Updating Wastewater Treatment in Puerto Rico

by

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Executive Summary

In the first part of this report, the use of chemically enhanced primary treatment (CEPT) is studied at the plant-scale at two sites (Vega Baja and Fajardo) in Puerto Rico. The two wastewater treatment plants (WWTPs), which are currently operating over their design capacity on a yearly basis, consist of primary settling tanks followed by fixed-film trickling filters. Previous studies, and local preference, mandated the use of aluminum chlorohydrate as the coagulant in both plants.

The chemical used at the Vega Baja WWTP had a dose of either 20 or 40 mg/l, and was applied for 9 hours during the day. The chemicals applied at the Fajardo WWTP were not the same for the duration of the experiment. It was initially dosed with aluminum chlorohydrate (Al content of 12.4%) at 43.5 mg/l for 14 hours. A different aluminum chlorohydrate solution (Al content of 11.6%) was utilized at the same dosage, but its application lasted for 17 hours.

In both WWTPs the primary clarifier and trickling filter received benefit from the use of CEPT. In both cases, the primary clarifier and trickling filter were operating at a removal percentage higher than expected with conventional primary clarification. An interesting relationship was seen between the primary clarifier and the trickling filter. As expected, when the primary clarifier increased its removal of BOD, the trickling filter removed less BOD. When the primary clarifier increased its removal of TSS and Total P, the trickling filter was able to remove more of each.

At Vega Baja, after the use of chemically enhanced primary treatment the BOD removal in the primary clarifier doubled to 65%, while TSS removal increased by a factor of four to 47%. Overall the effluent BOD concentration with CEPT was 12.5 mg/L, which is above the local compliance regulation limit of 5 mg/L for BOD, but is still a significant improvement. TSS in the effluent was 12 mg/L, which is well below their local compliance regulation limit of 30 mg/L for TSS.

At Fajardo, with the use of CEPT, the effluent concentrations were reduced to an average 14 mg/L for BOD and 16 mg/L for TSS, both below Fajardo's local compliance permit limits. At Fajardo two different coagulant solutions were tested, one of which provided better treatment at a reduced cost. These results indicate that CEPT can help the plants on this Puerto Rico meet their effluent standards

The final section of this report presents an overview of Puerto Rico's practices of local sludge treatment and disposal techniques. The characteristics of Puerto Rican sludge were studied to see which disposal techniques were applicable to this particular case. In addition, sludge management practices at Point Loma Wastewater Treatment Plant and at Orange County Wastewater Treatment System, both in California, were analyzed as a means to compare and contrast the methodologies discussed. Alternative practices and possible innovations are also detailed. It is now apparent that a passive approach to sludge management is not sufficient in itself to meet the changing needs of Puerto Rico. A proactive approach is essential for the maintenance and improvement of current infrastructure with a view to meeting sludge management needs.

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Chapter 1- Introduction

Wastewater treatment in Puerto Rico is currently undergoing a period of rapid change. Much of the infrastructure is outdated and overloaded, and because of this many of the smaller plants are not meeting their effluent guidelines. Normally a massive construction effort would be required to replace the older plants. However in this case a cost-effective retrofitting option is available. The goal of this project is to evaluate that option for use in Puerto Rico.

Another problem that Puerto Rico faces is the increased production of sludge from its wastewater treatment plants. Puerto Rico's Aqueduct and Sewer Agency runs 67 wastewater treatment plants that produce around 27,000 dry metric tons of sludge annually (Puerto Rico's Annual Sludge Report, 1999). In reality most of the population is centered around the metropolitan area and near four other big cities, which means the majority of this sludge comes from just seven wastewater treatment plants.

1.1 General Overview

The project took place on the island of Puerto Rico, a commonwealth government associated with the United States. Puerto Rico measures 100 miles by 35 miles with an area of 3,464 square miles. The topography varies from flatlands to mountainous central highlands. Its moderate, tropical-marine climate is ensured year-round by trade winds. The population is about 3.9 million people, most of who are US citizens. Today, island residents live in substantial middle-class circumstances, characterized by modern urban services and amenities (Puerto Rico Chamber of Commerce 2000).

One of the most prized services is wastewater treatment. This project involved two of the exisiting wastewater treatment plants. The location of the WWTPs is shown below in Figure 1.

FIGURE 1: MAP OF PUERTO RICO (LONELY PLANET 2000)

The WWTPs are located in Vega Baja and Fajardo. Vega Baja is about 27 kilometers (km) from San Juan, and Fajardo is approximately 50 km from San Juan. Both WWTPs are located on the northeastern side of the island, and their effluents eventually empty into the Atlantic Ocean. The northern coast of Puerto Rico is heavily populated and has a high influx of tourists from November to March. Thus, the WWTPs' effluent quality is important in order to maintain the coastal beauty and public health.

1.2 Background Information on Puerto Rico's Wastewater Treatment Plants

1.2.1 Project Background

The Puerto Rican government hired the Compania de Aguas de Puerto Rico (CAPR), a Vivendi company, to operate the 30 wastewater treatment plants in Puerto Rico. CAPR is in charge of operating and improving the WWTPs. Last year most of these WWTPs got injunctions against them. EPA, which was responsible for getting the injunctions in court, wouldn't lift the injunctions until the WWTPs could prove that their effluents were meeting the required limits. These limits are usually an effluent value of 30 mg/L TSS and BOD.

CAPR and the Puerto Rico Aqueduct and Sewer Authority (PRASA) created a compliance plan for these WWTPs in order to meet these requirements. They formed a

Polymer Addition Task Force as part of this plan. The Task Force included CAPR Technical experts, CAPR and PRASA regional managers and operators, MIT students, and chemical suppliers. Each team had a different objective in the task force. It was in this respect that this project developed. CAPR had MIT students M. Varona and L. Otero come in during the summer as part of MIT's Undergraduate Research Opportunities Program (UROP). The UROP students' main goal was to perform bench scale and full scale polymer testing. The students' tasks also included providing data accumulation and evaluation, and writing reports. The scope of work begun by the students was ultimately too large to be finished in a summer, which is where the current research came into the picture. By continuing from where the UROP students' final report (Otero and de Varona 2000) left off, the project goal of ultimately improving the performance of these WWTPs so they meet their limit requirements and get the injunctions lifted would be easily met. This would permit new development to attach to these WWTPs, and hopefully allow for future development around these WWTPs while safeguarding the environment.

1.2.2 Vega Baja and Fajardo Wastewater Treatment Plants

The two WWTPs chosen for this project were Vega Baja and Fajardo. These WWTPs were not only part of the background testing (Otero and de Varona 2000), but they are also very similar WWTPs in terms of their design. Both WWTPs have a trickling filter and a separate and parallel activated sludge train. In our studies, we have focused on the combination of chemically enhanced primary treatment (CEPT) followed by trickling filters. We have not changed or analyzed the parallel biological treatment system.

Trickling filters involve spraying the sewage over a bed of rocks or other media. As the water trickles through the rocks, a biofilm forms that removes organic carbon from the water. Occasionally the biofilm detaches from the rocks, so a settling tank is placed at the end of the trickling filter system (Metcalf & Eddy 1991). Vega Baja has two of these trickling filters that are operated in parallel; the flow from the primary clarifier is divided between the two trickling filters. Fajardo has a conventional trickling filter and a "biotower", which is simply a very tall trickling filter. These are in series; the water from the primary clarifier first flows through the trickling filter and then through the biotower (Otero and de Varona 2000).

The activated sludge trains in both of these WWTPs are one or two very compact package plants consisting of an aeration tank, a clarifier and usually an aerobic digester. In the aeration tank, air is bubbled into the tank to encourage microbial activity for the conversion of organic carbon to carbon dioxide. The settling tank allows for the removal of biomass, or sludge, created in the aeration tank, and the anaerobic digester consumes some of the sludge producing methane (Metcalf & Eddy 1991).

The Vega Baja Wastewater Treatment Plant is designed to handle 2.2 million gallons per day (MGD), and at the time of this study was handling an average flow of 1.6 MGD. The limits imposed by the injunction on this wastewater treatment plant are 30 mg/L of TSS and 5 mg/L of BOD. The Fajardo WWTP is designed to handle a flow of 4 MGD, and was handling an average flow of 2.2 MGD during testing. The injunction against the Fajardo Wastewater Treatment Plant specifies that it must achieve a TSS limit of 30 mg/L and a BOD limit of 28 mg/L (Otero and de Varona 2000).

1.3 Introduction to Chemically Enhanced Primary Treatment

1.3.1 Theories of Chemically Enhanced Primary Treatment

Traditional wastewater treatment plants use gravitational settling to remove many contaminants from the wastewater. This process usually removes 60% of the total suspended solids (TSS), 30% of the biochemical oxygen demand (BOD), and 30% of the nitrogen and phosphorus from the wastewater. Primary clarification is typically the first step in a series of treatment processes. Unfortunately in today's growing society where wastewater treatment plants are handling more wastewater that originally anticipated and environmental regulations are becoming more stringent, gravitational settling alone does not provide the necessary removal. Chemically enhanced primary treatment (CEPT) is a viable way of improving gravitational settling (Harleman 2000).

CEPT involves the addition of a coagulant to a settling tank in a wastewater treatment plant. The coagulant is usually an aluminum or iron salt, and is used to encourage the aggregation of particles in the wastewater into larger particles. These composites have a larger diameter than the original particles and therefore settle more quickly. Many particles that would not settle on their own, because they are too small, are incorporated into the flocs and descend to the bottom of the tank. Because more of the particles settle out, CEPT has a higher removal efficiency: 85% for TSS, 60% for BOD, 85% for phosphorus, and 30% for nitrogen (Harleman). The addition of CEPT can greatly improve the efficiency of a gravitational settler in a wastewater treatment plant (Harleman and Murcott 1992).

1.3.2 Orange County, California: Retrofitting with CEPT

The Water District of Orange County, California operates two wastewater treatment plants, one of which has a trickling filter and an activated sludge plant, similar to the WWTPs studied in Puerto Rico. Since the 1980s, Orange County has been adding chemicals to its influent to aid in coagulation and flocculation; they call this process Advanced Primary Treatment (APT) however it is the same as CEPT. The results have been wonderful; they achieved low enough levels of Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) that they were granted a waiver from full secondary treatment (Hetherington et al 1999).

The design of Orange County Plant #1 has CEPT plus a trickling filter and CEPT plus an activated sludge pant. This WWTP is able to handle an average flow of 60 million gallons per day (MGD). All of the influent is pretreated, and goes through chemically enhanced primary clarification. The wastewater is then divided into three parallel trains at the splitter box. A little more than half of the flow goes to the activated sludge plant. Eighteen MGD goes to the trickling filter, and the remaining four MGD goes straight to the disinfection step. The effluents of these three trains are blended and then combined with the effluent from Plant #2, which also uses chemicals, and sent to the ocean outfall. The diagram of Plant #1 follows in figure 2 (County Sanitation 1993).

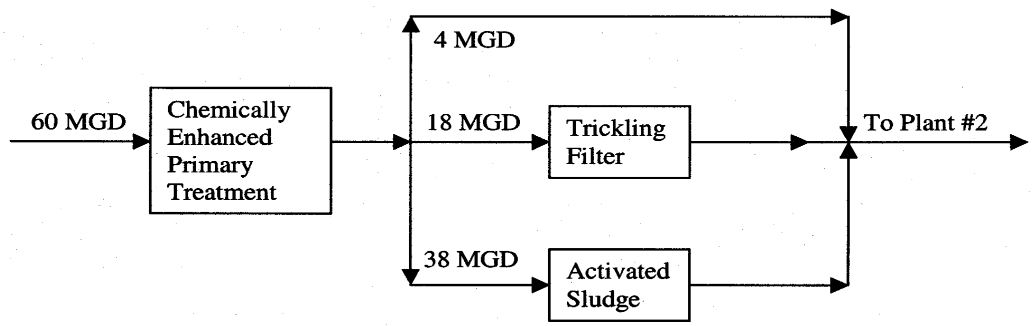

FIGURE 2: ORANGE COUNTY, CA WASTEWATER TREATMENT PLANT

The use of chemicals at Orange County consists of Ferric Chloride (FeCl3) and a small amount of anionic polymer, to aid in flocculation of the coagulated material. The FeCl3 is currently added at the grit chamber splitter box, to ensure proper mixing. It was added prior to the grit chambers, but the addition at this point was starting to interfere with other parts of WWTP operation. The dose of FeCl3 is between 20 and 30 mg/L. The anionic polymer is added just before or directly to the primary clarifier in a dose from 0.15 to 0.25 mg/L. The chemicals are added for 8 to 10 hours during peak flow only. The amount of FeCl3 and polymer added to the system is monitored carefully; jar tests to determine the proper dose of each chemical are performed weekly (Hetherington et al 1999).

The results at Orange County have shown CEPT to be quite beneficial. The average removal of BOD, shown in figure 3, by CEPT is 42% and TSS, shown in figure 4, is removed up to 75%. The water is then treated with either the trickling filter or the activated sludge process. The average additional BOD removal in the trickling filter is

85% and the average TSS removal is 44%. The additional removal of BOD in the activated sludge process is 96%, and TSS is removed by an additional 93%. The average effluent concentrations are 36 mg/L BOD and 20 mg/L TSS; that is about an overall removal of 90% in both BOD and TSS.

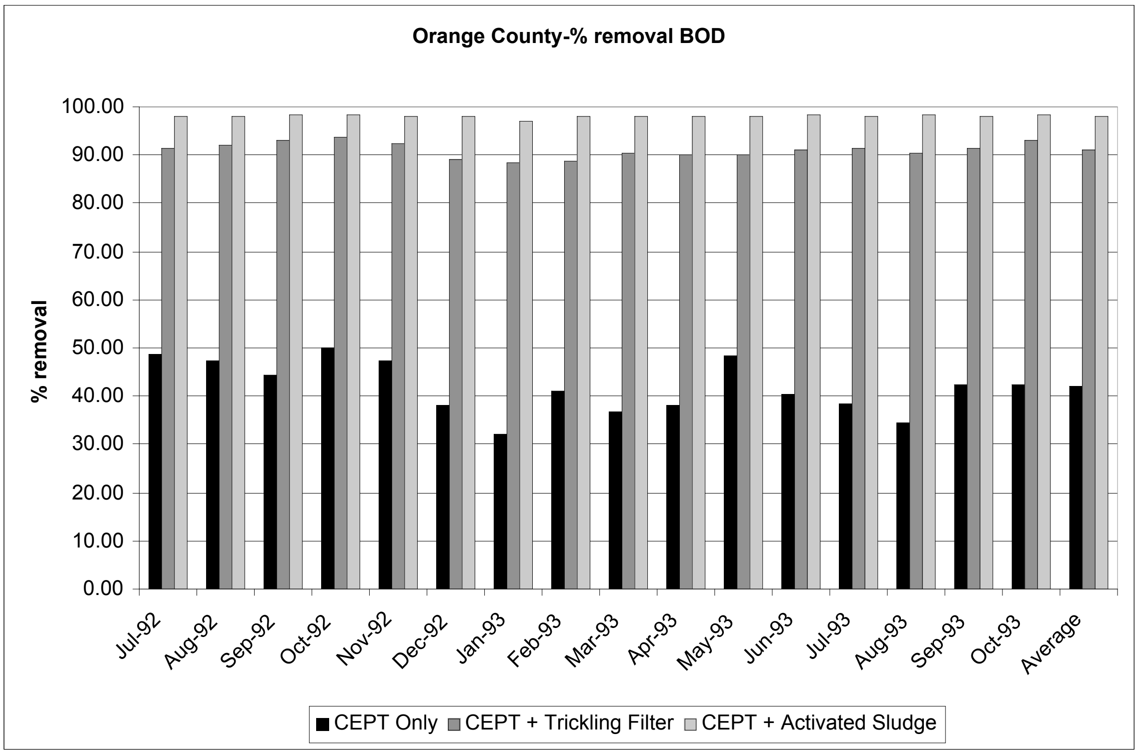

FIGURE 3: ORANGE COUNTY, CA- %BOD REMOVAL

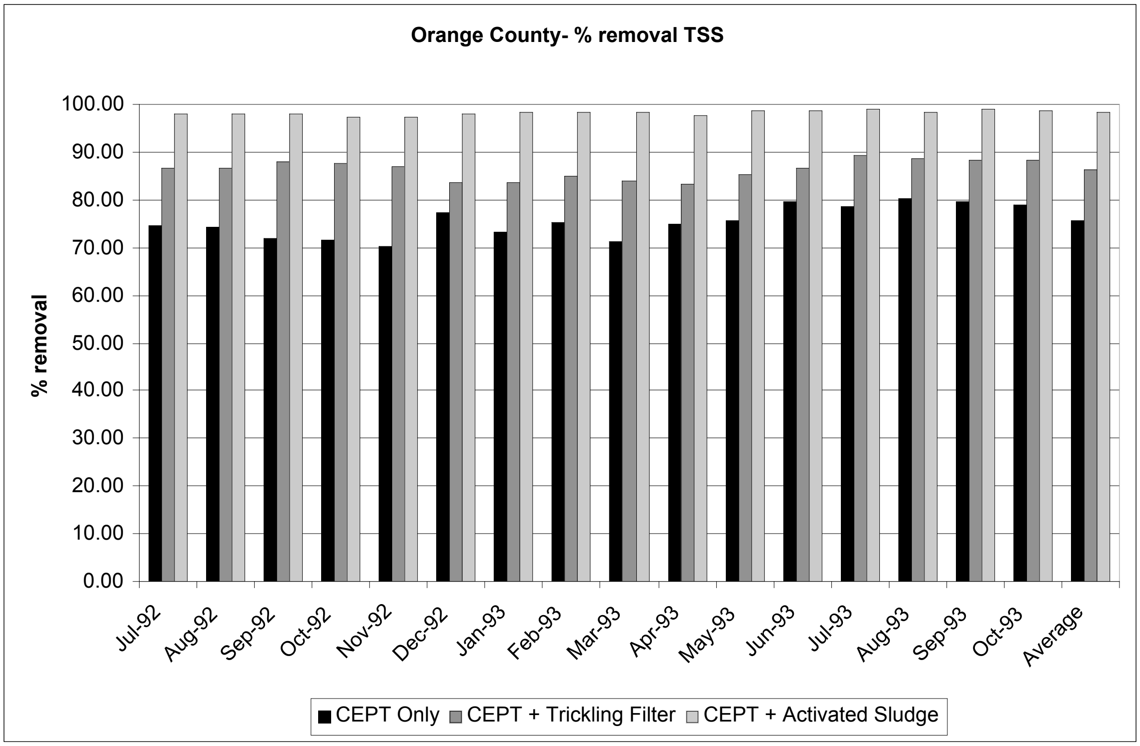

FIGURE 4: ORANGE COUNTY, CA- %TSS REMOVAL

Orange County has had some trouble with the implementation of Chemically Enhanced Primary Treatment, but over the years, they have found solutions to many of these problems. First of all, they found that if chlorine is added, for odor control, with the FeCl3, there is a problem with floating sludge. They solved this problem by simply adding the chlorine upstream of the ferric chloride. They also found that because the characteristics of the wastewater influent change periodically, they do not achieve optimum effluent quality. This was taken care of by periodically doing jar tests. These jar tests not only adjust the ferric chloride dose, but they also test the anionic polymer. If the polymer is found to not be performing well, the chemical vendor has an opportunity to submit a new polymer that would solve the problem. This allows for the chemical company to have the opportunity to remain as the supplier as well as for the WWTP to achieve optimum performance (Hetherington et al 1999).

Chemically Enhanced Primary Treatment has worked well in Orange County, California. They have reached low enough BOD and TSS effluent levels to meet their National Pollutant Discharge Elimination System permit and to receive a waiver from secondary treatment. CEPT has affected the performance of the trickling filter and activated sludge system. The trickling filter and activated sludge system are removing BOD and TSS as best as their design allows, maybe even a little better. The use of CEPT in Orange County allows the WWTP the option of not investing money into large capital projects and actually saves money in terms of sludge hauling. Advanced Primary Treatment is the cheapest, most effective way for the Orange County Wastewater Treatment Plant to meet its effluent requirements.

1.4 Otero and de Varona 2000 Results

The team's project is based in large part on prior work done on the plants in question. Prior results include analysis of the basic physical properties of the wastewater stream (COD, TSS, pH, temperature, turbidity, and residual chlorine), jar tests to recommend chemical selection and dosing, and on two of the five plants full-scale tests (Otero and de Varona 2000). This team chose two of the untested plants with similar treatment systems for the project. At both plants aluminum chlorohydrate was the recommended chemical. The results of the chemical selection jar tests can be found in appendix B, while analysis of the dosage jar tests is below.

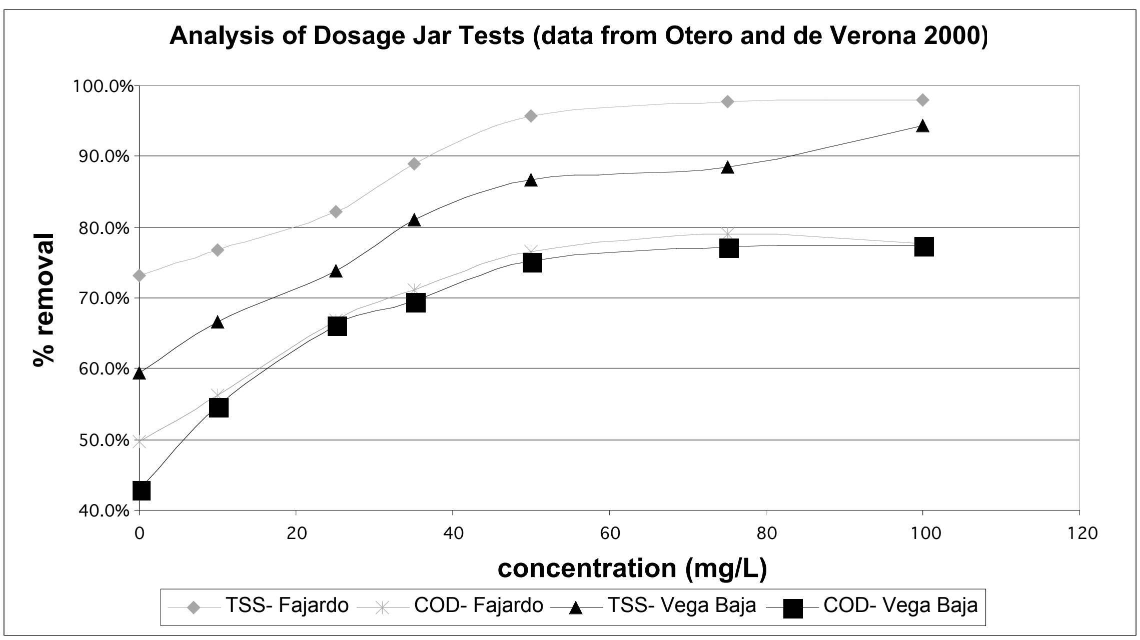

FIGURE 5: DOSAGE CURVE

In choosing a dosage for a plant the goal is to choose the dosage at which the returns in percent removal drop significantly. At both plants the maximum dosage that continues to provide a benefit in increased treatment is in the 40-60 mg/L range. Accordingly the team planned to dose both plants at a value of 40 mg/L.

