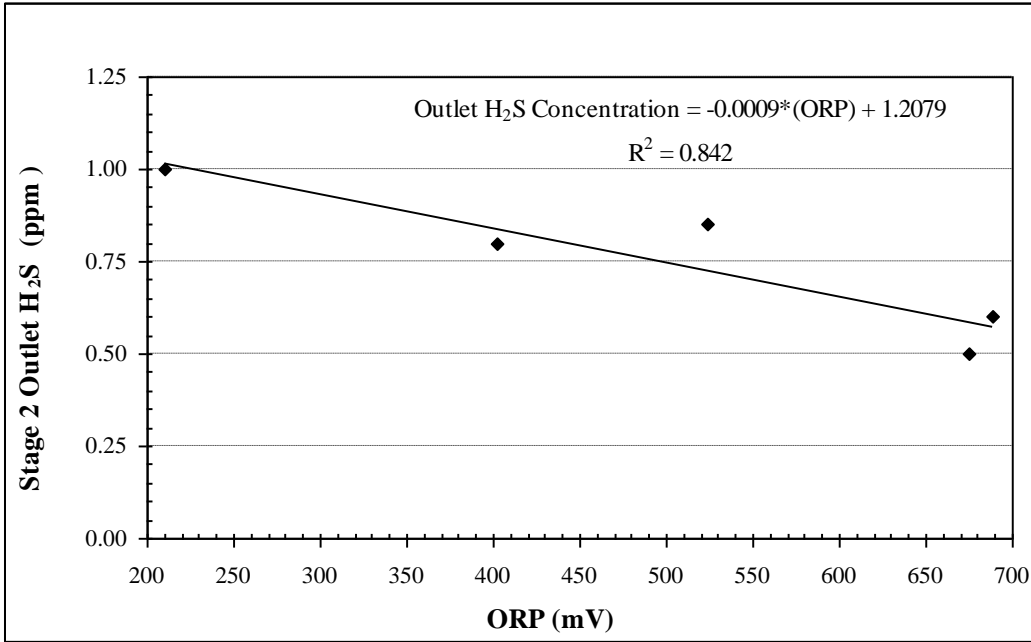


FIGURE 5
Stage 2 Outlet H₂S Concentration Versus pH

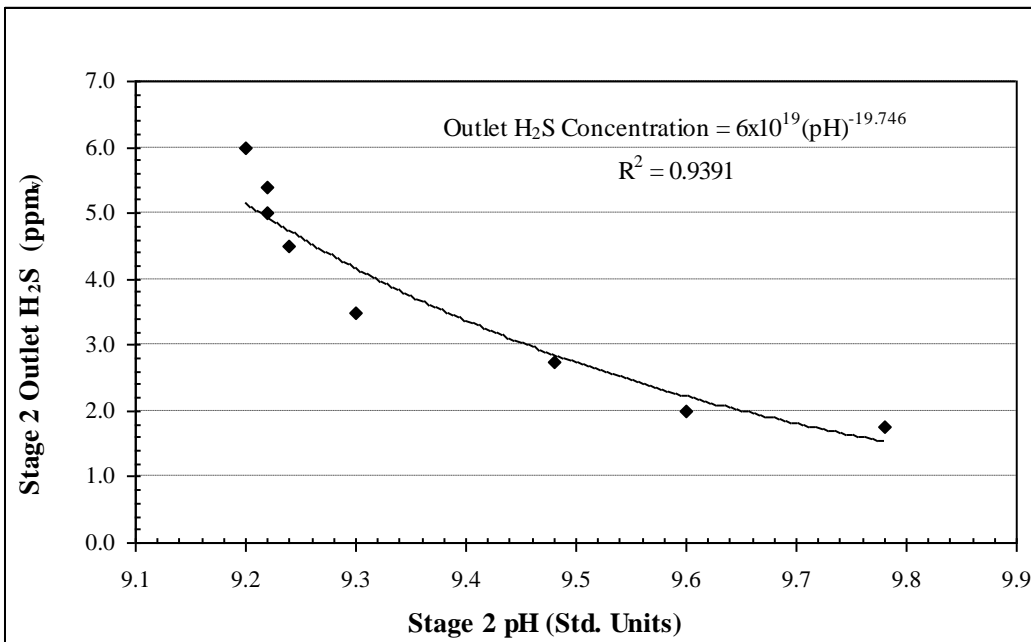


TABLE 2
PTS Chemical Consumption and Associated Chemical Cost Estimates

| Parameter by Stage | Treatment Scenario | | | | |
|--|------------------------------------|-----------------|-----------------------------------|-----------------|----------------|
| | Increased H ₂ S Loading | Baseline | Increased CO ₂ Loading | Baseline | Baseline |
| Scenario | A | B | C | D | E |
| # of Stages Used | 2 | 2 | 2 | 1 | 1 |
| Stage 1 | | | | | |
| Sump pH | 11.7 | 10.5 | 11.1 | 11.2 | 9.5 |
| Q_{Make-up Water} (gph) | 14 | 15 | 14 | 15 | 15 |
| NaOH Dose (mg/L) | 3,890 | 560 | 1,407 | 1,110 | 210 |
| Inlet H₂S (ppm_v) | 90 | 33 | 32 | 33 | 33 |
| Outlet H₂S (ppm_v) | 2.8 | 2 | 8 | 0.5 | 15 |
| Stage 2 | | | | | |
| Sump pH | 10.4 | 9.5 | 10.5 | NA* | NA |
| ORP (mV) | 510 | 450 | 726 | NA | NA |
| NaOH Dose (mg/L) | 385 | 203 | 317 | NA | NA |
| NaOCl Dose (mg/L) | 704 | 291 | 277 | NA | NA |
| Q_{Make-up Water} (gph) | 17 | 15 | 16 | NA | NA |
| Outlet H₂S (ppm_v) | 0.75 | 0.5 | 1.25 | NA | NA |
| Chemical Cost (\$/yr) | \$221,000 | \$57,000 | \$87,000 | \$37,000 | \$7,000 |

Notes: NA = not applicable. Costs shown reflect 2003 dollars. WTF capacity of 10 MGD with 30,000 cfm FDA off-gas flow rate.