Chapter 2: Methods

2.1 Vega Baja

The Vega Baja Wastewater Treatment Plant is a system with two different parallel systems. The primary is on the primary clarifier/trickling filter series, but there is also an activated sludge package plant that was assumed to be working properly. After the primary clarifier, there are two parallel trickling filters and secondary clarifiers (Otero and de Varona 2000). The primary clarifier works by mechanical settling, removing a large number of the heavy particles. Trickling filters consist of a large spray arm that sprays the wastewater over a bed of rocks, or in some cases a porous plastic material similar to nested waffles. As the water trickles over the medium, a biofilm forms that removes organic carbon from the water. The medium for the trickling filters at Vega Baja is large gravel. As the biofilm grows, some of the biomass detaches from the rocks, so a secondary settling tank is placed at the end of the trickling filter system (Metcalf & Eddy 1991). A plant schematic is included at the end of this section.

The Vega Baja WWTP is designed to handle 2.2 MGD (Otero and de Varona 2000), and is currently handling an average flow of 1.6 MGD. In addition, at the time of this study, all of the pretreatment was out of service, and a filter press for the sludge was not being used. The effluent limits on this WWTP are 30 mg/L of TSS and 5 mg/L of BOD. The full-scale tests planned on the Vega Baja plant will investigate how CEPT can help this WWTP meet these standards.

Prior research indicates that for this system the addition of 40 mg/L of GC-850, an aluminum salt, would provide the most efficient removal with the least amount of floating solids (Otero and de Varona 2000). The group started with the recommended chemical and dosage in our full-scale tests. The GC-850 was added to the influent of the primary clarifier, and rapidly mixed in the influent pipe. The original testing plan was to run one background day without applying chemicals and then 5 days of constant chemical addition at 40 mg/L to allow the plant to adjust. Unfortunately, unforeseen circumstances prevented the initial plan from being implemented.

While working at Vega Baja there was one main problem, floating sludge in the primary clarifier. The best way to describe the condition is a film on the surface of the water varying from a thin layer to one that was about 2 inches thick. This film appeared to be made up of the sludge that is created in the primary clarifier. The first idea of the team was that the chemical dosage was too high, and it was cut in half to 20 mg/L. When this did not clear up the problem, the team turned to the plant operators for ideas. After speaking with the plant operators, it became evident that the sludge was accumulating

FIGURE 6: FLOATING SLUDGE AT VEGA BAJA

because it was not being removed fast enough. At Vega Baja the sludge pump, which moves sludge from the storage tank on the primary clarifier to the anaerobic digester, runs only during the day when the operators are present. The CEPT application produces more sludge than typical primary settling because more solids are removed, and unfortunately when that sludge wasn't removed during the night a large portion of it fermented and resuspended, floating to the top. After discovering this we applied chemicals only when the sludge pump was running. This seemed to clear up the problem.

At Vega Baja we placed portable composite samplers – machines that take several samples over the course of 24 hours to provide a mechanical daily average – at the entrance and exit of the primary clarifier, and at the exit of the trickling filter. We used the existing samplers at the entrance and exit of the plant as well. Each sampling point was tested for total suspended solids, BOD5, COD, total phosphorus, and total organic carbon.

All samples that were taken during the full-scale testing of both plants were analyzed at the regional lab in Caguas. The samples were kept on ice until they reached the lab. Ice was also placed in the portable samplers to preserve the condition of the wastewater.

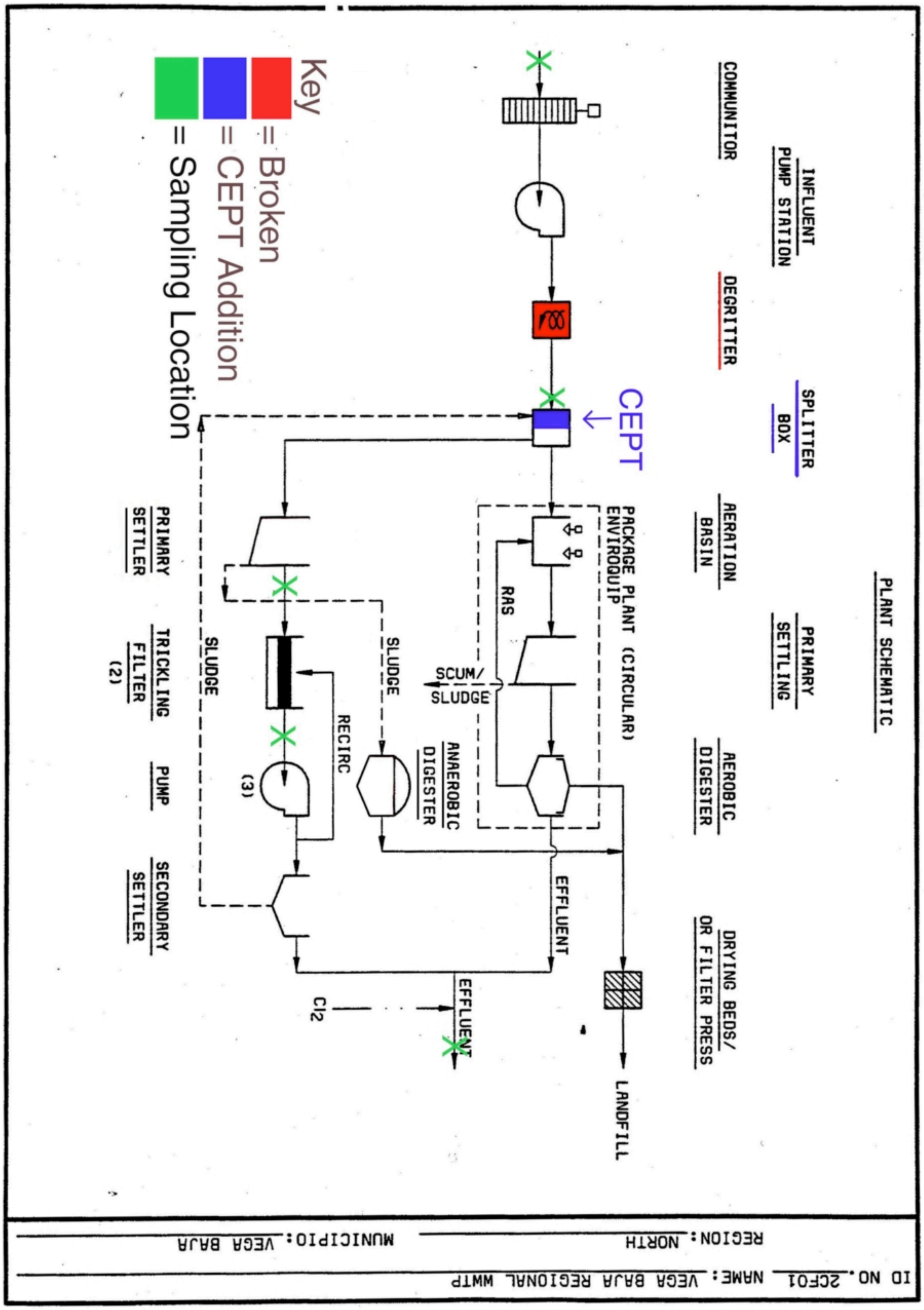

FIGURE 7: VEGA BAJA SCHEMATIC (ADAPTED FROM OTERO AND DE VARONA 2000)

2.2 Fajardo

The Fajardo Wastewater Treatment Plant is comprised of three parallel systems: an aeration plant, a package plant, and a trickling filter followed by a bio-tower (Otero and de Varona 2000). Both the package plant and aeration plant are assumed to be working efficiently, and independently meeting EPA standards. Our focus is on the primary clarifier/trickling filter chain.

The primary clarifier at Fajardo is very similar to the clarifier at Vega Baja, except that a chemical, an aluminum salt plus polymer at 45 mg/L, was already being added when we arrived. At Fajardo the trickling filter system is composed of a trickling filter, biotower, and secondary clarifier in series. The biotower in the Fajardo WWTP is basically a very large trickling filter.

In our study we added a chemical coagulant with a higher aluminum content and no polymer, to the entrance of the primary clarifier and then monitored the results. We placed portable composite samplers at the entrance to the primary clarifier, and at the entrance and exit of the trickling filter/biotower series. These sampling points are in addition to the permanent composite samplers at the entrance and exit of the plant. The sampling point at the plant exit draws from all three systems (package, primary, and aeration). Each sampling point was tested for total suspended solids, BOD5, COD, total phosphorus, and total organic carbon. A plant schematic is included at the end of this section.

The plant is designed to handle a flow of 4 MGD with the newly built package aeration plant (Otero and de Varona 2000). During the week the team was in Fajardo the total influent averaged 2.4 MGD, although over the past year the flow was as high as 9.5 MGD with monthly maximums typically around 4 MGD. During the testing the flow through the trickling filter was approximately 1 MGD. The effluent limits in Fajardo are the same as in Vega Baja for TSS (30 mg/L) but BOD is significantly higher than the Vega Baja limit at 30 mg/L (Otero and de Varona 2000).

In January there were several broken parts in the Fajardo WWTP. The trickling filter, pista grit, communitor and digester were all out of service. Although the lack of pretreatment is damaging to the life of the plant's equipment, a more immediate effect is caused by the non-functioning digester. Since there is a functioning anaerobic digester in the package plant the sludge from the primary clarifier is taken by truck from the clarifier to the package plant's digester. This led to the sludge storage tank on the primary clarifier being constantly full of sludge, and the sludge blanket in the clarifier consistently several feet deep in the center of the clarifier.

We based our chemical selection and dosing on preliminary studies of Fajardo and other WWTPs. The jar tests at Fajardo determined that the addition of approximately 40 mg/L of PAX-XL19, an aluminum based salt, would provide the most effective primary settling efficiency for the amount of chemical used (see Fig. 5).

Before our test at Fajardo 88 ml/minute of PAX-519 was being added constantly to the influent of the primary clarifier (this corresponds to a dosage at peak flow of approximately 45 mg/L). Originally we planned to halt the chemical dosage for at least a day before starting our tests, but the plant operators would not shut the chemical off for compliance reasons. Since the value was close to our recommended dose and seemed to be working effectively, we left the pump settings at 45 mg/L.

Our original schedule included 5 days of testing at a continuous dose of PAX-XL19. However problems arose with the trickling filter on our first and third day of dosing which caused the operators to stop the chemical addition. On the first day a whitish film appeared over the normal dark-green of the trickling filter. The cause of the whitish film is still unclear, since the chemical we added (aluminum chlorohydrate) was the same as the main component of the PAX-519 that was being added prior to our arrival. In order to prevent a possible overdose we lowered the chemical dose slightly to 44 mg/L and installed a timer on the pump for the chemicals. The timer stopped the addition of chemicals between 11:00 PM and 6:00 AM, during which low or no-flow conditions are present in the plant.

On the third day the majority of the trickling filter turned a dark brown color, and the chemical was again halted. Although we are confident that the problems on the third day were caused by the drying out of the filter during maintenance of the trickling arm the previous day, we were unable to convince the operators of the safety of the XL19, and they requested that we returned to the original 519. We did as they asked, and therefore our final days of sampling test the effectiveness of PAX-519 at the same dose of 44 mg/L.

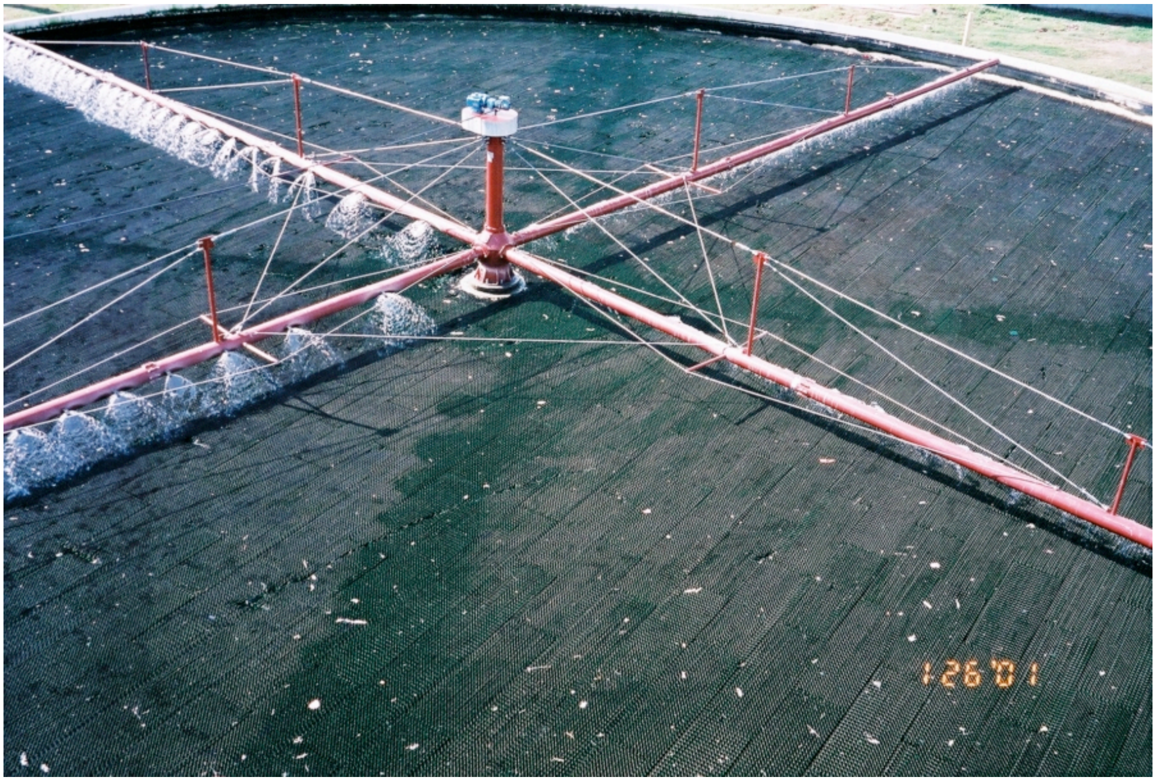

FIGURE 8: DRIED OUT TRICKLING FILTER AT FAJARDO – THE DARK LINES ARE THE NORMAL COLOR OF THE TRICKLING FILTER AND ARE WHERE THE ARMS WERE STOPPED FOR MAINTENANCE ON THE PREVIOUS DAY.

All samples that were taken during the full-scale testing were analyzed at the regional lab in Cauguas. The samples were kept on ice until they reached the lab. Ice was also placed in the portable samplers to preserve the condition of the wastewater.

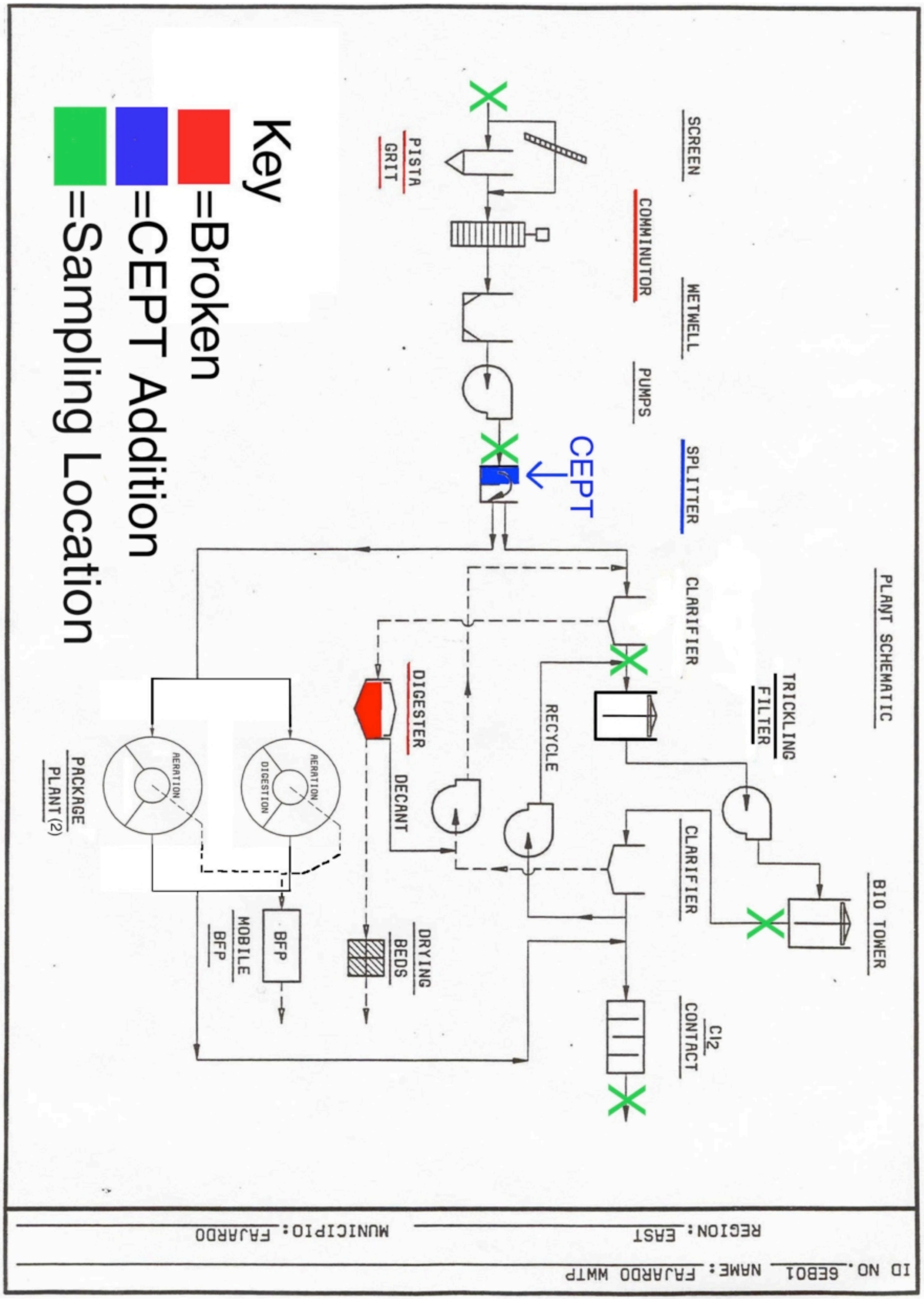

FIGURE 9: FAJARDO SCHEMATIC (ADAPTED FROM OTERO AND DE VARONA 2000)

Chapter 3- Effects of CEPT on Primary Clarifiers and Trickling Filters

3.1 Vega Baja

3.1.1 Biochemical Oxygen Demand

Data on Biochemical Oxygen Demand (BOD) was collected on three days during the testing at Vega Baja. On January 19, there was no chemical added to the system, providing a baseline for comparison. January 20 was a short day with a relatively low dose of chemical; the chemical was added at 20 mg/L for five hours. January 18th was a more typical day. The dosage was still relatively low, only 20 mg/L, but the addition time was nine hours, which is closer to how long the chemical would be added under normal operating conditions.

When examining the data for the primary clarifier, shown in figure 10, it is evident that the chemical must be run for a longer time to achieve removals that CEPT typically gives. The no chemical data shows that the primary clarifier is achieving removal of 34%, which is typical of a conventional primary clarifier. When the chemical is added at 20 mg/L for 5 hours, the percent removal increases to about 50%, and when it is added for 9 hours the percent removal jumps to 65%. The numbers for 20 mg/L of GC-850 at 9 hours, 65%, is what one would expect from CEPT being applied to a primary clarifier.

The trickling filter's removal efficiency, also shown in figure 10, seems to vary inversely with the effectiveness of the primary clarifier. When no chemicals were being added, the trickling filter was removing about 65% of the BOD, but when chemicals were added for 9 hours at 20 mg/L, the trickling filter only removed 30 % of the BOD. The combined removals of BOD for all three days are about 77%. This makes sense because the trickling filters are designed to remove BOD, and when the primary clarifier performs well, the trickling filter does not have to work as hard.

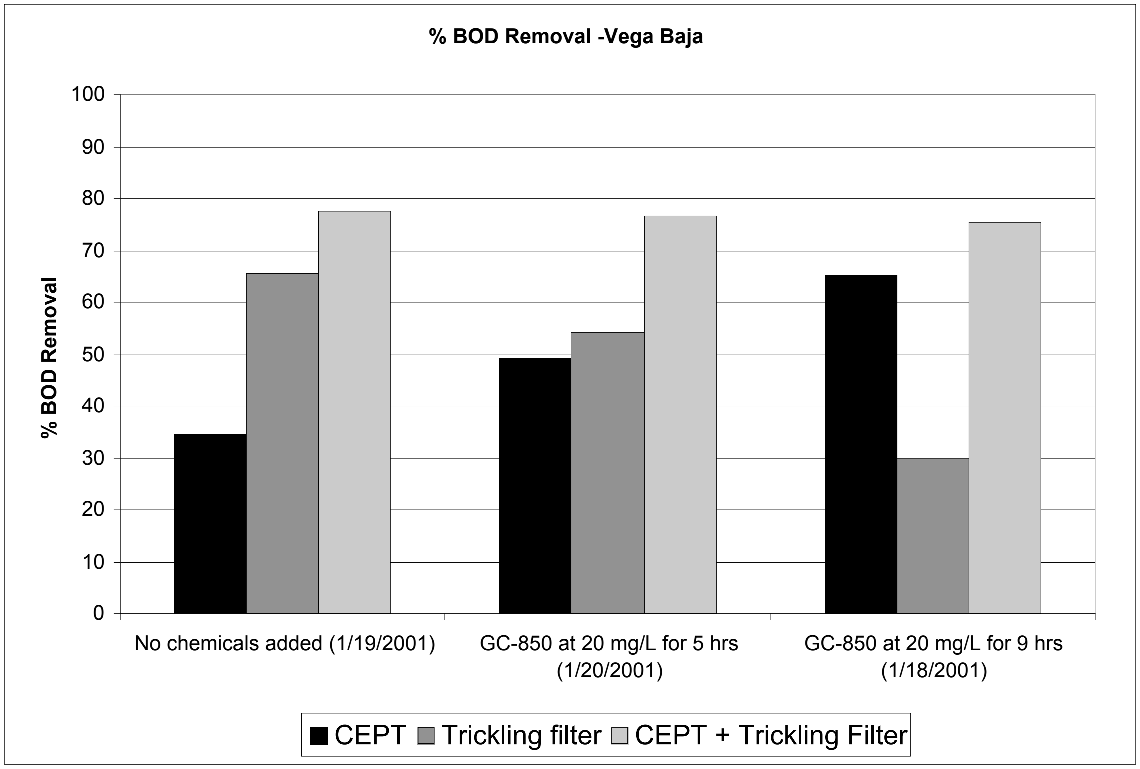

FIGURE 10: VEGA BAJA- % BOD REMOVAL

The combined removals of the primary clarifier and the trickling filter from figure 10 do not seem to change with the addition of chemicals. Prior to the 19th of January, the trickling filter has not been cleaned. It is likely that the data for the trickling filter could be skewed. On this day the chemical was added for the longest time, and the primary clarifier performed the best. The trickling filter's removal efficiency was low on that day because it need to be cleaned, so the measured combined removal of the CEPT and trickling filter is actually lower than would normally be expected.

3.1.2 Total Suspended Solids

In terms of Total Suspended Solids (TSS), there are six significant days. The 15th and 19th of January represent days where no chemical was added to the system. A dose of 40 mg/L of GC-850 was added on January 16th and 17th, but the time was different for those days. On the 17th, the chemical ran for only 5 hours, while on the 16th the chemical ran for 20 hours. On January 18th and 20th the chemical was run at a lower dosage, only 20 mg/L. Again there was a time difference in these days. The 20th was a short day (only 5 hours), while the 18th was a typical day with 9 hours of chemical addition.

Figure 11 shows the effects of CEPT on the primary clarifier and trickling filter for TSS removal. On the day of no chemical addition, low values for the removal of TSS in the primary clarifier are achieved. Only 7% of the TSS is removed in the primary clarifier, and 33% additional TSS is removed in the trickling filter. Conventional primary clarification typically achieves 60% removal of TSS, and a working trickling filter can remove up to 30% of the TSS.

When examining January 20th and 17th, a comparison between low dose (20 mg/L) and a normal dose (40 mg/L) can be made. On the normal dose day, January 17th, the removal of TSS was 60%, but only 38% of the TSS was removed on the low dose day. On both of these days, the time was only 5 hours, shorter than would be implemented for typical dosing in Vega Baja. It can be seen that a higher dose gives a much higher removal of TSS in the primary clarifier.

On these days the trickling filter had opposite results. When more of the TSS was removed, the trickling filter only removed 22% additional TSS, while on the lower dose day, the trickling filter removed 65% additional TSS. One reason for the decreases removal of TSS in Vega Baja could be due to the fact that the filter was flushed on January 18th. The dirty trickling filter on the 17th would not remove as much TSS from the system, thus lowering the percent removal.

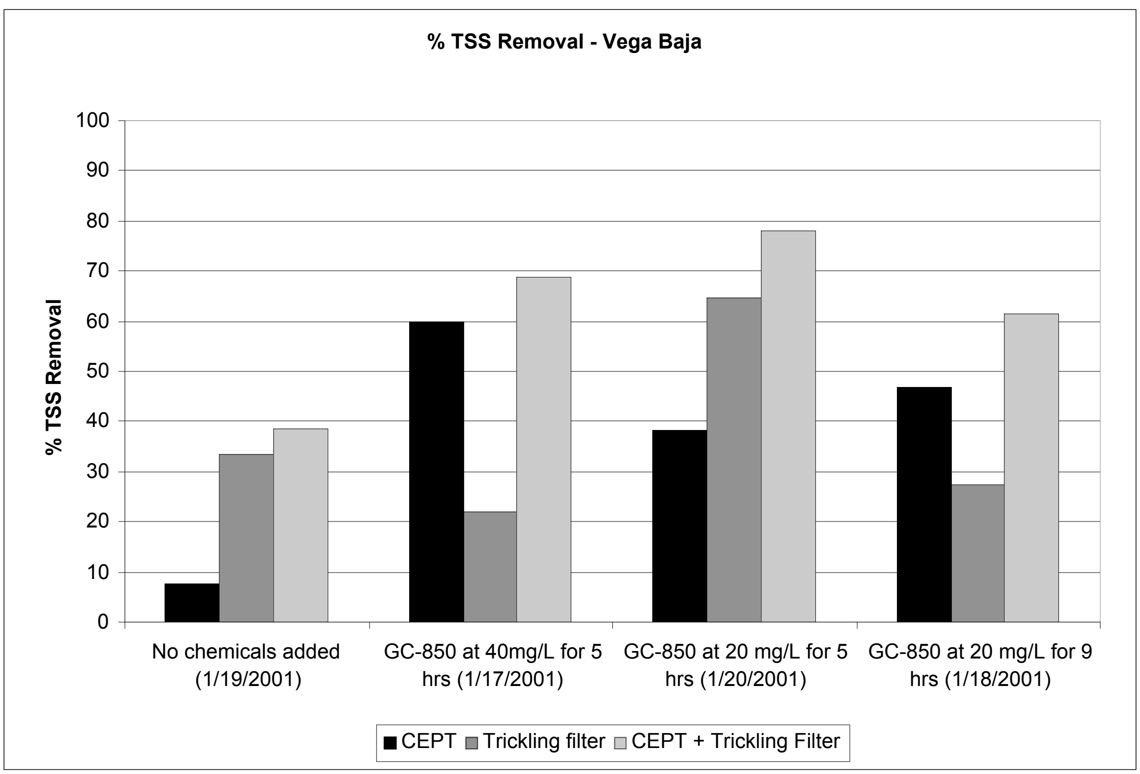

FIGURE 11: VEGA BAJA- %TSS REMOVAL

On January 18^{th} the chemical addition was only at 20 mg/L, but the time of addition was typical for Vega Baja operation. The primary clarifier removed 47% of the TSS; this value is much higher than was seen when no chemicals were added. When comparing January 20^{th} and 18^{th}, it is evident that a longer chemical addition time is necessary. When the chemical is added for 9 hours a removal of 47% in the primary clarifier is evident. The trickling filter was able to remove an additional 27% of TSS for the longer time period, but increased to 65% when the time was only 5 hours. Again the pattern of an increased removal of TSS in the primary clarifier leading to a lower removal by the trickling filter emerges.

When examining the removals of the combined primary clarifier and trickling filter, the best removal was when GC-850 was added for 5 hours at 20 mg/L. However, it should be noted that this day had the benefit of the clean trickling filter. In general the combined percent removals show that the use of CEPT increases the performance of the primary clarifier and trickling filter by at least 20%.

3.1.3 Total Phosphorus

The data for phosphorus removal at Vega Baja is not valid. The samples were collected in the beginning to the middle of January, but were not analyzed until the middle of February. While the samples were preserved and refrigerated according to EPA guidelines, the resulting numbers were not reasonable. For this reason, the data for phosphorus removal at Vega Baja was deemed invalid.

3.1.4 Summary

The use of CEPT at Vega Baja seems to improve the plant's ability to remove BOS and TSS from the wastewater. Tables 1 and 2 summarize the results at this WWTP. The primary clarifier appears to see the most benefit from the addition of GC-850. While the TSS removal is not as high as expected with CEPT, there is a vast improvement when chemicals are added to the primary clarifier. In Orange County, California, the average removal of TSS is higher than is seen at Vega Baja, but Orange County has been using CEPT for many years and has adjusted the chemical dosage to achieve optimum results (Hetherington et al 1999). The low removal of TSS at Vega Baja could be due to the problems with sludge removal and floating sludge. If the sludge were resuspending because it is not being removed quickly enough, this would increase the TSS in the water. The BOD shows great improvement as well, the numbers that are seen are typical of CEPT and are even better than those seen at Orange County.

Primary Clarifier	Conventional (Metcalf & Eddy 1991)	Typical CEPT (Harleman 2000)	Orange County, CA (County Sanitation 1993)	Vega Baja, No Chemicals	Vega Baja, 20 mg/L 9 hours
BOD	30%	55%-65%	42%	34%	65%
TSS	60%	75%-85%	75%	8%	47%
Total P	30%	55%-85%	N/D	N/D	N/D

Table 1: Comparison of Conventional, CEPT and Vega Baja Removals for Primary Clarifiers

The trickling filters at Vega Baja do not appear to receive any benefit from the use of CEPT. In terms of the BOD there is a great decrease in the amount removed by the trickling filter. The use of CEPT does not seem to affect the trickling filter's ability to remove TSS; only a few percent decrease is seen.

Trickling Filter	Conventional (Metcalf & Eddy 1991)	Orange County, CA (County Sanitation 1993)	Vega Baja, No Chemicals	Vega Baja, 20 mg/L 9 hours
BOD	60%-80%	85%	66%	30%
TSS	30%	44%	33%	28%
Total P	none	N/D	N/D	N/D

Table 2: Comparison of Conventional and Vega Baja Removals for Trickling Filters

The trickling filters are Orange county are removing much more BOD and TSS than the Vega Baja plant. This could be because the trickling filters at Vega Baja are not in good condition. There was an obvious problem with flies, and the larvae are feeding on the biofilm of the trickling filter. With some maintenance, the values for removal of BOD and TSS at Vega Baja should increase.

3.2 Fajardo

3.2.1 Biochemical Oxygen Demand

In terms of Biochemical Oxygen Demand (BOD), there are five significant days. The first three days had PAX-XL19 added to the plant with an average concentration of 43.5 mg/L, while the last two days had PAX-519 added at a concentration of 43.5 mg/L. The main difference between the days was the duration of chemical addition. Figure 12 summarizes the BOD data.

When comparing the 24th and 23rd of January, the time difference is most evident. With a four-hour increase in chemical addition time, 14% more BOD was removed from the primary clarifier. The trickling filter series dropped in its removal of BOD, by 14% with a time increase.

The highest percent removal seen, when PAX-XL19 was added for 14 hours, is 44%. This number is much less than expected for CEPT when applied to the primary clarifier. In fact all of the numbers are well below what is expected for the addition of CEPT.

Overall the trickling filter series for Fajardo removes the amount of BOD that is typically expected. Only two of the days show removals that are below typical. It is important to note that these are the days when the highest removal of BOD is seen in the primary clarifier. A pattern of decreased removal of BOD by the trickling filter with increasing removal in the primary clarifier can be seen.

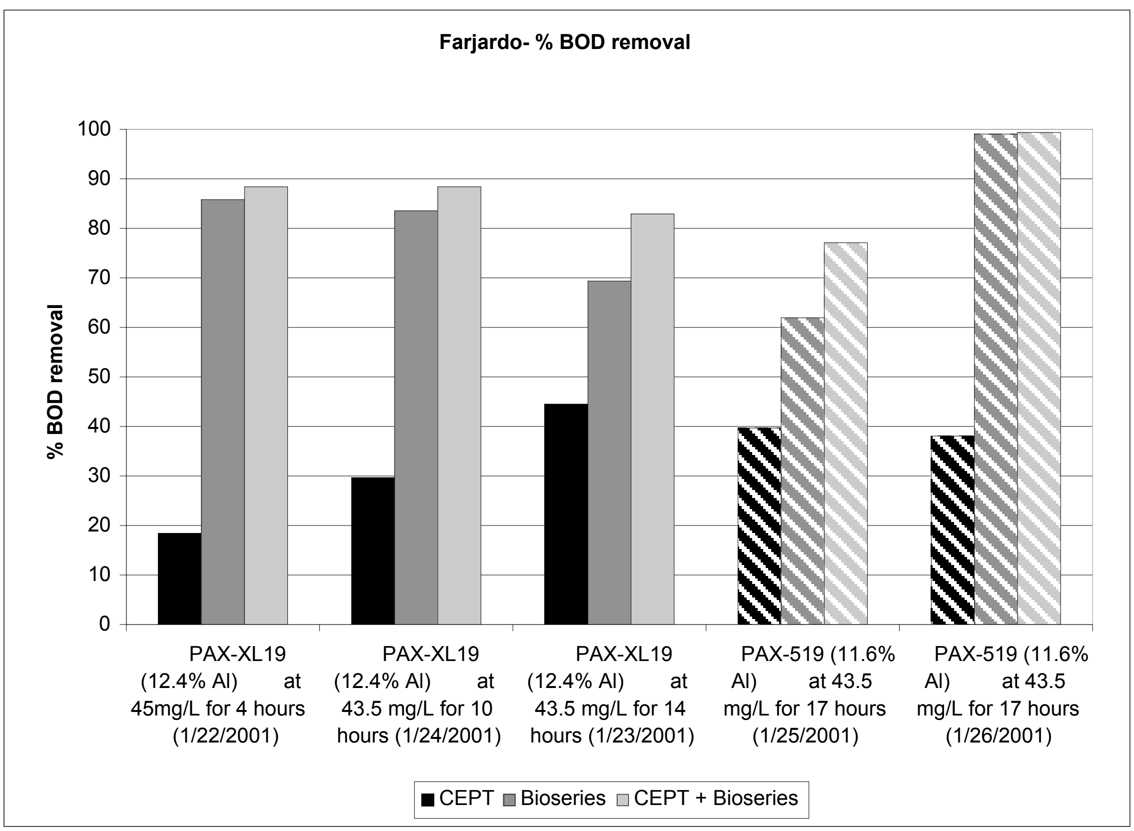
Farjardo- % BOD removal
% BOD removal
100
90
80
70
60
50
40
30
20
10
0
PAX-XL19 (12.4% Al) at 45mg/L for 4 hours (1/22/2001)
PAX-XL19 (12.4% Al) at 43.5 mg/L for 10 hours (1/24/2001)
PAX-XL19 (12.4% Al) at 43.5 mg/L for 14 hours (1/23/2001)
PAX-519 (11.6% Al) at 43.5 mg/L for 17 hours (1/25/2001)
PAX-519 (11.6% Al) at 43.5 mg/L for 17 hours (1/26/2001)
CEPT
Bioseries
CEPT + Bioseries

FIGURE 12: FAJARDO %BOD REMOVALS

Looking at the overall removals of the CEPT and bioseries, on average the PAX-XL19 performed as well if not better than the PAX-519. The gain in the trickling filter performance on the 26th of January is what seems to make the PAX-519 perform better that day.

3.2.2 Total Suspended Solids

For total suspended solids, all five days of the testing give significant results. Again the first three days had PAX-XL19 added and the final two days had PAX-519 added. When comparing the 23rd and 24th of January, it can be seen that an increased time of addition does not provide significant additional removal of TSS from the primary clarifier; the difference is only about 4%. Figure 13 summarizes the removals that were seen for TSS when chemicals were applied to the trickling filter train.

The highest percent removal in the primary clarifier is seen when PAX-XL19 was added for only 4 hours, but at a strength of 45 mg/L. This result is unexpected, and in light of the BOD data, it is probably not beneficial to cut the time and increase the dose. If we exclude this point, the best results for TSS removal in the primary clarifier, 68%, are seen with PAX-XL19.

Although the percent removals in the primary clarifier are promising, they are below what is expected with CEPT. Typically a removal of 75% or better can be achieved with CEPT. The best removals seen during this test are only around 68%.

The trickling filter data does not seem to follow the pattern of decreasing removal with increasing primary clarifier removals. In fact the opposite appears to be true; the increased removal of TSS in the primary clarifier allows the trickling filter to remove more TSS. The data is highly variable though; values range from 36% to 85%. A typical trickling filter can remove about 30% of the TSS from its influent. The reasons for the trickling filter's inability to remove TSS could be that the organics in TSS form are unavailable for the biota in the trickling filters to use.

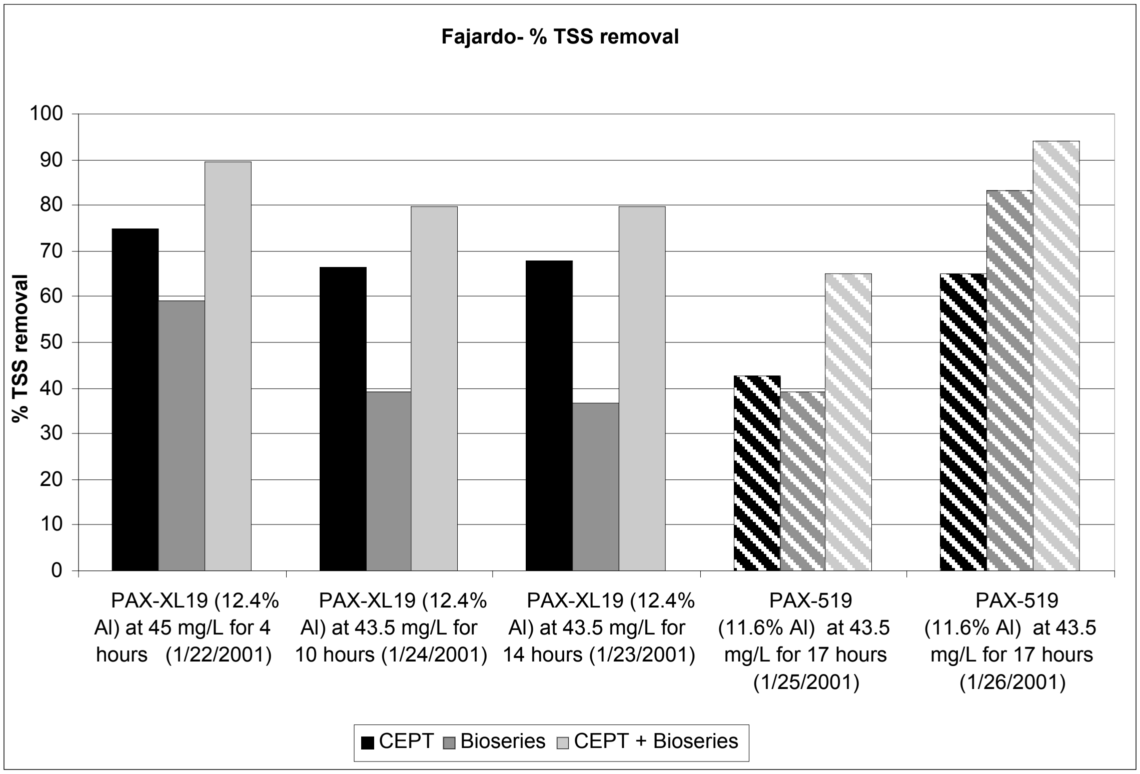

FIGURE 13: FAJARDO %TSS REMOVAL

The combined removals of the CEPT and bioseries again show that the use of PAX-XL19 removes TSS as well if not better than the PAX-519. The only reason that the PAX-529 would appear to perform better is the gain it receives from a good performance by the trickling filter. This is the same scenario that occurred with the BOD removals.

3.2.3 Total Phosphorus

For Total Phosphorus (Total P), there are five significant days. The first three days were the addition of PAX-XL19 at concentrations of about 43.5 mg/L, and the final two days were the addition of PAX-529 at 43.5 mg/L. The days of the experiment were quite similar, only variations in time or chemical used are different between the days. Figure 14 shows the data that was collected for phosphorus removals in the primary clarifier using chemicals and the trickling filter.

When examining the days when PAX-XL19 was added, it seems to show that Total P removal in the primary clarifier decreases with an increased time of addition.

The variation of these removals is about 14%. The best removal, when PAX-XL19 was added for four hours at a slightly higher dosage, is 62%. This value is within the expected range for CEPT applied to a primary clarifier. The other two days of PAX-XL19 have removals are close to the observed values for Total P removals from CEPT. The days when PAX-519 was added showed a percent removal in the primary clarifier that is well below the observed values for CEPT.

The values for Total P removal in the trickling filters are quite low, but it should be noted that trickling filters are not expected to remove much phosphorus. One curious observation is that the Total P data for the trickling filter does not seem to follow the pattern that is seen with BOD. The effectiveness of the trickling filter to remove phosphorus is increased with increasing primary clarifier Total P removal.

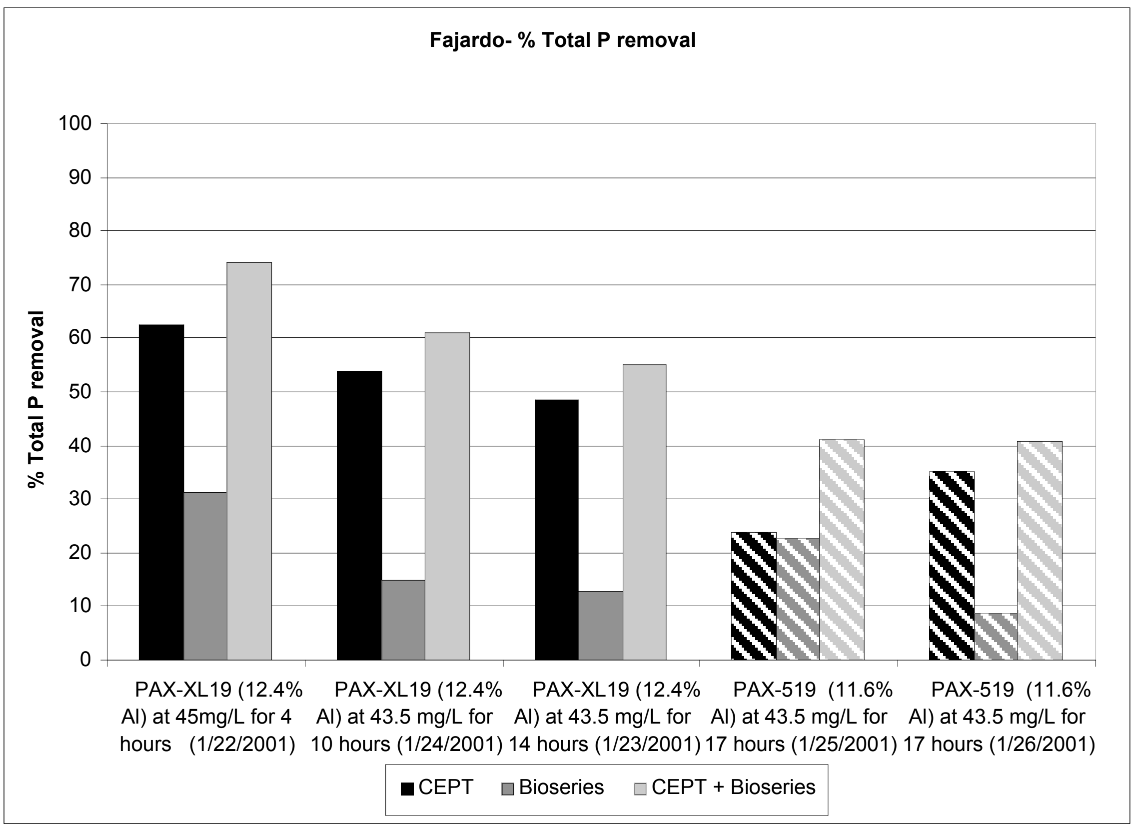

FIGURE 14: FAJARDO- %TOTAL P REMOVAL

When examining the combined removals for CEPT and the bioseries, it is evident that the PAX-XL19 works much better than the PAX-519. The only curious trend is the decrease in Total P removal with an increase in the time that the chemical is applied.

3.2.4 PAX-XL19 v. PAX-519

To examine the effectiveness of PAX-XL19 and PAX 519, the day when PAX-XL19 was added for 14 hours is compared to the average values for the days when PAX-519 was added for 17 hours. In terms of the performance of the chemicals in the primary clarifier, PAX-XL19 always works better than PAX-519. The difference in BOD is only a few percent, but both TSS and Total P vary by at least 14%. When examining the data for the overall performance of plant under the two chemicals, the results are very similar. The main difference is in the Total P removal, and in this case the PAX-XL19 clearly removes more of the phosphorus. One reason for the difference in performance is the aluminum content of the two chemicals. Since the metal is what promotes coagulation, a lower metal content would give lower removals. With this in mind, a higher dosage of PAX-519 should give results similar to those of PAX-XL19. Since a higher dosage in all probability costs more, the better chemical to use at Fajardo is PAX-XL19.

	Primary Clarifier, PAX-XL19	Primary Clarifier, PAX-519
BOD	44%	40%
TSS	68%	54%
Total P	48%	29%

Table 3: Comparison of PAX-XL19 and PAX-519

3.2.5 Summary

The use of Chemically Enhanced Primary Treatment would be beneficial to the Fajardo Wastewater Treatment Plant. The use of chemicals in the primary clarifier brings the percent removals to well above the conventional removal in a primary clarifier. In the primary clarifier, the use of PAX-XL19 gives results close to what would be expected with CEPT, and the values are similar to what Orange County California is achieving (County Sanitation 1993). The numbers for PAX-519 are not as close, and in general are only around conventional values for no chemicals.