FIGURE 6
SulfaTreat Inlet and Outlet Hydrogen Sulfide Concentration Profiles

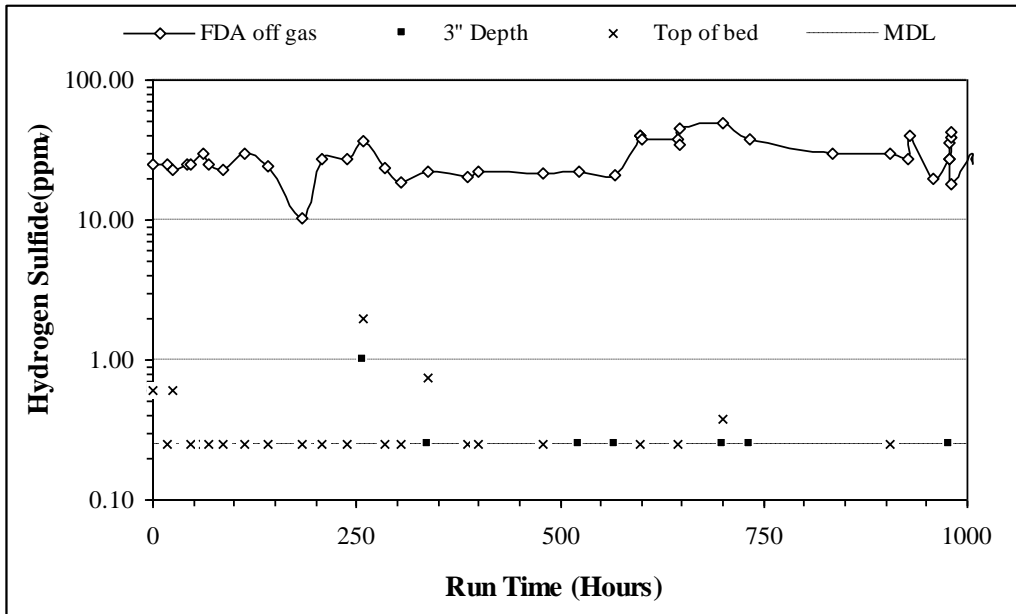


FIGURE 7
SulfaTreat Performance by EBRT and Inlet Concentration

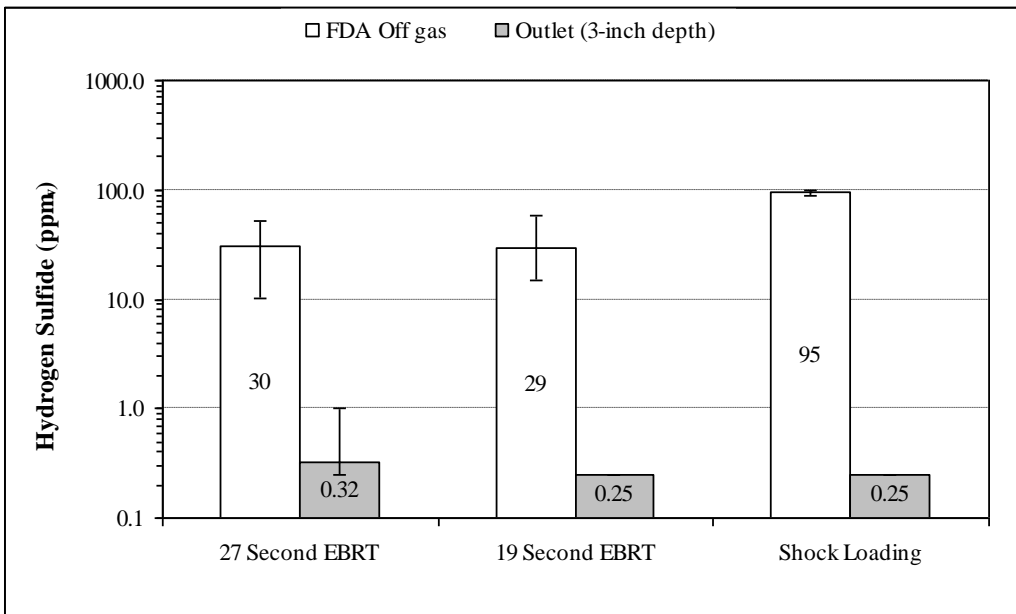


FIGURE 8
Carbon Odor Reduction Performance Data

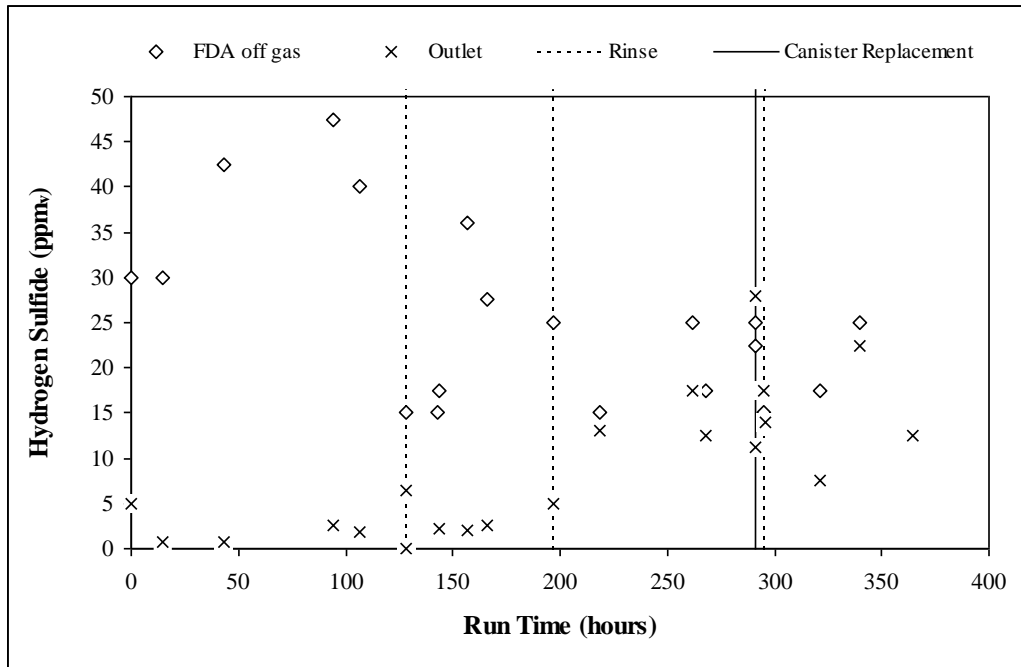


FIGURE 9
Biofilter Odor reduction Performance Data

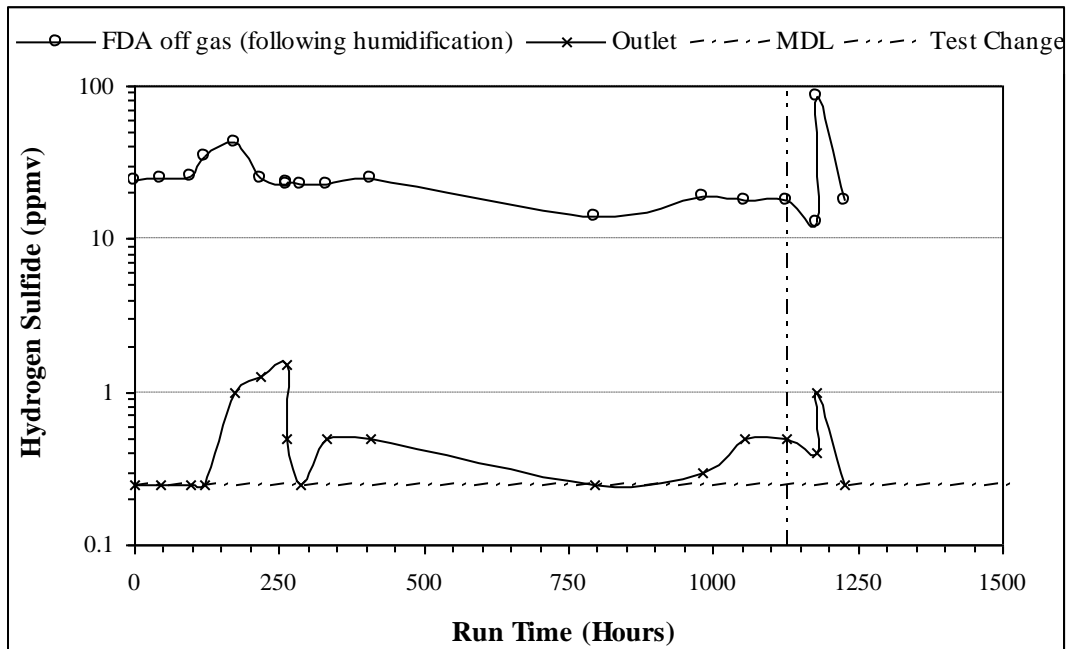


TABLE 3
Biofilter Media Analysis Data