Primary Clarifier	Conventional (Metcalf & Eddy 1991)	Typical CEPT	Orange County, CA	PAX-XL19	PAX-519

		(Harleman 2000)	(County Sanitation 1993)		
BOD	30%	55%-65%	42%	44%	39%
TSS	60%	75%-85%	75%	68%	54%
Total P	30%	55%-85%	N/D	48%	29%

Table 4: Comparison of Conventional, CEPT, PAX-XL19 and PAX-519 Removals for Primary Clarifiers

The trickling filters at Fajardo seem to performing well. The chemicals do not lower the removal of BOD out of conventional design range. The TSS removed is quite high, even higher than Orange County. A point to notice is the PAX-XL19 has a smaller removal than the PAX-519. This is most likely because there is less to remove in the PAX-XL19 case, since the removals in the primary clarifier are much higher.

Trickling Filter	**Conventional** (Metcalf & Eddy 1991)	**Orange County, CA** (County Sanitation 1993)	**PAX-XL19**	**PAX-519**
BOD	60%-80%	85%	70%	80%
TSS	33%	44%	37%	61%
Total P	none	N/D	13%	16%

Table 5: Comparison of Conventional, PAX-XL19 and PAX-519 Removals for Trickling Filter Series

3.3 Conclusion

The use of CEPT does not appear to hinder the operation of either the primary clarifier or the trickling filter. For the primary clarifier, it appears that the use of CEPT increases the removals of total suspended solids, biochemical oxygen demand, and total phosphorus. For Fajardo the use of CEPT ensured the performance of the primary clarifier was above the conventional removals. This was not the case at Vega Baja, but the use of CEPT increased the performance from 8% removal to 47%. At both plants, the removals of TSS with CEPT in the primary clarifier are below typical values seen. In terms of BOD, the use of CEPT in the primary clarifier ensures that the removal of BOD is above what is expected with conventional primary clarification. At Vega Baja, it worked so well that the removal seen, 65%, is about as high as CEPT typically gives. In Fajardo the BOD removal did not achieve the levels typically seen with CEPT, but the numbers seen are similar to Orange County, CA, which is a WWTP with a similar design(County Sanitation 1993). Total phosphorus values in the primary clarifier are not as good as expected with CEPT, but the use of CEPT guarantees that the primary clarifier removes more Total P than is expected with conventional primary clarification

The effects of CEPT on the trickling filter are related to the performance of the primary clarifier. At both WWTPs studied, the trickling filter appeared to remove more BOD when the primary clarifier less BOD. This is logical because the trickling filter uses the organics in the water to grow and survive, thus lowering the BOD. It was also seen at both plants that the increased removal of TSS in the primary clarifier allows the trickling filter to remove more TSS. The same pattern emerged for Total P at Fajardo.

The effects of CEPT on the primary clarifier and the trickling filter are positive. The trickling filter rarely performed below conventional design. This was true for the primary clarifier as well, unless it was performing poorly in the first place. In fact both pieces of equipment usually performed better than conventional design with the use of CEPT. Using CEPT in a plant with a primary clarifier followed by a trickling filter will not hinder the performance of the plant and will usually enhance it.

Chapter 4 - Compliance

4.1 Results and Analysis

4.1.1 Vega Baja

The benefits of CEPT at Vega Baja can be seen when examining the influent and effluent values of the wastewater treatment plant, which are shown in figures 14 and 15. It is important to note that the effluent values in this section are taken from the effluent for the entire plant, i.e. both the primary clarifier – trickling filter train and the package activated sludge plant (Fig. 7). For the following analysis it is safe to assume that the package plant operates at a constant removal rate, as it is unaffected by the chemical addition. Without chemicals the plant is able to bring the effluent BOD concentration down from 186 to 27.4 mg/L, which is an 85% removal. When chemicals are added, for 9 hours, the effluent BOD concentration drops from 143 to 12.5 mg/L; this is a 91% removal. The EPA limit for BOD in the effluent of the plant is 5 mg/L, which was not achieved during the testing. It seems though that a higher dose (30 to 40 mg/L) running for 9 hours should bring the effluent value of BOD very close if not under the strict EPA limit of 5 mg/L.

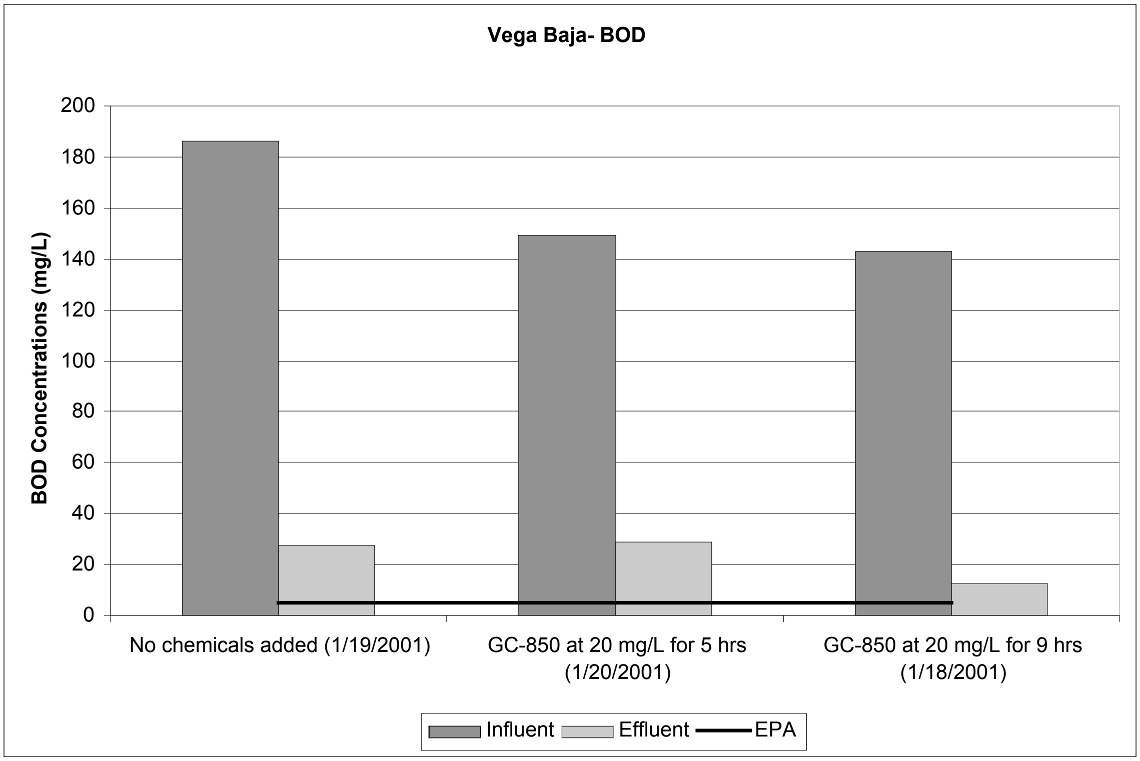

FIGURE 14: BOD INFLUENT AND EFFLUENT VALUES FOR VEGA BAJA

When examining the influent and effluent values for TSS at Vega Baja, it is clear that the plant is in compliance with the EPA limitations of 30 mg/L. On the day when no chemicals are added, the TSS is lower than some of the days when CEPT is added. This is not what was expected, and its cause is unclear. Perhaps it is a byproduct the resuspended sludge, or perhaps the cleaning of the trickling filter affected the removal efficiency. There is a slight positive effect on the days when 20 mg/L of GC-850 was added: the plant was able to remove 90% of the TSS, and on the no chemical day, 86% of the TSS was removed. However, this small difference is statistically insignificant.

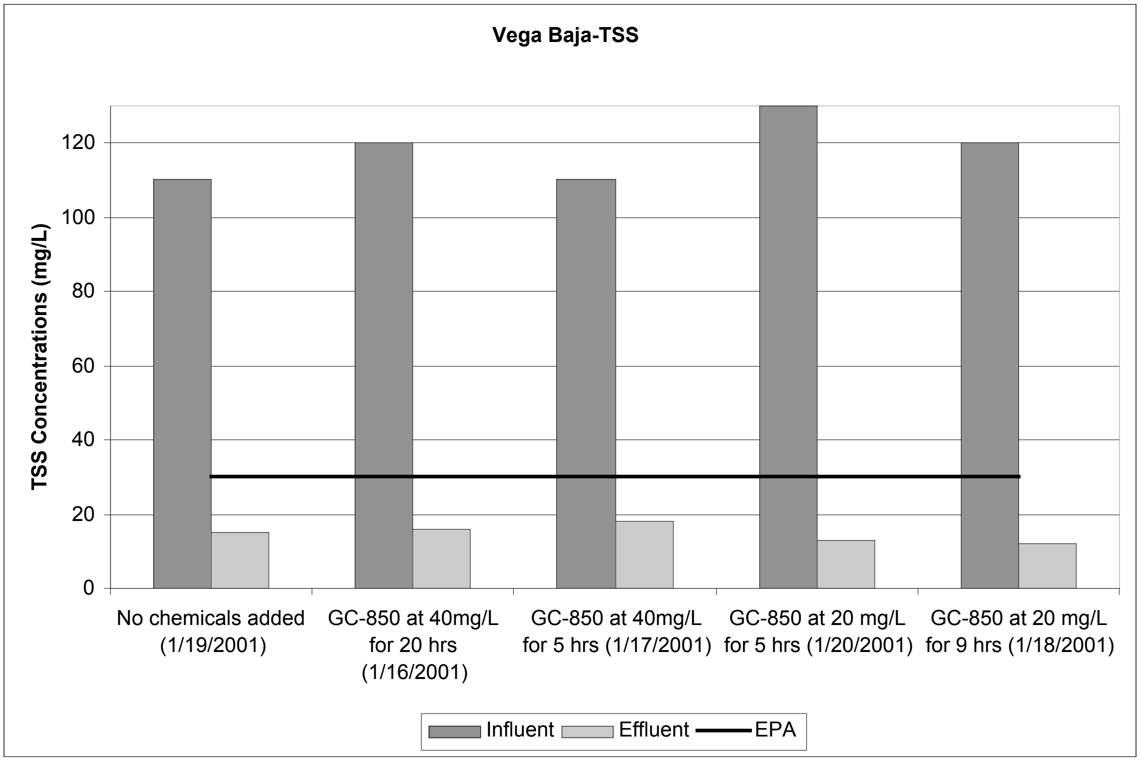

FIGURE 15: TSS INFLUENT AND EFFLUENT VALUES FOR VEGA BAJA

Overall the use of CEPT at Vega Baja seems to be a success. The effluent values are very close to if not under the EPA guidelines set. It is probable that a dose of 40 mg/L running for 9 hours each day could lead to removals that meet the 5 mg/L BOD standard, but this should be investigated further.

4.1.2 Fajardo

When examining the influent and effluent values, it is seen that the effluent values of BOD, shown in figure 16, are all well bellow the EPA limit of 28 mg/L. The lowest effluent value is 10 mg/L when PAX-XL19 is added for 14 hours, but the highest percent removals, around 96% are seen from both PAX-XL19 and PAX-519.

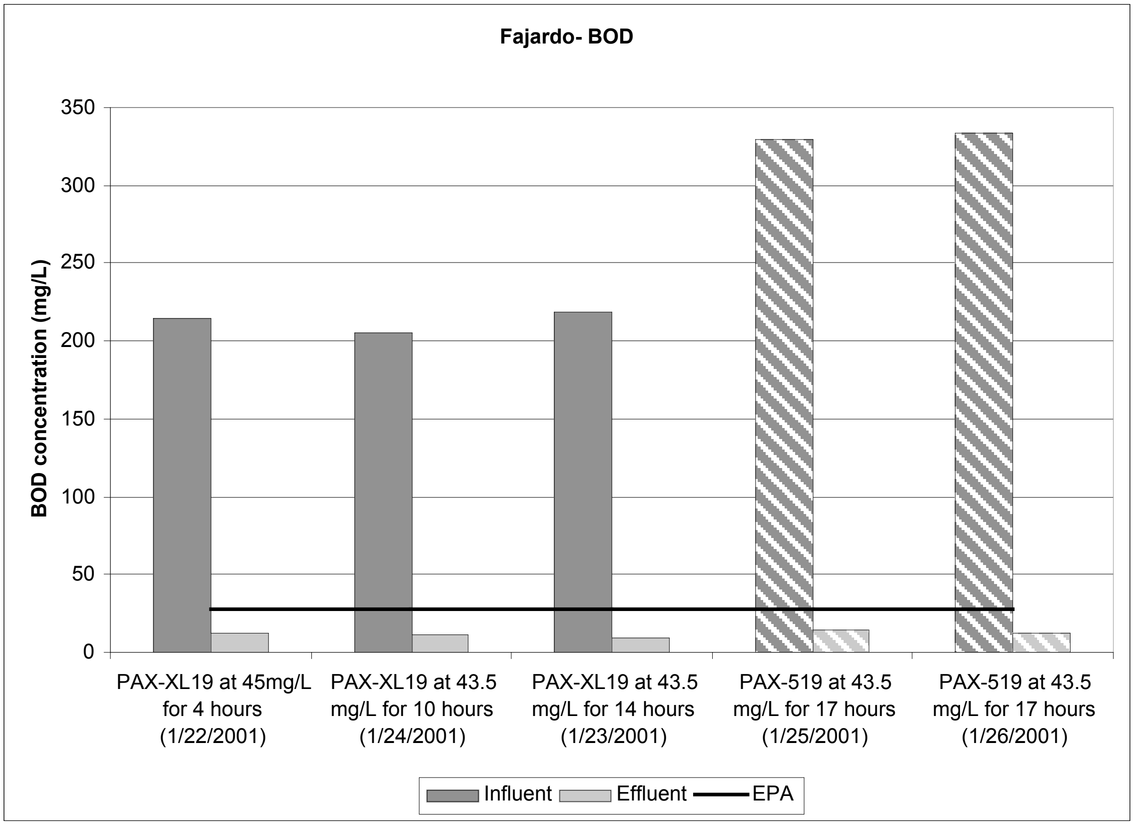

FIGURE 16: BOD INFLUENT AND EFFLUENT VALUES FOR FAJARDO

In examining the influent and effluent values for Fajardo's TSS removal, which are shown in figure 17, it can be seen that all effluent levels are below the EPA limit of 30 mg/L. Overall the percent removal of the plant for TSS is around 95% when any chemical is used for more than 14 hours. Fajardo has not had a big problem in the past meeting the TSS standards set by the EPA; it was only out of compliance 2 months in 2000.

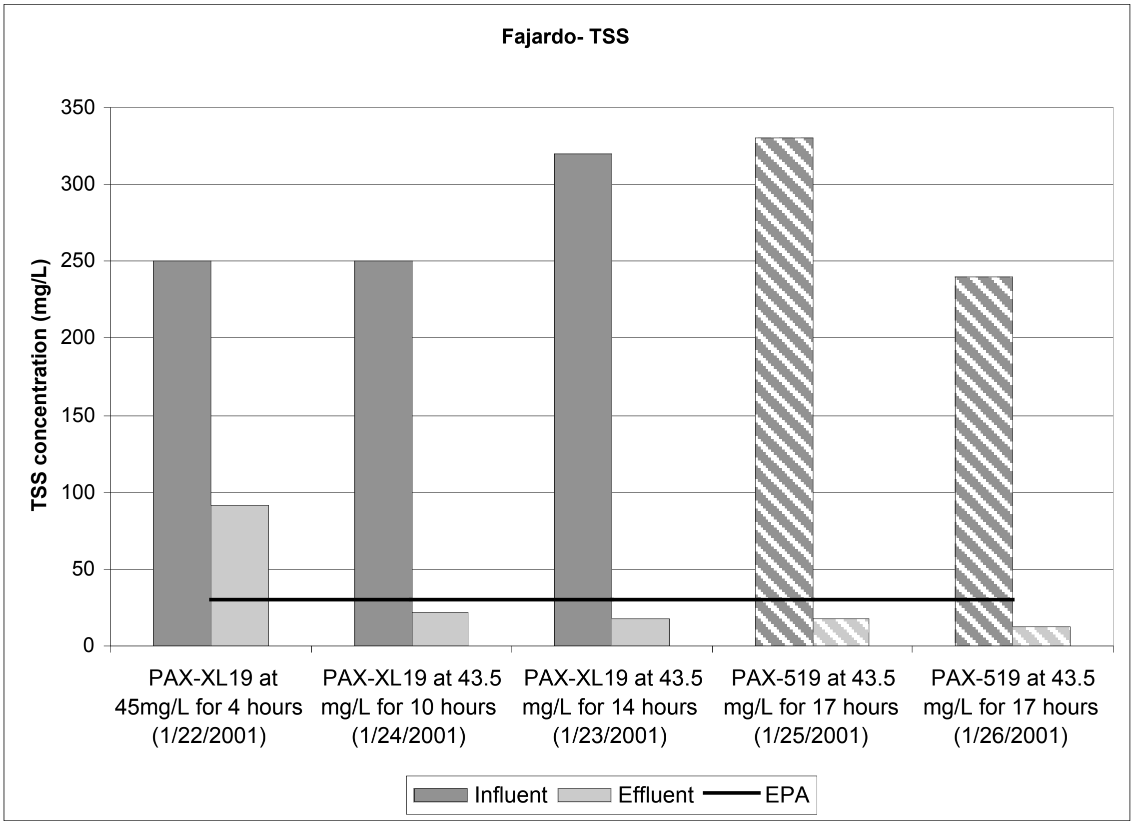

FIGURE 17: TSS INFLUENT AND EFFLUENT VALUES FOR FAJARDO

When examining the influent and effluent values for Total P at Fajardo (Figure 18), it is clear that all values are well below the EPA limit of 7.5 mg/L. Not only are all of the effluent values well below this limit, but often the influent values are below the EPA limit as well. Fajardo did not seem to have a problem meeting the EPA limit in 2000; it was never out of compliance. In terms of percent removals, the biggest is seen with PAX-519, but that is the only day when the influent value was above the EPA limit for the effluent. Overall the highest removal rate was achieved with PAX-XL19.

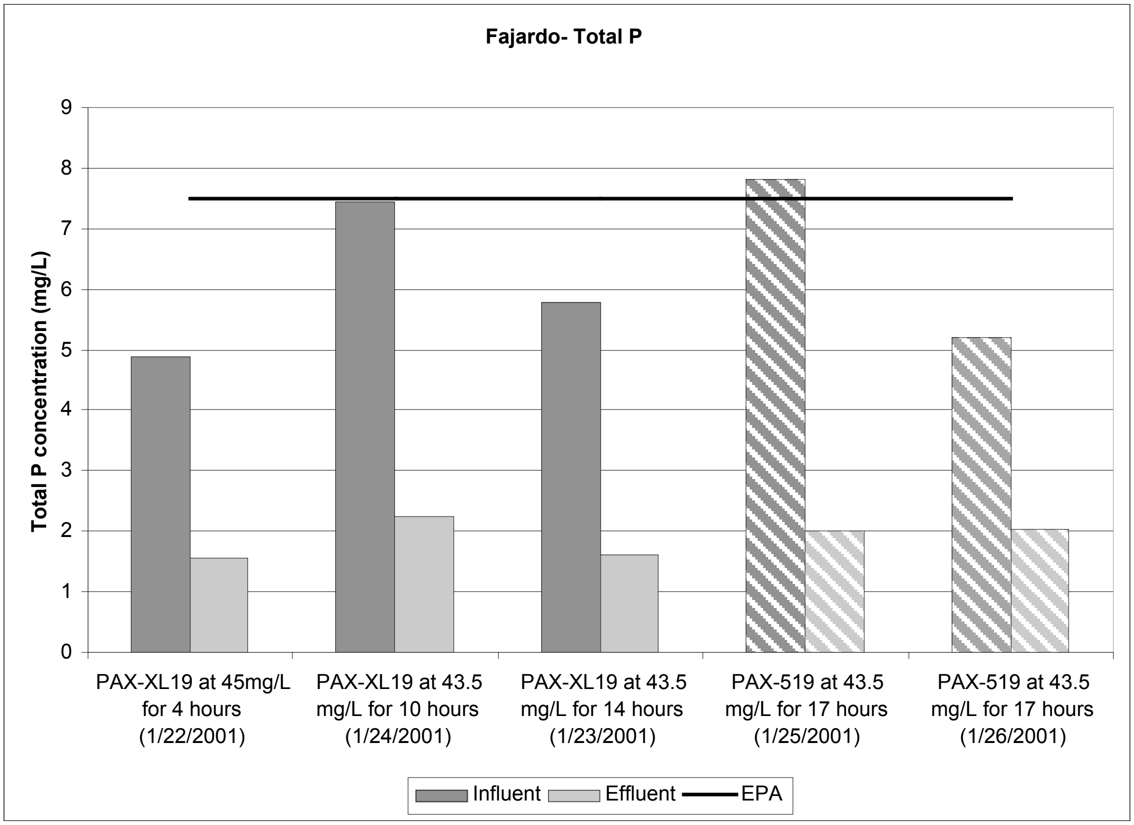

FIGURE 18: TOTAL P INFLUENT AND EFFLUENT VALUES FOR FAJARDO

4.2 Cost Analysis

4.2.1 Vega Baja

The cost of GC-850, the suggested chemical to be used in Vega Baja Wastewater Treatment Plant is $0.35 per pound. If the chemical were dosed at 20 mg/L for 9 hours per day, the cost for one day of operation would be $22. This same dosage and time of dosage would only cost about $8,000 per year. If the dose were increased to 40 mg/L, the cost would increase to $44 per day or $16,000 per year. This is a small price to pay for the results seen in this experiment.

4.2.2 Fajardo

The cost of PAX-XL19, the chemical recommended for use at the Fajardo Wastewater Treatment Plant (Otero and de Varona 2000), costs $0.33 per pound. At the recommended dosage of about 40 mg/L the cost for one year of chemical addition is approximately $30,000. Not only does this chemical perform better, it also costs less. The PAX-519 costs $0.45 per pound or roughly $40,000 per year.

Even though PAX-519 was performing adequately, PAX-XL19 can achieve compliance at a lower cost. Given its lower expense and better performance, especially in terms of total P reduction, PAX-XL19 is clearly the better chemical for Fajardo.

4.3 Recommendations

4.3.1 Vega Baja

Testing at Vega Baja showed that the use of Chemically Enhanced Primary Treatment would be beneficial to the wastewater treatment plant in reducing the total suspended solids and biochemical oxygen demand in the effluent. The chemical that is recommended is the aluminum chlorohydrate compound GC-850, and it should be added to the splitter box to insure proper mixing. The dosage of this chemical needs to be investigated a bit further. The chemical was used at a dose of 20 mg/L, but the effluent concentration of BOD was not below 5 mg/L, which is required by the WWTP's NPDES permit. The chemical was tested at this low dose because there was a problem with floating sludge. It is the opinion of this team that the floating sludge was caused by the sludge not being removed at all times while the chemical was running. Also, if the chemical is only added from 7:30 am to 3:30 pm, the dosage could be increased to 40 mg/L, the original dose the team tried.

It is possible that Vega Baja could benefit from applying CEPT to both the trickling filter chain and the activated sludge chain. In Orange County, California this is the current practice. They were able to improve the performance of their activated sludge processes as well as their trickling filter series. By doing this, Orange County was able to achieve BOD effluent values under 5 mg/L (County Sanitation 1993), which is the requirement for Vega Baja. If all of the flow is diverted to the primary clarifier, and the flow is then split between the activated sludge pant and the trickling filters, it could bring the entire WWTP into compliance with its NPDES permit, including the very low BOD effluent concentration requirement. That the clarifier could handle the flow of the entire plant is feasible; experience with CEPT in California indicates that the primary clarifier could handle two to three times the flow with increased removal rates if implemented properly.