| Parameter | Units | Sample Location | | |
|-----------------------|----------------------------|-----------------|---------|---------|
| | | Top | Middle | Bottom |
| Approximate Depth | (inches) | 4 | 15 | 28 |
| Total Microbial Count | (CFU/ g)* | 1.8E+06 | 1.9E+06 | 7.8E+06 |
| PH | (Std. Units) | 7.9 | 7.4 | 7.4 |
| Moisture Content | (% dry weight) | 22.5 | 15.2 | 18.9 |
| Ammonia-Nitrogen | (mg/kg NH ₄ -N) | 3.5 | 5.9 | 20.7 |
| Nitrate-Nitrogen | (mg/kg NO ₃ -N) | 8.5 | 8.6 | 1.0 |
| Total Nitrogen | (%) | 0.4 | 0.3 | 0.2 |
| Total Sulfide | (%) | 0.5 | 1.5 | 4.7 |
| Total Carbon | (%) | 37 | 39 | 35 |
| Total Organic Carbon | (%) | 35 | 37 | 34 |
| Inorganic Carbon | (%) | 2.0 | 2.3 | 1.1 |
| Magnesium | (mg/kg) | 76 | 44 | 70 |
| Phosphorus | (mg/kg) | 45 | 41 | 36 |
| Potassium | (mg/kg) | 616 | 643 | 825 |

Notes: CFU/g = colony forming units per gram of media.