The team also recommends that jar tests be performed with composite samples of water from the WWTP. While Otero and de Varona performed jar tests in their initial testing, they used grab samples because composite samplers were not available (Otero and de Varona 2000). Composite samples provide a better representation of the wastewater stream of a plant over the course of a whole day. Also, another aluminum-based chemical was recommended by the chemical manufacturer and should be tested. This chemical is supposed to "settle better" than the GC-850 and the company recommends it for wastewater treatment (Medina 2001). Jar tests should also be performed to find the optimal dosage of the final chemical chosen.

After jar tests have been completed or while they are being performed, it is recommended that the samples be analyzed for total phosphorus as well as total suspended solids, biochemical oxygen demand, and the appearance of floating sludge or how quickly the particles settle. CEPT has been shown to be beneficial in removing up to 85% of the Total Phosphorus in wastewater, and should be effective here for Phosphorus removal. In choosing the proper chemical for Vega Baja all three of these parameters should be considered.

In terms of equipment and maintenance, there are a few things that need to be fixed or implemented. Much of the pretreatment at Vega Baja was broken; the WWTP operators were working on fixing the problems. It is also recommended that the WWTP invest in roofs for the sludge drying beds. Roofs would keep the rain from rewetting the sludge, thus allowing the sludge to be held in the drying beds for a shorter time. If this link in the sludge chain is changed, the WWTP should be able to handle any extra sludge from CEPT. Another recommendation is for the plant operators to use the filter press for sludge processing. This would remove some of the water from the sludge. Again this would mean that the sludge would spend less time in the drying beds.

Another recommendation is that the sludge pump be fixed so that it can run constantly. This would allow a continuous chemical addition, which would lead to higher removal rates. Until the pump can be fixed, a timer should be installed with the chemical pump. A time can be set to turn on at 7:30 am and off at 3:30 pm; the plant operators wouldn't have to turn the chemical on and off everyday. Finally the team recommends that a flow meter/chemical pump combination be installed. The chemical/chemical pump combination would be used to adjust the amount of chemical being added to the waste stream based on the flow. This assures that the proper dose is being applied no matter the flow.

The other recommendation that the team has is to provide CEPT specific training for the plant operators. This is necessary because the plant operators will be the people who see the effects of CEPT on the WWTP and should be prepared to fix any problems that may occur. In Vega Baja the plant operators did not want to see any film or scum on the surface of the primary clarifier. With CEPT they must accept a small amount and know how to handle large amounts. The plant operators knew how to handle the large amounts of scum by breaking it up with water and turning off the chemical. The plant operators also need to know how to tell if the CEPT dose is being effective. A quick test of either TSS or COD, which can be done with a testing kit, in the effluent would let the operators know if the dose was working well. These tests do not necessarily have to be performed daily, but should be performed weekly. This allows the plant operators to have some control over the dosing of the chemical into the WWTP that they operate.

4.3.2 Fajardo

At the Fajardo WWTP, two different aluminum chlorohydrate chemicals were tested, PAX-XL19 and PAX-519. It is the opinion of this team that the WWTP use PAX-XL19. Not only is it cheaper, but the results also show that it also performed better than PAX-519. PAX-XL19 should be applied to the WWTP at a dose of 44 mg/L from 6:30 am to 11:30 pm. The point of application should be in the splitter box where the water flows toward the primary clarifier.

Most of the pretreatment at Fajardo as well as the anaerobic digester was broken and needs to be repaired as soon as possible. Currently all primary sludge produced is being pumped into the anaerobic digester of a package plant. Because the use of CEPT increases the amount of primary sludge, a functioning anaerobic digester for the primary clarifier would prevent overloading the anaerobic digester in the package plant. It also would allow the sludge to be removed from the primary clarifier more rapidly.

While the team was working at Fajardo, the biota on the trickling filter died. This happened when the plant operators stopped the arms to perform maintenance on the motor. The day was very hot and the arms were stopped for a couple of hours. If possible the plant operators need to minimize the time that the arms are stopped. For trickling filters to work properly the WWTP's waste stream be applied continually to keep the biological growth alive. If it is not possible to stop the arms for shorter times, the maintenance on the motor should not be done during the hottest part of the day or on extremely warm days.

Another recommendation is to install a flow meter/chemical pump combination at the point of chemical dosing. The flow at Fajardo is very variable. There were times when we were at the WWTP at 10 or 11 am and there was no flow in the splitter box. If a constant rate of chemical dosing is applied, the primary clarifier could be receiving far too much chemical at some points, and too little at others. The flow meter would measure the flow and the chemical pump would adjust to keep a constant dose of 44 mg/L. If the flow meter/chemical pump equipment is installed, the proper dose of chemical would always be applied.

The plant operators at Fajardo were more open to applying CEPT at their WWTP. A small amount of floating scum on the top of the primary clarifier did not bother them. This could have been because chemicals had been used at this WWTP before we arrived. Still they were not completely used to the idea of using chemicals and the problems that could happen. The plant operators were quick to blame the chemical for any problems with the trickling filter. When the trickling filter died because the arms were stopped for maintenance on the motor, the plant operators were sure that the chemical had killed the trickling filter. When the plant operators thought that the chemical was the problem, they quickly turned off the chemical and samplers. They need to not assign blame to the chemical without examining other possibilities. This would come with a little training on what kind of problems are likely to happen with the chemical and experience with using the chemical.

Jar tests should also be done at Fajardo periodically to make sure that the chemicals are working properly and at the proper dose. Kits that test the influent and effluent for TSS or COD would be an easy way for the plant operators to monitor the daily performance of the chemicals. Jar tests performed on a weekly or monthly basis would insure the dose is proper for the conditions of the influent.

4.3.3 How to pick a chemical and test it

Chemically Enhanced Primary Treatment is a technique that could be applied to many of Puerto Rico's poorly performing WWTPs. It would save in large capital investments to add additional "package plants" or build other treatment alternatives at the WWTP. For this reason the team decided to include a procedure on how to choose a chemical for wastewater treatment and how to implement it on a full-scale basis. The following section is adapted from Harleman and Murcott 1992.

4.3.3a How to choose a chemical

Choosing a chemical is typically done with jar tests, which consist of using one-liter jars and mixers. The test should use composite samples of wastewater taken from the entrance to the primary clarifier, or wherever the chemical is to be applied. The wastewater samples should be taken at several times throughout the day to account for any changes in the influent. The wastewater should be well mixed and divided among the 6 jars.

The next step is to choose the mixing intensity for the testing. This depends on where the chemical is to be added. If the location is the aerated grit chambers, the mixing intensity should range from 80 to 100 rpm. If the pumps are the selected location, a mixing intensity of 100 to the maximum the mixer can handle is appropriate. A mixing intensity of 40 to 60 rpm should be used if the chemical is to be added in piping with elbows and 20 to 40 rpm if it is added to piping with no elbows. Finally, if the chemical is to be added to the influent channel into the sedimentation tanks, the mixing intensity should be 20 rpm.

The first part of the jar testing should just be used to eliminate chemicals that obviously do not work for the wastewater. This can be done with visual indicators such as clarity, rate of floc formation and settling, size of floc, and amount of floating solids. Once this is done a more detailed test with each chemical that appears to work will be performed. The details of how long to mix during the testing follows.

As soon as the chemicals are added, the initial mixing should begin. The mixing should continue at the maximum intensity of the mixer for 30 seconds to insure proper mixing. The mixing intensity should then be reduced to the appropriate rate, and the jars should be allowed to mix for 2 minutes. If the use of a polymer is desired, it should be added at this point, and the mixing intensity should be increased to the maximum of the mixer for ten seconds to allow for proper mixing of the polymer. If there is no polymer this step can be skipped. Next the mixing intensity should be decreased so that it is 80% of the original value and the water should mix at this slow speed for an additional three minutes. Finally the mixer should be turned off and the jar should be left alone for five minutes.

Once chemicals have been eliminated, a more detailed analysis of each chemical can be done. The jars need to be labeled depending on the concentration of the chemical being tested. The first jar should be the control, with no chemical being added. The next five jars should have increasing concentrations of the chemical. For initial jar tests, the chemical concentration should be incremented by 20 mg/L, ranging from 20 mg/L to 100 mg/L. The chemicals should be diluted before addition so the final concentration is as labeled on the jar. The mixing should follow the same procedure as for the initial screening of chemicals.

After these steps are completed, analysis can be performed on the final supernatant. Visual parameters such as clarity, rate of floc formation and settling, size of floc, and amount of floating solids can be used to eliminate certain chemicals and dosages. Actual tests of turbidity, TSS, COD, and orthophosphate can provide definition between concentrations of the same chemical or two chemicals that appear to work similarly. Using COD is recommended because it is a much quicker test than BOD, and the percent removals of COD are about the same as for BOD. If it is desired, the jar tests can be repeated with smaller increments in the concentration once a rough estimate of the concentration is known.

4.3.3b Full-Scale Testing

Once the laboratory optimal concentration is determined, the full-scale testing can begin. The chemical should be added at the desired concentration with a chemical pump, usually supplied by the chemical manufacturer. The chemical should be applied for at least a few days to allow the system to adjust to the chemical. While this process is going on, composite samplers should be placed at least before the chemical addition and after the primary clarifier. The wastewater taken from these samplers should be tested for TSS, COD or any other parameter desired. This will allow a quick picture of if the chemical is working as well as predicted and if the dose needs to be changed. It is recommended to test the influent and effluent of the WWTP for these same parameters to see if the overall reduction with CEPT is satisfactory. If the CEPT is working as desired, but the WWTP effluent is not satisfactory, composite samplers may be set up to see if there are problems with other parts of the WWTP. If after a few days, the effluent levels are not acceptable, the chemical dose should be adjusted.

Chapter 5 - Further Studies

5.1 Seawater Addition

One developing technology that may be of interest in Puerto Rico is the use of seawater and seawater derivatives in wastewater treatment. The effect was discovered when unusually high tides caused seawater to flow into the influent of the VEAS WWTP in Norway. The higher quality effluent was discovered, and ever since the plant has been actively adding 2-3% seawater to the waste stream. In lab tests this addition of seawater at a constant iron dose produced the maximum phosphorus removal. No extra sludge or corrosion was produced by this addition (Sagberg et al 1990). This technique is especially effective when used in combination with CEPT, and has been shown to work with both ferric chloride and aluminum chloride coagulants. Seawater addition could be especially useful in Puerto Rico as a large fraction of the island's sewage is treated in six large CEPT-only plants (average flows between 8 and 45 MGD) with ocean outfalls.

There are several benefits of adding seawater to sewage in the treatment process, most importantly increased phosporus removal. Other benefits include the reduction of heavy metals. Mechanistically these benefits are the product of seawater's magnesium ions, which lead to coagulation of various species. One study used seawater liquid bittern, a form of seawater with magnesium ions concentrated by a series of evaporation pans, to achieve greater than 90% removals for cadmium, chromium, lead, mercury, nickel, and zinc, and between 70 and 90% removals for arsenic, copper, and nickel (Ayoub et al 2001). While these are preliminary lab results, they look promising for future techniques that could be applied to treatment plants with heavy metals in their influent. Another pilot plant study used 9-10% seawater in digester sludge dewatering liquor to achieve 70% P-removal and recover struvite granules which could be used as fertilizer (Matsumiya et al 2000). Again this is only a pilot test, but the possible rewards of producing a utilizable fertilizer while treating wastewater are worth looking into.

The use of seawater in wastewater treatment processes seems particularly valuable to Puerto Rico since many of the plants are located on the coast and have easy access to seawater. Depending on a particular plant's location, seawater may also be cheaper than the additional chemical dosing required to achieve similar removal methods.

One example of this on a large scale is Hong Kong. In Hong Kong toilets flush with seawater since freshwater is scarce leading to a sewage seawater concentration of roughly 20%. CEPT treatment in Hong Kong removed 75% BOD, 85% TSS, and 35% P with a relatively low dose of 10 mg/L ferric chloride (Harleman 2001). Although the concentration of seawater in the influent is higher in Hong Kong than might be practical in Puerto Rico, the possible benefits in removal efficiencies deserve further study.

5.2 Ferric Chloride vs. Aluminum Salts

In reading Otero and de Varona's report on their work in Puerto Rico, all of the chemicals recommended were aluminum salts. Because iron salts are traditionally used in wastewater treatment, the question came up of why aluminum salts were suggested for use in Puerto Rico. Apparently the plant operators in Puerto Rico were unwilling to try iron salts because they were of afraid of corrosive effects (Otero and de Varona 2000). This led to the question why do many of the wastewater treatment plants in the United States use iron salts if iron salts really do cause these problems. The answer is simple; iron salts give better removals as well as being cheaper even with the problems of corrosion.

Murcott (Murcott and Harleman 1992) surveyed several wastewater treatment plants in the United States for several factors including if the WWTP uses chemicals and what kind. Several WWTPs replied that they used Ferric Chloride or Alum at different dosages. Some of these WWTPs also reported the removals of BOD, TSS and Total P that they see between their influent and effluent. Examining this data showed one astonishing fact. The average percent removals between alum and ferric chloride for BOD and TSS are virtually identical, when these chemicals are added at doses typically seen in a WWTP. The average BOD removal was around 60% and the average TSS removal was around 75% for both alum and ferric chloride. The big difference was in the ability of the chemical to remove Total P; this is shown in figure 19. The WWTPs that used alum, at a dose typically seen in a WWTP, were only able to remove, on average, 62% of the Total P, while the WWTPs that used ferric chloride, at an average dose typical of WWTPs, were able to remove and average of 73% (Murcott and Harleman

1992). It seems that iron has a better chance at removing phosphorus from the wastewater than aluminum.

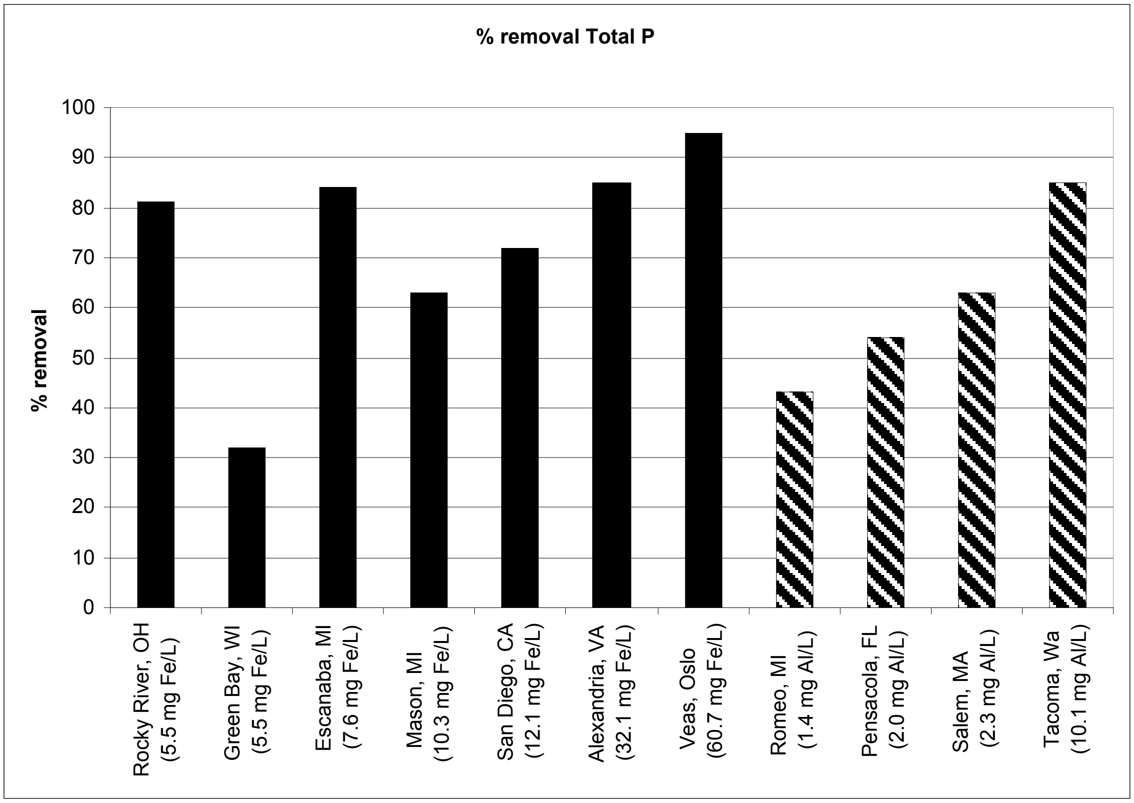

FIGURE 19: TOTAL P REMOVAL BASED ON AMOUNT OF IRON OR ALUMINUM USED

Because the ferric chloride appears to remove phosphorus better than aluminum salts, this topic needed to be investigated further. First of all a search for any data on the amount of iron and aluminum required for certain removals of Total P was conducted. What was found was that on a mole-to-mole basis a higher amount of iron is needed to remove the same amount of Total P from the wastewater.

% Phosphorus Reduction	Mole Ratio Al:P	Mole Ratio Fe:P
75	1.4	1.3
85	1.7	1.9
95	2.3	3

Table 6: Mole Ratio of Metal Required for an Increased Total P Reduction (EPA 1976)

This is especially true for higher removals of phosphorus, as shown in table 6. It is interesting to notice that as a higher percent removal is desired, the amount of iron and aluminum required increases. If one examines the equations that describe how phosphorus is removed by metal salts, it would appear that one mole of metal should remove one mole of phosphate. There are several factors that influence how well these reactions work including alkalinity and final pH of the effluent, competing anions and cations such as sulfate, flouride and sodium, quantity and nature of the total suspended solids, intensity of mixing and microorganisms or other colloidal particles present (EPA 1987).

In comparing WWTPs that remove the same amount of Total P from Murcott's work, the WWTPs that use alum use a smaller metal dose, but must use a much higher dose of chemical (Murcott and Harleman 1992). This is because the metal content of the alum solution is much less than what is in an aluminum chlorohydrate solution. Table 8 below shows two sets of plants with identical %Total P removals but different metal salts.

WWTPs with Same %Total P removal	%Total P removed	Metal Dose (mg Me/L)	Concentration (mg/L)
Mason, MI (FeCl3)	63	4.1	30
Salem, MA (Alum)	63	2.2	50
Alexandria, VA (FeCl3)	85	12.6	93
Tacoma, Wa (Alum)	85	9.9	225

Table 7: Plants with the Same %Total P Removed and Metal Dose Required

One reason that ferric chloride is used so extensively in wastewater treatment plants in the United States is that it is much cheaper than aluminum salts. Ferric Chloride usually costs around $0.14/lb, while aluminum salts can cost around $0.35/lb. Using Murcott's numbers for the metal dose need to remove 85% of the Total P, a cost analysis for Vega Baja and Fajardo is performed and the results are shown in Table 8.

Plant	Chemical	Metal Dose (mg/L)	Chemical Dose (mg/L)	Cost of Chemical ($/year)
Vega Baja[a]	**GC-850**	2.2	18	$30,000
	FeCl3	4.1	30	$16,000
Fajardo[b]	**PAX-XL19**	9.9	80	$57,000
	PAX-519	9.9	85	$83,000
	FeCl3	12.6	92	$30,000

Table 8: Cost Analysis for Various Metal Salts
a. Flow is 1 MGD, chemical run for 9 hours
b. Flow is 1 MGD, chemical run for 17 hours

For Vega Baja, the cost of reducing Total P by 85% from the influent value using GC-850, the WWTP would have to spend around $30,000 per year. For the same results with ferric chloride the cost would be around $16,000 per year. The cost of using ferric chloride is much lower, saving $14,000 dollars, and this difference could offset maintenance associated with corrosion in the WWTP. For Fajardo to reduce the Total P by 85%, the use of PAX-XL19 would cost around $57,000 per year, and the use of PAX-519 would be about $83,000 per year. In contrast the cost of ferric chloride would be a little over $30,000 per year. Using the ferric chloride would save the WWTP at least $27,000 a year. This savings would most likely cover some if not all of costs associated with corrosion from the ferric chloride.

Talking with Jesse Paguiero, the plant operator at the Point Loma Wastewater Treatment Plant, gave a perspective as to why his WWTP uses ferric chloride. Point Loma is a WWTP in California that just uses chemically enhanced primary treatment, not any other treatment like trickling filters or activated sludge, to meet its NPDES permit standards. The WWTP has been using ferric chloride at a dose of 25 mg/L for the last several years. When asked directly about the corrosion that ferric chloride causes, he said that they had also had problems. They had to line the sediment basins with a nylon coating and have replaced pipes with ones that are resistant to iron corrosion. He also said that if they continually test the amount of ferric chloride used to make sure they are not overdosing, the amount of corrosion is reduced. When asked why another chemical was not used, Mr. Paguiero said that they tested other chemicals and never found one that worked better, for the price including corrosion problems, than ferric chloride (Paguiero 2001).

Puerto Rico should consider using ferric chloride in its wastewater treatment WWTPs. The main benefit of switching to ferric chloride is in the reduction of total phosphorus (Total P); on average ferric chloride is able to remove 10% more Total P than alum in actual WWTPs when the chemicals are used at typical dosages. The other benefit of using ferric chloride is the cost of using chemicals in the WWTPs. If the dosages in Murcott's work are applicable, using ferric chloride would save Vega Baja $14,000 per year and would save Fajardo $27,000 per year. While ferric chloride has its problems with causing corrosion in the WWTPs, the reduced cost more than makes up for any of the costs associated with the corrosion. If Puerto Rico wants to reduce its effluent Total P level and costs, it should consider the use of ferric chloride in its WWTPs.

If Puerto Rico insists on using an aluminum salt to remove phosphorus from wastewater, it should consider switching to a different aluminum compound. Jar tests using polyaluminum chloride (PAC) and aluminum chlorohydrate, the chemical used in Puerto Rico, show that the PACs perform much better than either alum or aluminum chlorohydrate, but the aluminum chlorohydrate performs worse than both alum and PAC (EPA 1987).

Chapter 6- Sludge Management in Puerto Rico: Present and Future

6.1 Introduction

As the 21st century dawns, the wastewater industry faces the daunting problem of how to best treat and dispose of the residuals of wastewater treatments, better known as sludge. The wastewater treatment process has changed little in the past 50 years, and treatment plants configurations vary little in principle. Wastewater treatment plants can be either conventional or advanced primary, trickling filter, activated sludge, or some combination of these. Wastewater treatment plants are enormous capital investments that last for generations, which explain why municipalities are unwilling to take the risk of implementing untried technology.

As the level of wastewater is improved across the world in order to uphold water standards, the amount of sludge produced increases (Outwater, 1994). Sludge management, being the costliest part of wastewater treatment plant operations, has always been a difficult task. As options to dispose of sludge diminish, governments find themselves with serious sludge management problems on their hands. In general, the regulations have started to limit the use of previous inexpensive practices of placing sludge in landfills, or applying them to lands. Due to decreasing options for sludge disposal, small countries, especially developing ones, face increasing sludge management problems as they improve the efficiency of their wastewater treatment. One country facing such problems is Puerto Rico.

To understand the manner in which Puerto Rico manages its sludge at this moment, and to analyze the options open to it, one must start by studying the characteristics of its sludge. Then, one must delineate the techniques it uses now to treat and dispose of its sludge, in other words to describe how it manages its sludge. The thesis will also look at two plants in the United States, Point Loma and Orange County, and study how they manage their sludge. Finally, options will be laid out for Puerto Rico from among several techniques, and recommendation will be made as to the best practices to implement in order to improve their outlook for the future as it concerns sludge management.

6.2 Characteristics of Sludge in Puerto Rico

Sludge is a difficult matter to characterize, since it tends to be a heterogeneous mixture composed of many different components. The characteristics of sludge depend on its origins, the amount of aging that has occurred, and the type of processing the sludge has received. Quantity and quality of sludge vary widely and depend on the origin of the wastewater, type of treatment, and plant operation practices. A sampling program that accurately reflects and monitors sludge quality is critical to figure out the best way to treat and dispose of sludge. Table 9 shows a list of the standard sampling parameters for sludge in US.

Standard Sludge Analysis	
Standard Parameters	**Priority Pollutants**
pH	Metals and other inorganics
Chlorides	Pesticides
%Volatile Solids	Halogenated aliphatic hydrocarbons
Total Nitrogen	Monocyclic aromatic hydrocarbons
Ammonia	Halogenated ethers
Nitrates	Phthalate esters
Total Phosphorus	Polychlorinated biphenyls and related compounds
Available Phosphorus	Nitrosamines and other N compounds
Potassium	
TCLP	
SOUR	

Table 9: Standard Sludge Analysis (From outwater, 1994)

The characteristics of sludge can be separated into physical, chemical and biological elements. Puerto Rico does not have the rigorous monitoring system of sludge, and it does not do biological testing or periodic chemical testing of its sludge.

6.2.1 Physical Composition

Sludge from diverse treatments displays different characteristics. Puerto Rico's sludge can have six different physical compositions depending on the wastewater treatment performed by the plant. Most of the sludge, about fifty percent, comes from activated sludge plants. Their sludge is generally brown, and fluffy. If the waste activated sludge is in good condition, its odor tends to be mild, but as the sludge approaches septic conditions, it can reek. Approximately fifteen percent of the sludge comes from trickling filter plants, which means this sludge or "humus" as it is sometimes called, tends to be brownish, light, and quite harmless when fresh. It has a slower decomposition rate than the other undigested sludges, unless it is saturated with worms, whereas it becomes quite foul. Nine percent of the plants use both activated sludge and trickling filter processes, thus their sludge tends to be quite dark in color and has a combination of the characteristics of the two types of sludge mentioned above. Another eleven percent of the plants use chemically enhanced primary treatment (CEPT). CEPT plants add metal salts or polymers to their primary clarifier tanks in order to improve the removal rates of total suspended solids (TSS), biochemical oxygen demand (BOD), and Phosphorus from the wastewater by improving solids settling through flocculation and coagulation (Morrissey, 1992). CEPT sludge ranges between dark gray and black in color, and is quite smelly. It can be slimy in texture, but the iron or aluminum hydrate tends to give it a gelatinous consistency. Its decomposition rate tends to be slower than for conventional primary sludge, for which the sludge tends to be gray, slimy, and very smelly. Seven percent of the plants use advanced secondary treatments, which indicates that their sludge is primarily a mixture of advanced primary clarifier sludge, and either trickling filter sludge, activated sludge or both (PR's Annual Sludge Report, 1999). See figure 20 for a chart on types of lsudge in Puerto Rico. A big physical component of sludge is water. It exists in four major phases: free water, capillary water, colloidal water, and intracellular water (Outwater, 1994). It tends to influence the treatment options for sludge, and how it can be handled. No data on water content for Puerto Rican sludge was available.

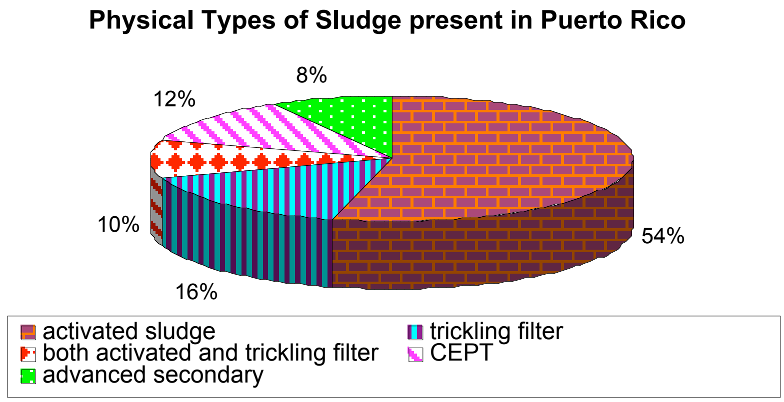

FIGURE 10-PHYSICAL TYPES OF SLUDGE PRESENT IN PR

(ADAPTED FROM PR'S ANNUAL SLUDGE REPORT, 1999)

6.2.2 Chemical Composition

Contaminant levels in sludge tend to vary by the time of day, the day of the week, and even the season of the year (Outwater, 1994). This explains why it difficult to quantify the exact components of sludge. Variance in sludge contaminant levels can also be due to areas of incomplete mixing in digesters, and rain levels in the area. Please see Table 10 for a general range of characteristics in both raw and digested sludges.

Typical Chemical Composition of Raw and Digested Sludge				
Item	**Raw primary sludge**		**Digested sludge**	
	Range	**Typical**	**Range**	**Typical**
Total dry solids (TS), %	2.0-7.0	4.0	6.0-12.0	10.0
Volatile solids (VS), %	60.0-80.0	65.0	30.0-60.0	40.0
Grease and fats (ether soluble, % of TS)	6.0-30.0	----	5.0-20.0	----
Protein (% of TS)	23.0-30.0	25.0	15.0-20.0	18.0
Nitrogen (N, % of TS)	1.5-4.0	2.5	1.6-6.0	3.0
Phosphorus (P_2O_5, % of TS)	0.8-2.8	1.6	1.5-4.0	2.5
Potash (K_2O, % of TS)	0.0-1.0	0.4	0.0-3.0	1.0
Cellulose (% of TS)	8.0-15.0	10.0	8.0-15.0	10.0
Iron (not as sulfide)	2.0-4.0	2.5	3.0-8.0	4.0
Silica (SiO_2, % of TS)	15.0-20.0	----	10.0-20.0	----
pH	5.0-8.0	6.0	6.5-7.5	7.0
Alkalinity (mg/l as $CaCO_3$)	500-1500	600	2500 -3500	3000
Organic acids (mg/l as HAc)	200-2000	500	100-600	200

Table 10-Typical Composition of Sludge (From Outwater, 1994)

According to the types of wastewater treatments performed in Puerto Rico, its sludges should contains approximately 1.5 to 4% total solids, 53 to 74% volatile solids, 3.4 to 5.6% Nitrogen (N) dry weight, 2.3 to 5.6% Phosphorus (P) dry weight, and 0.2 to 0.7% Potassium dry weight (Noyes Data Corporation, 1979). This will vary by region and type of treatment used by wastewater plants in area.

There are chemicals of concern that must be monitored in sludge according to EPA regulations. Among these are heavy metals, pesticides, and certain volatiles. Table 11 delineates the types of chemicals found in Puerto Rican sludge, and the chemical concentration averages, minimum and maximum for all of Puerto Rico's wastewater treatment plants for a year. See Appendix C for further information on Puerto Rico's plants. Puerto Rico does not have very significant levels of any of these in its sludge. This means that their sludge is safe to dispose of in any of the manners described in chapters 3 and 5. See Appendix D for a table of the chemicals regulated and their required concentration limits in sludge. One detail that must be monitored is how treatment changes these components since some tend to concentrate the contaminants in the sludge.

Chemical Analysis of Sludge in PR					
Chemical	**Average Value**	**Limit Allowed**	**Maximum Value**	**Minimum Value**	**Units**
Total Arsenic	0.006	5.0	0.086	<0.003	mg/L
Total Barium	0.141	100	1.2	<0.1	mg/L
Total Cadmium	0.010	1.0	0.079	<0.002	mg/L
Total Chromium	0.026	5.0	0.162	<0.002	mg/L
Total Lead	0.052	5.0	0.231	<0.05	mg/L
Total Mercury	0.002	0.20	0.007	<0.002	mg/L
Total Selenium	0.004	1.0	0.128	<0.001	mg/L
Total Silver	0.008	5.0	0.063	<0.001	mg/L
pH	6.99	2.0-12.5	12.6	5.16	S.U.
Releasable Cyanide	<1	250	<1	<1	mg/Kg
Releasable Sulfide	4.82	500	50.8	<1	mg/Kg
Paint Filter Test	3.47	NA	96	0	ml/100g

Table 11-Chemical analysis of sludge in PR (Calculated from PR's Annual Sludge report, 1999)

6.2.3 Biological Composition

All sludge contains a diverse group of life forms, which play both beneficial and detrimental roles in its treatments and uses. Puerto Rico does not do biological testing of its sludge, but the following paragraphs should give an idea of the types of biology that may be found in them. Microorganisms in sludge can be separated into: bacteria, protozoa, rotifers, and fungi. A limited number of these can be pathogenic. Bacteria are the smallest of the microorganisms. They reproduce mostly by cell division. They are also very hard to classify. Their composition consists of 80% water, and 20% dry matter, of which approximately 90% is organic. Their dry matter is composed approximately of 48% carbon, 10% nitrogen, 2.0% phosphorus, 2.75% potassium, 0.6% sulfur, and trace elements like magnesium, sodium, and iron. It also contains about 55% proteins, 10.5% carbohydrates, and small amounts of lipids, and organic acids (Girovich, 1996). Types of bacteria found in biosolids include actinomycetes, coliforms (i.e. E.coli), fecal streptococci, and salmonella species.

Viruses, characterized as acellular particles that contain genetic reproductive information, but need a host cell to live, may be found in untreated sludge as more than 100 different types. They are exceptionally small, usually between 0.01-0.25 microns, and are very host-cell specific (Girovich, 1996). It is hard sometimes to destroy viruses, and thus there is special concern about their survival in sludge, since sludge is being reused beneficially more and more every day.

Protozoa are single celled animals that comprise an extremely diverse group, and tend to be between 5 to 1000 microns in size. Not all protozoa need oxygen; in fact, to some it is toxic. They can be characterized as either free living or parasitic. Protozoa are of four different nutritional types: autotrophs, saprobes, phagotrophs, and carnivores. Autotrophs are plant like forms capable of absorbing sunlight and using carbon dioxide to create organic compounds. Saprobes are animal like forms that have no chlorophyll nor need light, but depend on soluble organic compounds. Phagotrophs are forms that feed on bacteria, and carnivores feed on other protozoa. One of their requirements for survival is the availability of water, thus they can be found in all wastewater treatment plants that are aerobic. They are quite important for the activated sludge process, and can also be found in trickling filters, oxidation ponds, and wetlands. They play a very important role in the removal of bacteria from wastewater, and they aid in the flocculation of suspended particulate matter and bacteria, which is important to both the clarification of the water and the formation of sludge. Their survival hinges on a pH between 6.0 and 8.0 (Girovich, 1996).

Rotifers are small, simple macroinvertebrates found in both wastewater and biosolids. They exist as free-swimming organisms that tend to vary in size from 40 to 500 microns. Their average life ranges from 6 to 45 days. Rotifers are mostly beneficial animals in aerated lagoons where they feed on phytoplankton and in activated sludge processes where they eat large amounts of bacteria and boost floc formation. In aerobic processes, rotifer's actions appear to help reduce the biological oxygen demand (BOD).

Helminths, which are parasitic intestinal worms and flukes, and nematodes, which are roundworms, are free living both microscopic and macroscopic animals. They can be found in aerobic processes with plenty of oxygen and microbial food like trickling filters. Their ideal pH ranges between 3.5 and 9.0, and they may survive temperatures up to 117 ºF (Girovich, 1996). The biggest danger to humans comes from roundworms like *Ascaris lumbricoides*, since most helminthes and nematode eggs and cysts amass in primary biosolids.

Fungi, which come in over 80,000 species, consist of tubular, filamentous branches that range in diameter from 10 to 15 microns. They reproduce by forming spores that can be quite hard to destroy. Approximately 50 fungal species can be responsible for various human infections (Girovich, 1996). Their dependence on moisture is moderate and they can be found on dry biosolids while absorbing moisture from the air. Fungi are very good at surviving wide ranges of pH and temperature. For a list of specific pathogens and the diseases associated with them, please look in Appendix E.

6.3 Sludge Treatment and Disposal in Puerto Rico

6.3.1 Treatment

Puerto Rico's 67 plants do not all have the same system for wastewater treatment or for sludge treatment. Treatment should ideally be performed on the sludge before it is disposed of or reused. Most of PR's plants use digestion as a first treatment, either aerobically or anaerobically, and then dewater it, through either natural or mechanical methods (Cepeda, 2001). No matter what the final disposal method chosen for the sludge, the costs of processing, transporting, and disposing of the material continue to increase; therefore, treatment plant operators must find ways to reduce the volume of sludge. Moreover, since sludge contains a large amount of water--up to 97% moisture content--this is best accomplished by ridding the sludge of as much water as possible (Snow, 1996).

6.3.1.1 Digestion

Puerto Rico employs both aerobic and anaerobic digestion in its plants. Digestion usually refers to the biological breakdown of the organic matter in sludge. Digestion makes the sludge easier to dewater in general. It is employed as a way to stabilize the sludge, reduce its volume, and reduce the pathogens in it. Biosolids are usually thickened prior to digestion. Digestion can occur either aerobically or anaerobically.

Aerobic digestion involves the oxidation of microorganisms to water, carbon dioxide, and ammonia. The biological processes associated with it depend on the type of sludge being digested. The configuration of aerobic digesters is usually an open tank fitted with diffuse or surface mechanical aerators. The tank shape tends to depend upon the selected method for mixing and/or aeration. This type of digester usually has some type of decanter incorporated into the design so that thickening can occur. Again, the supernatant is directed to the top of the plant process. Designs for aerobic digesters include mesophilic digestion, autothermal thermophilic aerobic digestion (ATAD), and pre-stage ATAD (Snow, 1996). ATAD is further discussed in section 6.5. Pre-stage ATAD involves using aerobic digestion upstream of anaerobic digester to achieve pathogen destruction, and is an easy update for treatment plants.

In conventional or mesophilic aerobic digestion, the ammonia is oxidized further into nitrate. Around 75% of the microorganism, cellular material can be oxidized since there is inert or organic material that cannot be biodegraded further. Operators must keep the levels of dissolved oxygen (DO) at no less than one mg/L DO all through the reactor, sustain the mixing, and uphold the residence time. Additionally, removing the supernatant, either by decanting or by drawing it off after the sludge has settled for at least 45 minutes should provide a denser digested product (Snow,1996.) This thicker product reduces the energy required for further treatments like dewatering.

Anaerobic digestion can be portrayed as a multistage process in which microorganism convert different types of complex organics, into simpler ones which in turn are converted by other microorganisms into even simpler compound and finally, into carbon dioxide, water, methane, and hydrosulfuric acid. There are three stages of microbial transformations during anaerobic digestion. The first one turns the sludge, which is mostly complex organics with lipids, cellulose, and proteins, into simpler molecules like organic acids, alcohols, ammonia and carbon dioxide. The second stage converts these products into hydrogen, carbon dioxide, and simpler organic acids. Finally, acetate, carbon dioxide, and hydrogen become methane, more carbon dioxide and water. This last stage represent the rate-limiting step since the methane-producing bacteria tend to be slow growers, in part due to their pH sensitivity which must be between 6 and 8. The optimum operating conditions for anaerobic digesters vary with sludge feed, but alkalinity, pH, temperature, gas production, and volatile acids and solids concentration are important parameters for reactor performance. A recent improvement on anaerobic digesters are egg-shaped reactors which improve the efficiency, and reduce the maintenance required mainly through configuration modifications (Snow, 1996).

For anaerobic digesters, a two stage concrete, cylindrical covered tank is the standard configuration. The sludge is pumped into the first tank, where mixing and the majority of the digestion happen. In the second tank, the sludge is thickened through a settling technique, and then removed to be disposed of as previously determined. The supernatant, or liquid that floated to the surface of the tanks, is sent back to the beginning of the treatment plant for further treatment (Culp, 1979). See figure 21 for a schematic of a typical anaerobic digester.

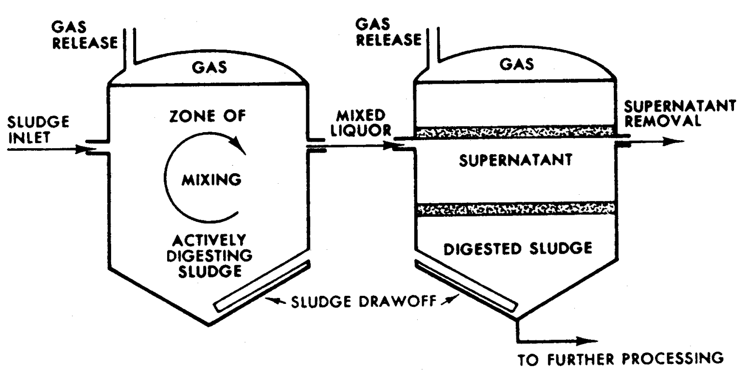

FIGURE 21-TYPICAL TWO-STAGE CONFIGURATION OF AN ANAEROBIC DIGESTER (FROM CULP, 1979)

6.3.1.2 Dewatering

Most of Puerto Rico's treatment plants use sand drying beds, which are the traditional method for dewatering sludge. They can be either covered or uncovered, and in PR, they are mostly uncovered, which tends to delay the dewatering. If the right conditions are present, the sludge cake it produces can be as good as cake from mechanical systems. They require little operator care, but usually can only be used with digested sludge since raw sludge smells and does not dry well when applied too thickly. The beds use different mechanisms to dewater the sludge. These encompass gravity drainage, capillary action through the sand, and evaporation from the surface of the beds.

Sand beds drying rates can be quite sensitive to the amount and rate of precipitation, number of sunny days, relative humidity, and wind velocity. Their construction is usually done by laying down between 10 to 30 centimeters (cm) of sand over 20 to 50 cm of gravel. The sand grains usually range in diameter from 0.3 to 1.2 millimeters (mm). For optimum permeability that accelerated the dewatering, the sand should consist of uniformly graded particles with less than 5% fines. Fines are necessary for soil stability, and a decrease in fines reduces the ability of the soil to support loads. The water filtrates through the gravel while the sand on top catches the finer particles of the liquid sludge. The piping under these layers has a minimum diameter of 10 cm with a slope of at least 1%. The collected liquid is returned to the beginning of the treatment plant. Sometimes sand beds are enclosed to keep out foul weather, and to keep odors and insects under control. Enclosing appears to reduce the area needed for the bed by about 20% (Outwater, 1994). One important parameter that must be controlled is the ventilation of the bed, which controls the amount of moisture and optimizes the evaporation.

One problem with sand drying beds is the removal of the sludge from the beds. Methods for sludge removal can include hand labor, and various forms of mechanical tools that don't depend on the sand for support. To use some of these tools, like small utility tractors with front-end loaders, concrete slabs can be built into the bed, or geotextiles can be installed into the bed, thus improving the support offered by the bed. Another problem is that sludge needs to be well digested to control odor, and insect problems (Culp, 1979). See figure 22 for a picture of a sand drying bed at the Vega Baja plant in PR.

FIGURE 22-SAND DRYING BEDS IN VEGA BAJA PLANT

Another dewatering technique in Puerto Rico is lagoons. They are quite simple and do not require a lot of capital as long as the climate is hot and dry, the land can be acquired cheaply, and the immediate radius of the lagoon is uninhabited. This all applies to Puerto Rico, except the land is no longer cheap, but it was inexpensive at the time the lagoons were first constructed. Drying lagoons are periodically emptied of sludge and then the land refilled. Sludge layers of 36 cm tend to empty in about 4 months. The data on lagoons sludge is very limited. They are not the most popular choice due to several issues. Lagoons tend to smell more than sand beds, thus the sludge must be stabilized before it can be put in the lagoon. Further odor control is difficult because of the relatively large surface area. They are also quite sensitive to climate conditions since heavy precipitation and colder weather both slow the thickening of the sludge significantly. The sludge may also leach from the lagoon, threatening groundwater, or nearby surface waters (Outwater, 1994).

Puerto Rico also employs belt filter presses in a couple of its plants. It appears to be trying to upgrade from the sand bed method to mechanical methods like the belt filter. Puerto Rico has had some problem with operators not wanting to use them, either because of lack of training, or because of contract issues (Cepeda, 2001). Belt filter presses came into use for dewatering around the 1970's, when it was adapted from the papermaking industry. They produce a drier cake than vacuum filters through a three-step process. These steps are: conditioning/flocculation, gravity drainage, and compression shear. Conditioning is the first step required for belt filter dewatering. The sludge from this step is pumped onto a moving porous belt where gravity drains the free water from the sludge. This section is usually either a rotating screen thickener, or a long gravity piece of belt. This essential step removes 50 to 75% of the total water removed by this method of dewatering. Next, the sludge is squeezed between two continuous woven fiber belts with increasing pressure. The belts pass over a chain of rollers, which provide shearing action and more pressure (Outwater, 1994). Water gets pushed out the holes between the fibers, which leaves the sludge solids on the belts. At the end of the chain, the dewatered cake gets scraped from the belts and drops onto a conveyor or other appliance for further processing or final disposal. To prevent clogging, wash water, with a pressure of 80 psi or more, and a water flow rate at least 50% higher than the sludge flow rate to the press, is continuously applied during the process. This method, if the filter run is long enough, will produce a drier sludge cake than any other mechanical method (Vesilind et al, 1986). For a layout of the process, see figure 23.

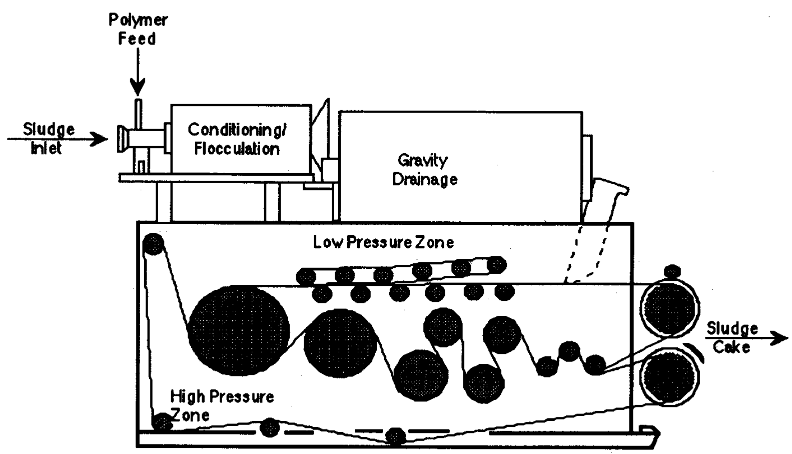

FIGURE 23-BELT FILTER PRESS (FROM OUTWATER, 1994)

6.3.2 Disposal

Sludge can be disposed both treated and untreated. After the treatments mentioned above, Puerto Rico disposes of the approximately 27,000 dry metric tons of sludge it produces by either landfilling it, composting it, or land applying it. See figure 24 below for a chart showing the percent of sludge disposed by each manner mentioned above (PR's Annual Sludge Report, 1999). Options for disposal methods are getting very scarce. Many landfills are rapidly filling up, and it's hard to get permits, and locations to build new ones, especially on an island like PR. As more advanced treatment of wastewater are implemented, the amount of sludge being produced increases, while the manners in which to dispose of it are reduced.

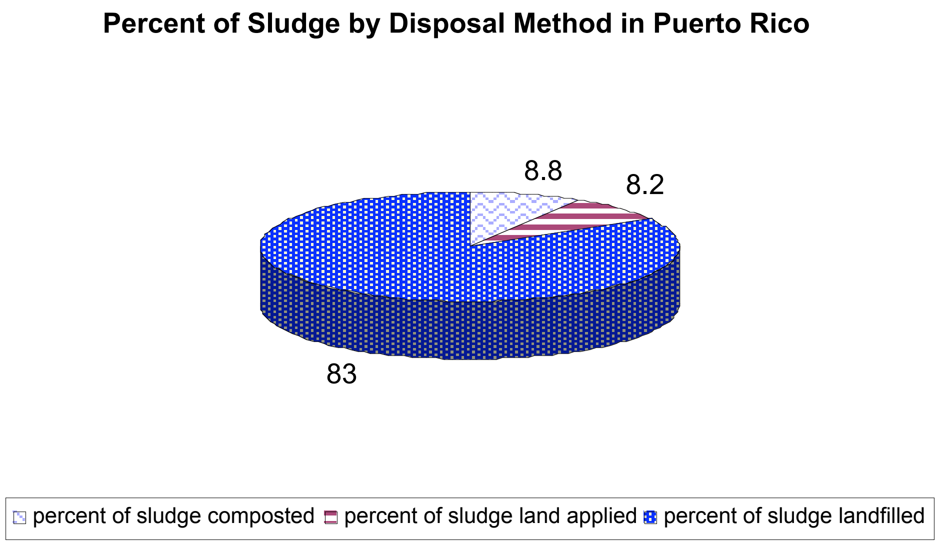

FIGURE 24- PERCENT OF SLUDGE BY DISPOSAL METHOD IN PUERTO RICO
(ADAPTED FROM PUERTO RICO'S ANNUAL SLUDGE REPORT, 1999)

6.3.2.1 Landfills

Puerto Rico landfills about 83% of its sludge. This sludge comes from 65 of Puerto Rico's 67 plants. Before sludge can be landfilled, it must be dewatered and stabilized, and then it is trucked to a nearby landfill that accepts sludge. Depending on the type of landfill, it can be entombed, or buried to decompose. Puerto Rico divides the 21,251 metric tons of dry sludge it landfills between twelve landfills. Landfilling requires space, demands pre-treatment, and has increasing costs associated with it. Landfilling also concentrates organic wastes and may result in point-source contamination for future generations to deal with. This type of disposal may seem practical at this moment, but as Puerto Rico's population increases, the amount of sludge will increase, and the space in and the number of landfills will decrease. In the last 6 years, about 30 landfills have been closed, which means that more than half the landfills in Puerto Rico have had to close. Most have been closed due to old designs that did not adequately protect the public and the environment. EPA has mandated that another twenty-three landfills close by 2005. That leaves thirteen landfills for the whole island divided by regions. New disposal methods must be adopted for the majority of this sludge, before space runs out (Cepeda, 2001).

For sludge to be landfilled the most important criteria is its shearing strength, which must be at least 15 to 20 kN/m^2. This value is hard to achieve through dewatering with centrifuges or belt filter presses, even at optimum running conditions. The addition of quicklime before or after mechanical dewatering tends to increase the shearing strength (Otte-Witte, 1988).

The cost of landfilling in Puerto Rico is normally $41 per metric ton of waste. Assuming this applies to sludge wastes, and that it is the same for all twelve landfills used for sludge, it would cost $871,291 to landfill all the wastes. The cost can go as high as 40% more than this estimate (Cepeda, 2001).

6.3.2.2 Composting

Puerto Rico composts the sludge from one plant, Arecibo RWWTP, which accounts for approximately 8% as dictated in figure 24. This plant also receives part of the sludge from two other plants, Aguadilla RWWTP and Camuy RWWTP. Both Arecibo and Aguadilla are coastal CEPT plants, which indicates they use chemically enhanced primary treatment. This means they produce more sludge on average than conventional primary treatment plants, plus since they are in heavily populated areas, they produce more sludge than most of the other plants. The composting facility is located in Arecibo as well (Puerto Rico Annual Sludge Report, 1999). It is not clear what type of composting the Arecibo facility performs, although it is suspected they carry out the windrow system. Thus, all three types of composting are described below.

Composting has been growing in popularity as an alternative treatment/disposal for sludge since the 1960's. Composting is based on enhanced biological decomposition. It is a natural aerobic process carried out by thermophilic microorganisms, which degrade organic wastes into a stabilized, useful product that has been freed of odors and pathogens. The wastes are degraded sufficiently that further decomposition is impaired and will not cause problems during use of product. Composting does not require the use of digested or stabilized sludge, but the sludge should undergo dewatering prior to composting. The conditions necessary for composition include 10 to 15% oxygen concentration, with a carbon: nitrogen ratio of 27:1, 30% volatile solids concentration, and a pH that can range between 6 and 11. This type of environment provides the necessary setting to sustain microbial growth and reproduction. The sludge feed should have about a 40% solids content (or 60% moisture), and a good balance of carbon and nutrients (Naylor, 1996).

There are three types of composting processes: the windrow system, the static pile system, and the enclosed reactor system. In the windrow system, the material to be composted is place in long rows that are turned at regular intervals to increase aeration and contact between bacteria and food. The feed must also be mixed with a bulking material, like wood chips, or dried solids, before being laid on the compost row. It also requires the use of digested sludge since it requires open areas that have no control over odor and vermin problems (Sherwood *et al.*, 1988). Some advantages include simple treatment processes, low capital costs, and products that are marketable and easily reused. Some disadvantages are the large amount of labor involved, odor problems, and large space required for operations (Vesilind *et al*, 1986).

In the enclosed reactor system, or the in-vessel system as it is also known, the composting is performed inside closed containers. The system can be of two types, either plug flow or dynamic. The plug flow system has a hydraulically operated ram as part of an enclosed bin, which pushes material flow through out the unit. The dynamic model contains a large rotating drum that mixes the sludge and bulking agents for about 24 to 48 hours (Spellman, 1997). Some advantages to this system are elimination of odor and vermin problems, less land required for operations, and better control with a continuous operation. Disadvantages may include larger capital costs than other two composting methods and more energy required to carry out operations (Vesilind *et al*, 1986).

The most popular system is the static pile system, which can be single pile or extended aerated pile. The air is either blown or drawn through the piles. This permits the pile to remain in place instead of having to be mixed periodically. This preserves aerobic conditions in order to prevent septic condition, and allows for better temperature control. This type of pile is also better, because the forced air can be used to cool piles where temperatures rise above 75°C, which could result in combustion and fire. One disadvantage of this model can result from the forced air pushing the odors outside of the facility range, although odor control is better than with the windrow system (Sherwood *et al.*, 1988). It is also exposed to the element and has large labor and energy costs. Some advantages include low space requirement for operations compared to windrow system, and relatively low capital costs (Vesilind *et al*, 1986).

After the composting is completed approximately 26 days after sludge was laid on the piles, curing and drying of the resulting residuals must take place. Curing refers to the final stages in microbial metabolization of any remaining nutrients in the piles. It ensures complete odor elimination, and pathogen destruction. Drying can be an optional step, but is required if screening to recover wood chips or other bulking material is to be performed. It takes place under a structure equipped with a roof to protect the new compost from the elements. Drying occurs by either drawing or blowing air through the piles, or by mixing it with a front-end loader. Both methods may be used in any combination (Spellman, 1997).

6.3.2.3 Subsurface land application

Puerto Rico uses land application as a disposal technique at two of its treatment plants. These are Barceloneta RWWTP, and Humacao WWTP. This takes care of approximately 2,314 dry metric tons of sludge. Both are applied on land behind the plants, which diminishes trucking expenses. The sludge is applied as liquid sludge, thus dewatering is skipped in the treatment process. The equipment used to inject it into the subsurface of the soil consists of a conventional tilling machine retrofitted to go deeper into the soil, and then another machine flattens the soil to keep odors and vermin problems to a minimum (Cepeda, 2001). Land application usually requires storage of the sludge between the time it is generated and the time it is applied due to rate differences. Sludge application rates depend on weather conditions, field conditions, and application method. In a place like Puerto Rico, second-stage anaerobic digesters could serve as storage basins, since weather conditions and field constraints are minimal. Land application can be applied with the view of growing crops or other vegetation on the land, or of growing nothing at all, as is done in PR. As mentioned earlier, heavy metal concentration, water content, and nitrogen concentration can all affect the rate of land application, in particular heavy metals (Culp, 1979). Puerto Rico has insignificant concentrations of metals in the majority of their sludge, and its nitrogen levels are well above the minimum required to improve soil nutrients, plus it has good amounts of phosphorus and potassium, which are also needed for plant growth. Land application is further discussed in section 6.5.

6.3.2.4 Incineration

In 1998, Puerto Rico had to stop incinerating any of its sludge. This was due to a court order that the EPA obtained to force them to close their two incinerators, which were multiple hearth furnace (MHF) incinerators, and were in violation of the Clean Air Act. They were also fined $80,000, and are going to spend an additional $700,000 to install new fluidized bed incinerators at the plant. Both old incinerators were located at the Puerto Nuevo wastewater treatment plant located in Puerto Nuevo, Puerto Rico. See figure 25 for an interior view of an MHF. Incineration is the most effective manner in which to stabilize sludge, and almost dispose of it. It fully oxidizes the organics, and completely eliminates odors and pathogens. It consists basically of thermal oxidation at very high temperatures that degrade the organics, which produces an inert ash, and achieves a 90% volume reduction of the sludge. The first step is drying the sludge to get a cakey consistency, and then exposing it to temperatures of 850 to 900 ºC. The most common units are the multiple hearth units like the ones Puerto Rico decommissioned, and the fluidized bed model that they will soon implement (Vesilind *et al.*, 1986). One concern with incineration is the production of dioxins, a chemical family that poses a serious health concern. Another concern is the concentration of contaminants in the ash, which may leach under acidic and anaerobic conditions (Arundel, 2000).

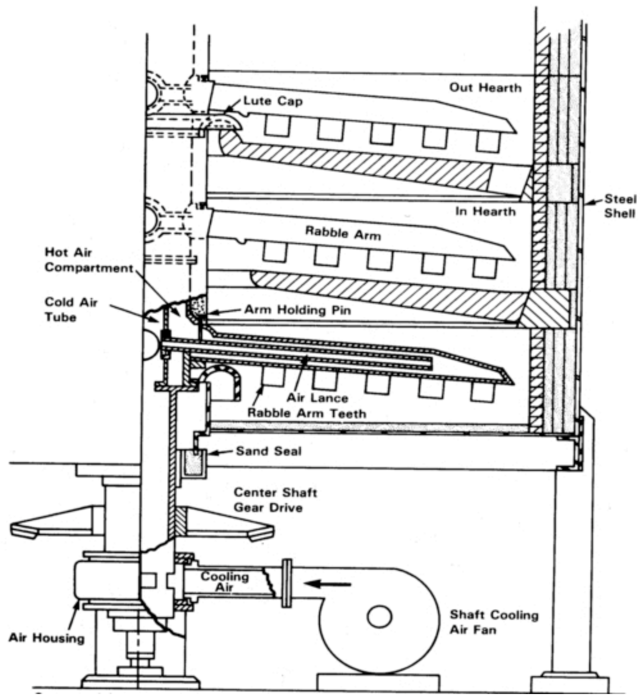

FIGURE 25 -INTERIOR VIEW OF A MULTIPLE HEARTH FURNANCE (FROM EPA SEMINAR, 1983)

Multiple hearth furnace incineration (MHF) is a simple and durable system that can burn more than one type of material with no effect from feed rate oscillations. It consists of a round steel shell surrounded by a series of solid hearths, which the sludge enters from the top and travels down their length by gravity while rotating rabble arms attached to a central rotating shaft assist it. The upper hearths are used for drying since the middle combustion zone emanates hot gases that travel upward through the wet sludge. The lower hearths are for cooling the ash since it is exposed to the cold air coming up the bottom and providing oxygen for the combustion processes (Vesilind *et al*, 1986). They can have from four to twelve hearths ranging in diameter from 50 inches to 20 feet (Culp, 1979).

Fluidized-bed incinerators were first used in 1962. It is composed of an upright cylindrical vessel that has lower grid that supports a sand bed. Dewatered sludge enters above the grid while combustion air flows upward with an average pressure of 4.3 psi. This fluidizes the combination of hot sand and sludge. The single chamber vessel maintains a temperature of 760 to 820ºC in the sand bed, with the combustion zone at the higher temperatures. Residence times are in the second ranges. The ash is carried upward with the combustion exhaust, and removed by air pollution control equipment. There is some save in reheating since the sand bed serves as a reservoir for heat (Culp, 1979). See figure 26 for a side view at fluidized bed incinerator. A unit that includes waste heat boilers, and air pre-heaters can improve the setup.

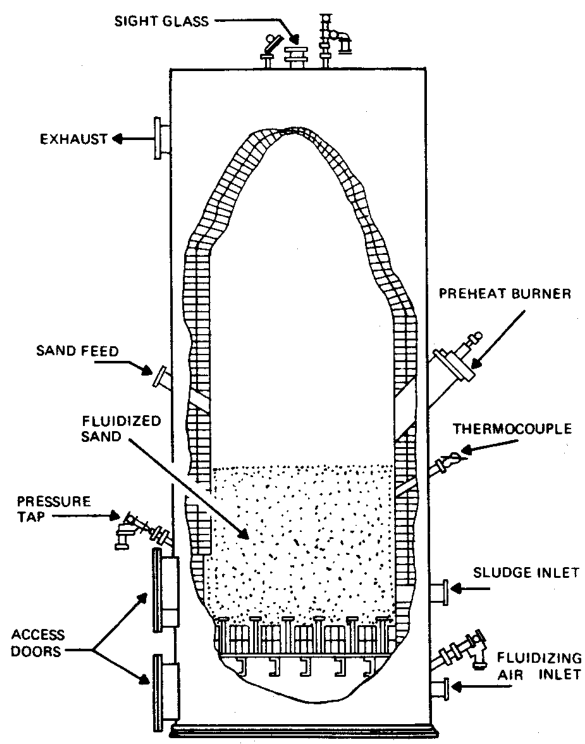

FIGURE 26- SKETCH OF A FLUIDIZED-BED INCINERATION (FROM VESILIND ET AL, 1986.)

Incinerators are usually part of a system that includes thickener methods, dewatering devices, and the incinerator equipment with air pollution controls. Advantages include maximum reduction of sludge solids, small land requirements, and complete pathogen destruction. Some disadvantages include higher costs than other methods, needed treatment for the flue gases, and other operational problems that may arise. Incinerator prices range between $3,000,000 and $6,000,000 for every eighteen dry metric tons of sludge per day combusted (Vesilind *et al*, 1986). They also have high operation and capital costs, although the fluidized bed model is a bit less expensive than the MHF system.

6.4 Case studies in Sludge Treatment and Disposal: Point Loma and Orange County

6.4.1 Point Loma

Point Loma is one of the most researched and documented chemically enhanced primary treatment (CEPT) plants in the US, and has been operating as such for 15 years. It is located on the Point Loma peninsula, west of central San Diego. It was originally built in the 1960's to improve the quality of the water in the San Diego Bay, and was operated as a conventional primary treatment. In 1985, the plant was retrofitted for CEPT in order to improve the total suspended solids (TSS) percent removal of 50% with conventional primary treatment. By using ferric chloride as a coagulant and an organic ionic polymer as a flocculant, they were able to improve the TSS percent removal to 85%. They had trouble initially convincing the government that chemically enhanced primary treatment was sufficient to provide effluent in accordance with the regulations. They finally won a waiver granted by the EPA from upgrading to secondary treatment. They are currently the only large US city treating their wastewater without secondary biological treatment (Morrissey and Harleman, 1992).

Point Loma treats approximately 190 million gallons of wastewater per day servicing about 2 million people. The plant is currently undergoing an upgrade to increase their capacity to 240 million gallons per day. It sends it sludge to the Metro Biosolids Center, where it is united with North City water recovery facility sludge. Both plants produce approximately 34,500 dry metric tons of sludge. Table 12 has average values for certain chemicals and other parameters monitored in the sludge at the Point Loma plant (City of San Diego, 1999). There are no troubling amounts of any chemicals considering the types of sludge disposals used at this plant, but if the sludge reused contains higher values than the average reported in table 12, it may not be safe both for human health and the environment according to EPA 40 CFR 503 regulations. See Appendix F for further information on their monthly concentrations.

Point Loma Wastewater Treatment Plant Average Chemical Values in their Sludge			
Parameter	**Average**	**MDL**	**Units**
pH	7.95		PH
Total Solids	29.6		WT%
Total Volatile Solids	55.5		WT%
Total Kjeldahl Nitrogen	4.58	0.1	WT%
Sulfide Total	38190	50	mg/kg
Sulfide Reactive	115.9	60	mg/kg
Cyanides Total	2.6	0.1	mg/kg
Aluminum	13120	11	mg/kg
Antimony	ND	50	mg/kg
Arsenic	5.65	0.64	mg/kg
Barium	468.2	0.5	mg/kg
Beryllium	ND	0.2	mg/kg
Cadmium	ND	5	mg/kg
Chromium	68.8	7	mg/kg
Cobalt	5.35	2.8	mg/kg
Copper	502.8	4	mg/kg
Iron	74630	6	mg/kg
Lead	39.9	29	mg/kg
Manganese	316.2	0.8	mg/kg
Mercury	1.1	6	mg/kg
Molybdenum	14.92	2.8	mg/kg
Nickel	44.3	4	mg/kg
Selenium	3.99	1.52	mg/kg
Silver	34.1	3	mg/kg
Thallium	ND	23	mg/kg
Vanadium	28.5	1.5	mg/kg
Zinc	754.7	50	mg/kg
Chlorinated hydrocarbons	27770	600	ng/kg
Phenols	85700	800	ug/kg
Base/Neutral Compounds	113420	330	ug/kg
Purgeable Compounds	25630	275	ug/kg

MDL=Method Detection Limit

Table 12 -Average Chemical Values in Point Loma Sludge
(adapted from Point Loma annual monitoring report, 1999)

6.4.1.1 Treatment

Sludge treatment at Point Loma consists of thickening, anaerobic digestion, and dewatering. Sludge is first thickened in the sedimentation tanks, and then pumped into the anaerobic, high, rate, mesophilic (temperature range from 27-41°C) digesters. This kind of process, through aggressive mixing and while operating at the optimum temperature of 35ºC, produces high degradation rates, which use the reactor volume most efficiently. This results in a homogenous sludge product. For the process to be most efficient, the sludge should not be pumped into the tank unless it's at least 8% solids. The methane produced in the process is used in two ways: some of it is flared and some is combusted to provide energy for the plant's boiler. Sludge is usually kept in the digesters for 15 days, which reduces the capacity to remove sludge from the plant. This can be improved upon by increasing the density of the sludge (City of San Diego, 1999).

The sludge is then pumped to the Metro Biosolids Center, were it is dewatered by centrifuging. The metro center has eight centrifuges it uses for both Point Loma and North City, which is the water reclamation plant in San Diego. Centrifuging appears to achieve a 32% solids concentration in the dewatered sludge at this center.

Centrifuge dewatering uses gravitational forces, and density differences to separate water from sludge solids. They come as disc, basket or solid bowl centrifuges, and the disc configuration is the most common. Solid bowl centrifuges can be found as countercurrent or concurrent, and either high or low speeds. The solid bowl centrifuge is composed of a solid walled bowl, which rotates at high speeds to produce accelerations of at least 4000 rpm in very short time frames (Vesilind et al, 1980.). Recent improvements have resulted in centrifuges that operate at 700 rpm, which results in lower power consumption and disruption of partly dewatered sludge already in the centrifuge (Culp, 1979). The sludge is pumped into the revolving bowl, where the solids move away from the rotating axes of the centrifuges due to density differences while the liquids move towards the center of the bowl. Two configurations of solid bowl centrifuges exist: co-current and counter-current. The co-current design has the solid and liquid portions traveling in the same direction with the liquid being separated either by an internal skimming tool, or by ports in the bowl. The counter-current design has the solid and liquid phases traveling in opposite directions, with the liquid brimming over weir plates. The liquid is usually sent to the head of the plant to undergo treatment again. Figure 27 shows a sketch of a counter-current centrifuge. The newest centrifuges can achieve solids concentration of approximately 30% in the sludge, an improvement of 8% over older models. This is proven by the results with this technique at the Metro Biosolids Center. One disadvantage of centrifuges is how vulnerable they are to grit abrasion, and their high cost of operation.

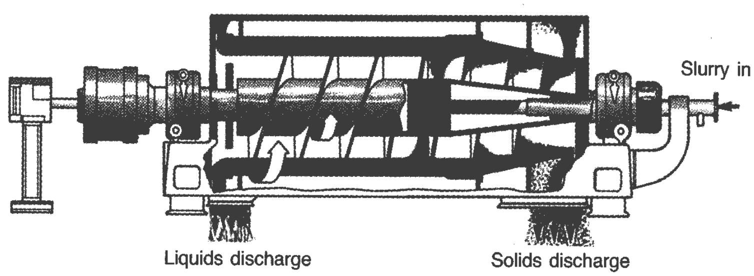

FIGURE 27-COUNTER-CURRENT CENTRIFUGE ASEEMBLY (FROM ARUNDEL, 2000)

6.4.1.2 Disposal

After the sludge has been dewatered at the Metro Center, it is hauled away for disposal. This sludge comes from both Point Loma and North City Point Loma sends it sludge to be land applied, or to landfills. See figure 28 for an idea of how much of each type of disposal is practiced. The places that reuse the sludge vary from year to year, but there are at least six places nearby that can land apply it. These are: in California, Proctor Valley, UC Research Center, BioGro Otay Ranch, BioGro Riverside, and San Diego County, and in Arizona, ECDC/AG Tech. In 1999, only 164.8 dry metric tons were reused by BioGro Otay Ranch. These tons were directly applied to fields in the San Diego County as Class B Biosolids. The other 34335 dry metric tons were disposed among three landfills, which are the Copper Mountain, the Miramar, and the Otay landfills. This last one took the majority of the sludge (City of San Diego, 1999).

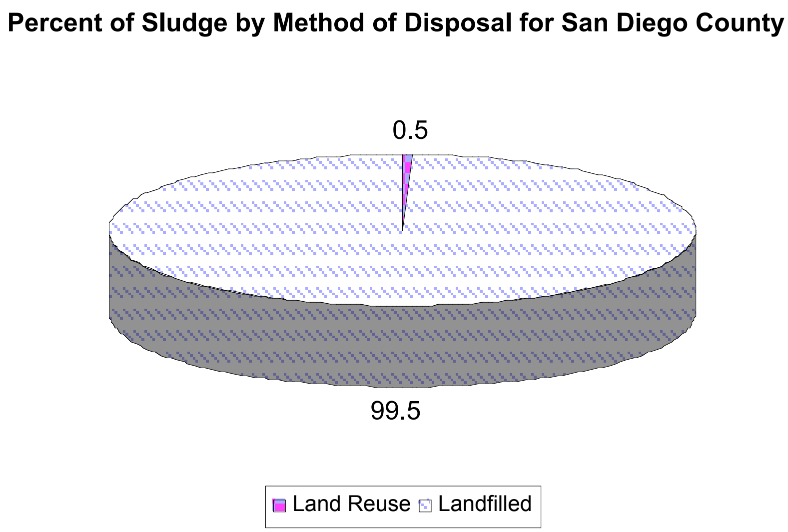

FIGURE 28-PERCENT OF SLUDGE BY METHOD OF DISPOSAL FOR SAN DIEGO (FROM CITY OF SAN DIEGO , 1999)

6.4.2 Orange County

Orange County Sanitation (OCS) district is located near the Los Angeles area in California and services 470 square miles and 2.1 million people. It operates two facilities, Fountain Valley and Huntington Beach, that work closely together to treat the 243 millions gallons of water from the area that passes through the plants every day. Both plants use CEPT treatment and then partial secondary treatment. The first plant uses trickling filters and conventional activated sludge to achieve secondary treatment, while the second plant only has pure oxygen activated sludge (OCSD, 2001). Orange County got a waiver from EPA, which allows it not to implement full secondary treatment by using flocculating chemicals in their primary and secondary treatments. These chemicals are ferric chloride at 20 mg/L and an anionic polymer at 0.15 mg/L, both added for 12 hours per day. They only treat 50% of their flow with secondary treatment. Orange County produces approximately 42,500 dry metric tons of sludge per year. Through their wastewater treatment processes using chemical, they have reduced the amount of activated sludge produced, which in turn has reduced the overall amount of sludge produced at the plant (Harleman, 2001).

6.4.2.1 Treatment

Orange County treats its sludge by thickening it, then anaerobically digesting it, and finally dewatering it. It uses dissolved air flotation (DAF) thickener. They have four DAFS for all the sludge produced by the secondary treatment from both plants. DAFs work by using compressed air to separate solids from water. As the air and water mix, solid particles are lifted to the surface by rising air bubbles in the tank. The floating solids are then collected by a series of tank skimmers while the water is recycled back to the head of the plant to be reprocessed. The solids formed in the DAF are pumped to the anaerobic digesters. DAFs tend to produce 5% solids concentrations (US Filter, 2001). Orange County uses four anaerobic digesters to break up their sludge from secondary treatment, and thirteen anaerobic digesters to deal with their CEPT sludge (Harleman, 2001). These digesters consume most of the volatile organics in the sludge, kill many pathogens, and stabilize the sludge as explained in section 6.3. The digesters must be kept at an average of 37°C, and the sludge is digested for an average of 25 days. Orange County recovers the methane gas produced during digestion, which they dry and compress to produce energy through their Central Power Generation system (OCSD, 2001). This consists of five generators between the two plants running at between 2500 and 3000 kW by using the digester gas (67% of the fuel) and natural gas (33% of the fuel) to produce electricity. The system produces about 300,000 kW/day, which is enough to power the plant and sell $400,000 of electricity per year to a utility (OCSD, 2001).

Once the sludge has been digested and reduced in volume on average by 45%, it is sent to be dewatered. There are nine belt filter presses at the Orange County plants, the same model used in Puerto Rico. Before being passed through the belts, small doses of an organic chemical are added to congeal the solids for easier dewatering. These produce a soft gelatinous cake that can achieve at most 25% solids concentrations in the sludge, which is great for their disposal methods (Harleman, 2001).

6.4.2.2 Disposal

Orange County disposes of its sludge by contracting out the composting of its biosolids or letting someone else use it for direct land application. They started doing this in 1971, and they even operated their own composting site for 2 years. At this time, they reuse 100% of its sludge. They use the following contractors: Wheel a-brator Clean Water System, Inc, Bio Gro Division, Pima Gro Systems, Inc, and Tule Ranch. The composting took place in Arizona, and the land application occurred in California.

6.4.3 Summary of Case Studies

Point Loma and Orange County both produce more sludge than all of Puerto Rico by 20% or more. Yet, they have good management programs in place, especially Orange County, since 100% of its sludge is reused by composting it or land applying it. This could be an alternative system that Puerto Rico could implement, maybe not at a 100% like Orange County, perhaps at 50%. This would have to be implemented at a smaller scale in PR because they do not have as much farmland as Orange County and the surrounding areas, and also because croplands are not all in the vicinity of the plants, which might cause transportation issues. Another aspects of this plants that Puerto Rico could apply at its plants is the harnessing of digester gasses to produce electricity. They could just use it as they do in Point Loma to provide energy for their boilers. They could also retrofit the plants to use the methane from the digesters combined with natural gas to produce electricity as Orange County does, and power the whole plant with this electricity.

6.5 Alternative Technologies for Sludge Treatment and Disposal in Puerto Rico

6.5.1 Treatment Technologies

One of the major reasons for the treatment of sludge is to eliminate or reduce pathogens to acceptable levels. Treatment methods include stabilization, digestion, and dewatering. Puerto Rico, as described in section 6.3, performs both digestion and dewatering. Puerto Rico digests anaerobically or aerobically depending on the plant, and uses sand drying beds or belt filter presses to dewater the sludge.

6.5.1.1 Stabilization and Conditioning Techniques

Conditioning is an integral and often necessary process associated with any reuse or disposal of wastewater solids. It is usually the first step performed on sludge and consists of changing its chemical and/or physical properties to allow the separation of the solid and liquid fractions. Conditioning can be performed by either chemical or physical methods. These methods include the addition of organic or inorganic chemicals, thermal treatment, freeze/thaw technique, and the addition of bulking material.

Chemical addition refers to the practice of putting chemicals in the sludge to cause the solids to flocculate (clump together). Among inorganic flocculants, one can mention ferric salts and lime. The method requires large additions of these chemicals to the sludge, which tend to increase the volume and weight of the sludge cake by 20 to 50%. They may also reduce the heat value of the biosolids, and could add metals to the final sludge product. They seem to increase the effectiveness of dewatering filter presses and vacuum filters. Organic flocculants are mostly polymers, usually cationic ones since sludge is negatively charged. They are effective at lower dosages, and do not have a significant effect on sludge cake quantities. Polymers appear to work better when they have been aged.

Thermal conditioning can be performed at either atmospheric or high pressure. The thermal conditioning at high pressure breaks the wall of microorganisms in the sludge, which allows the bound water to escape. This type of conditioning which changes the sludge’s physical properties transforms the sludge into a drier cake when compared to that produced by chemical conditioning. High-pressure thermal conditioning is usually followed by dewatering with vacuum filter. Thermal conditioning at atmospheric pressure implies that the solids are heated to 60°C at atmospheric pressure. This can increase the solids concentration by 6%, and decrease the needs for polymer addition by 25%. Unfortunately, the heating may increase the potential for odors if the sludge is cooled outside of a container.

6.5.1.2 Digestion Techniques

A different type of aerobic digestion from the one used in Puerto Rico is autothermal thermophilic aerobic digestion. It is performed under a temperature range of 40 to 80°C, which is also referred to as thermophilic conditions. Autothermal refers to the fact that no outside heat supply is required for this methodology. The heat released by organic decomposition can maintain the thermophilic operating temperatures of around 55°C in the reactor, if it is properly insulated. The configuration of the ATAD system consists usually of two stage procedures that incorporate mixing, aeration, and foam control apparatus. Single systems exist, but have less success at destroying pathogen. There are some key requirements for this system. First, the feed must be at approximately 5% solids with no less than 2.5% volatile suspended solids. Otherwise, there won't be enough solids to maintain thermophilic conditions. If the sludge has a solids concentration higher than 6%, adequate mixing or oxygen transfer may be impaired. Typical heat production ranges between 14,200 and 14-600 kJ per kg of $O_{2,}$ and the requirements for oxygen are 1.42 kg of O_2 per kg of volatile suspended solids. The thermophilic conditions prevent nitrification, and any associated oxygen demand. ATAD reactors are mostly shaped conically with flat bottoms. This means that if the grit is not removed by upstream processes in the plant, it can accumulate in the reactor, which may cause problems that may require retrofitting the reactor. The sludge is fed once per day as a batch, to achieve the 23 hours of undisturbed digestion that gives high pathogen destruction. Depending on design and equipment selection, aerobic digestion can have the following advantages over anaerobic: lower strength supernatant lowers the impact to treatment plant, resulting end product dewaters better, and the potential for odor and hazard from explosive gases is lowered. It has two big disadvantages: no methane production and continuous oxygen supply raises costs (Snow, 1996). This type of upgrade for Puerto Rico is probably not necessary since their conventional digesters appear to perform efficiently at this time.

6.5.1.3 Dewatering Techniques

Dewatering can sometimes be the only processing required before digested sludge can be beneficially reused. Common dewatering methods produce a sludge cake that is non-fluid, easily handled, and quite non-offensive. Besides the two dewatering techniques employed by Puerto Rico, there are various other methods that may be used. Dewatering tends to remove more water from the sludge than gravity thickening, plus it produces a greater reduction in volume. A reduction in volume translates into lower capital and operating costs to dispose of the sludge. As mention earlier, sludge possesses four phases of water. Free water is easily separated from the sludge by gravity. Capillary and colloidal water is usually removed after conditioning through mechanical methods. Intracellular water requires thermal treatment to be removed.

6.5.1.3.1 Natural Dewatering

Natural dewatering methods comprise sludge lagoons; sand drying beds; Wedgewagter drying beds; *Phragmites* reed beds, and freezing techniques. These techniques use less power and run usually on either the force of gravity, the power of the sun, or biological processes. Natural dewatering requires less energy than mechanical systems, and less attention from operators. Puerto Rico, as was mentioned, uses sand drying beds for dewatering at most of its plants, as well as sludge lagoons in a small number of the plants.

Wedgewater filter beds were developed in the 1970's in England. The filter beds were first fabricated out of a stainless steel medium called Wedgewire, but today they are mostly made out of high-density polyurethane because it is cheaper. The stainless steel beds are produced as mats at least 3 ft wide, by whatever length is needed, which are then laid over concrete floors on structural supports. The polyurethane beds comes as tiles with dimensions 12 by 12 by 2 inches high which are self supporting. They come with dovetail joints (male and female) to facilitate installation and removal (Outwater, 1994).

Wegdewaters work on the same principle as the sand drying beds, but its materials create a capillary action that drains the water faster. It has a loading capacity twice that of sand beds, at two dry pounds of solids per square foot. Their drying rate is also faster, with sludge reaching 15 to 20% solids in about 4 days under optimal conditions; compared to the sand beds, which take 4 weeks. Wedgewater beds also require 16 times less surface area than sand beds. To operate the filter beds successfully, they must be flooded to just above the middle surface prior to applying sludge treated with polymer. If the operator carefully controls the drainage rate initially, a hydraulic continuum will be created that speed up the flow of the water through the media. The result is a faster drainage than when sludge is applied to a dry or unsaturated surface. The beds are cleaned of the sludge with a tractor (Outwater, 1994). This method could be useful in Puerto Rico since it decreases area needed for operations, and reduces the time needed for dewatering compared to sand beds. It may not be worth the costs involved in installation, and operation, when compared to the benefits.

Sludge freezing is a relatively current addition to the natural dewatering techniques. Its effects have been known for at least the past 60 years, but until recently, no applicable design had been available. The process involves the freezing and thawing of sludge in cycles to turn it from a gelatinous material to a gritty material that easily drains. The freezing of the sludge changes its structural characteristics, by conglomerating the particles into large clumps surrounded by frozen water. When the thawing starts, the water drains off quite rapidly due to the large pores and channels created by the freezing. This means that the sludge can reach solids concentration of 20% under rapid drainage conditions, and concentration of approximately 60% solids can be reached with barely any additional drying time. Unfortunately, this method is not applicable to Puerto Rico where the temperature never drops below 40ºF, unless it could be done mechanically, and then the cost would probably outweigh the benefits of the system (Kukenberger, 1996).

Another recent technique for sludge dewatering is reed bed systems, which are a variation on submerged constructed wetlands. This system has been widely applied all over the world to various degrees. They are an improvement on the traditional design of sand drying beds. The process eliminates the removal of the dewatered sludge after each application, and instead requires the planting of reeds—*Phragmites communis*---in the sand. Sludge can then be applied for up to 10 years before the beds have to be emptied.

The beds can be of any shape to accommodate existing land conditions and areas. The reed beds are usually constructed by laying a 40-mil plastic liner into the shape desired and covering it with a 10-inch bottom layer of stones that are approximately 1-in in diameter. There is also a middle layer of pea gravel about 4 to 5 inches thick, and another layer on top of that one which is sand stacked 6 inches thick, where the reeds are planted. Liquid sludge, after being treated, is applied to the reed bed with a metered system of gravity fed pipes and troughs, at a solids concentration ranging from 2 to 7%. When fully loaded, the bed should have about four inches of liquid on its surface, which then drains down into the pipe system to be returned to the start of the wastewater plant (Outwater, 1994).

The *Phragmite*s reeds are well suited for the drying bed process. They have root systems that grow vertically only until the pea gravel layer, thus they don't interfere with water drainage. They have nodes in their roots that can survive sludge contaminants, and that sustain microflora, which live off the organic matter in sludge. The root system grows horizontally through the sludge, using the water as it does this, and draining water from the sludge by providing channels through which it can run down into pipe system. Eventually, the sludge is reduced to 97% solids (Outwater, 1994).

Unfortunately, this system does not fare as well in southern regions since the reeds need a dormant period for winter root growth. Thus, the system as is would not work in Puerto Rico, unless an alternate reed plant that had a similar efficiency to *Phragmites* reeds and needed no dormant period could be used. Also, large treatment plants that process more than 5 million gallons of wastewater a year may not want to implement this type of dewatering system due to cost and logistic considerations (Outwater,1994). See figure 29 for a sketch of the beds.

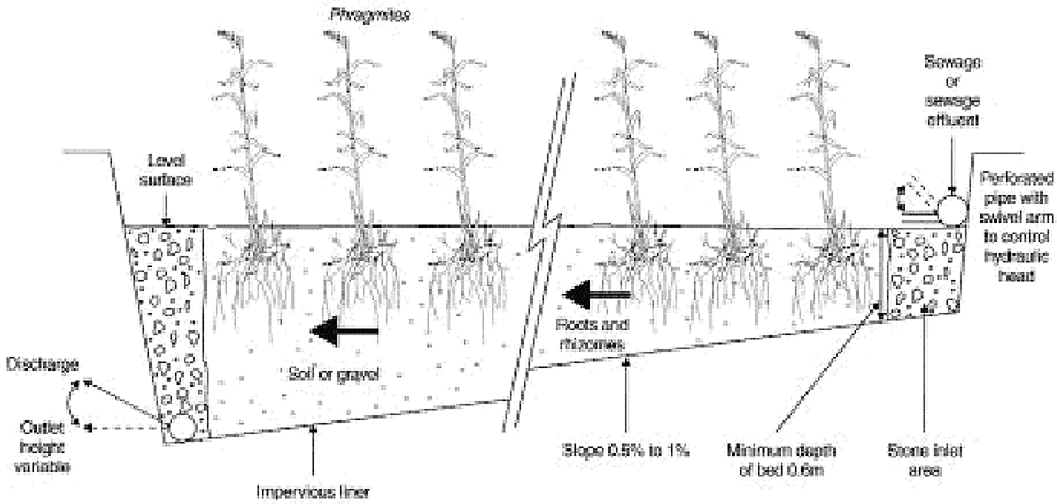

FIGURE 29-SKETCH OF REED DRYING BEDS (FROM DEPARTMENT OF TRANSPORT, 1997)

6.5.1.2.2 Mechanical Dewatering

Sludge must be conditioned before it can undergo mechanical dewatering; which eases the separation of the solids from the water. Types of mechanical dewatering techniques that can then be applied include vacuum filters, belt filters presses, rotary presses, pressure filters, and centrifuges. Puerto Rico employs belt filter presses at some of the wastewater treatment plants as mentioned in section 6.3. The methods described below have both advantages and disadvantages over the belt filters, which are worth investigating in terms of economics and benefits, but that is outside of the scope of this thesis.

Vacuum filters are the most common mechanical dewatering devices being used today. Typically, it consists of a large horizontal drum rotating while partially submerged in a basin of wet and unfiltered sludge. To support the dewatering sludge, the surface of the drum is overlaid with a filter medium composed of a mixture. The drum is divided into sections that extend the length of the drum, and each section is placed under vacuum by automatic rotary valving. When a section rotates through the basin, a vacuum is applied, which causes a layer of sludge to form on the filter medium. Continuous drainage of moisture from the layer of sludge can occur by maintaining the vacuum on the section as it leaves the basin. Drainage continues until the section is about to reenter the basin, at which point the sludge cake is removed from the filter mechanically. One method of removal is a fixed scraper blade, which can be seen as part of a sketch of a rotary drum vacuum filter in figure 30. To assist in cake removal, air blowback is sometimes done just before the section reaches the scraper. Sludge that has been conditioned with organic and inorganic chemicals as wells as thermally conditioned can all be successfully dewatered by this method. One major disadvantage of this system is the delays caused by shutdowns when the filter medium needs to be washed since the sludge tends to cover it and prevent filtration (Krukenberger, 1996).

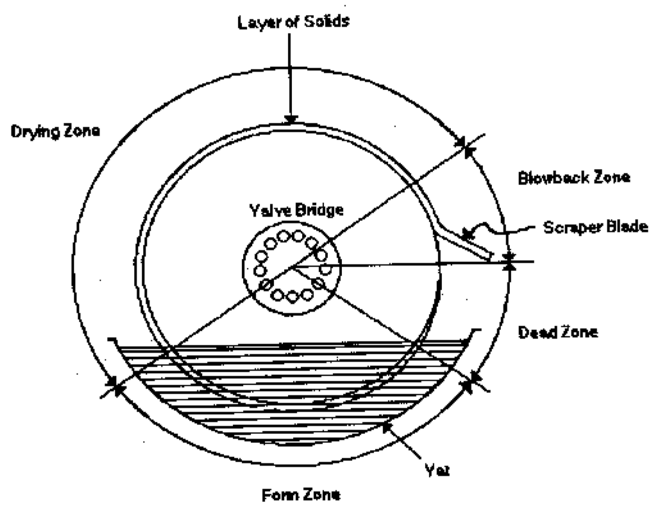

FIGURE 30-ROTARY DRUM VACUUM FILTER CYCLE (FROM OUTWATER, 1994)

Rotary presses are a recent development in dewatering techniques. The press is composed of a peripheral channel with walls consisting of rotating filter parts. The sludge is pumped into this channel, where it experiences compression created by the rotation of the machine, which forces the liquid through the pores of the filter. The cake, which is formed in the interior channel, gets extracted. See figure 31 for schematics. The press functions as a continuous dewatering mechanism, and it requires supplementary equipment similar to belt-filter presses and centrifuges. To use rotary presses for dewatering, the sludge must undergo polymer conditioning. The device, which takes up little space, can be installed in various sizes (Krukenberger, 1996).

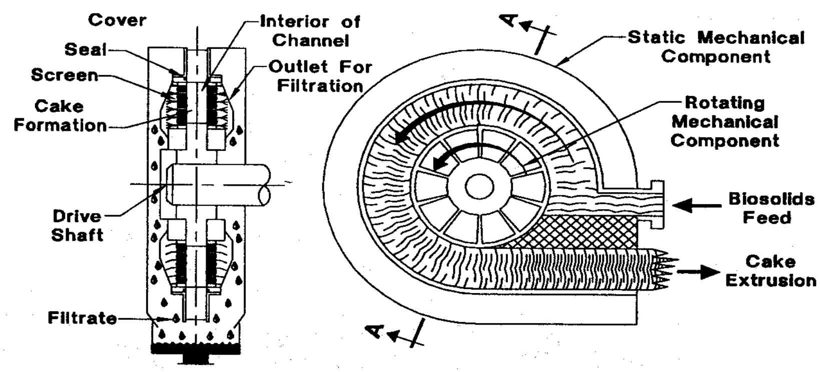

FIGURE 31-ROTARY PRESS, SIDE VIEW AND CROSS SECTION SHOWN (FROM KRUKENBERGER, 1996.)

Pressure filters, which are also called plate and frame presses, are composed of recessed plate presses that may be either fixed or variable volume apparatus. They are run as batch processes, and auxiliary equipment includes storage and batch tank to kept the sludge at a volume that allows it to be fed to the press. At large plants, more than one press can be used to keep storage at a minimum amount. This type of dewatering can achieve a solids concentration of more than 40% in sludge (Culp, 1979). The sludge should usually be conditioned with both lime and ferric chloride. Polymer conditioning works with this type of dewatering only sometimes. The benefits of using polymers, which include lower metal content in the sludge, and lower costs, may offset this lower efficacy. The plates filters are aligned horizontally to allow release by gravity of the cake sludge into a receiving bin or conveyor. The plates reside on a fixed frame, which keeps the plates in position during the dewatering process. In fixed volumes presses, the biosolids are pumped into the plates for a set period of time during which the pressure increases continually and thus pushes the liquid through a filter cloth. The time period needed is indicated by how long the sludge filtrates in the chambers. Variable volume presses contain a diaphragm after the cloth media. In this system, the recessed chambers are filled with sludge, and then air or water is pumped into the diaphragm, creating pressure in the chamber. The liquid then is also forced through the cloth. This type of pressure press can achieve a higher pressure, while reducing cycles, and giving more consistent dewatering results (Kukenberger, 1996). See figure 32 for the schematics of a pressure filter.

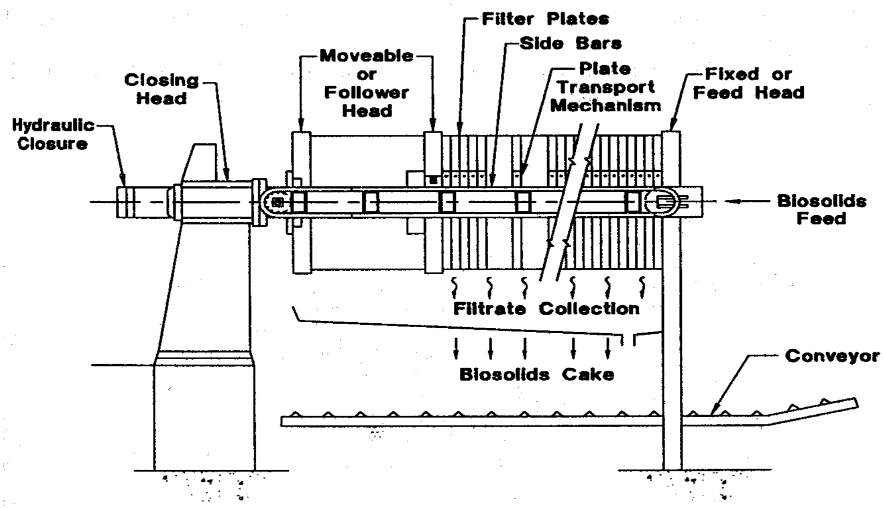

FIGURE 32-PRESSURE FILTER (FROM KUKENBERGER, 1996)

6.5.2 Disposal technologies

Disposal options are becoming more limited every day due to lack of space for land disposal, stricter regulations, and public disapproval. The more common options include landfilling, incineration, land application, and composting. There have been recent studies performed into turning sludge into or construction materials. As mentioned in section 6.3, Puerto Rico landfills, composts, land applies, and may soon incinerate its sludge.

6.5.2.1 Land Application

Organic matter in soils tends to determine the productivity of the soils, even though it only occupies the top 10 inches of the soil. Sludge application can improve the conditions and nutrient contents of the soil, and thus create a more favorable environment for growing vegetation and preventing erosion. Sludge also tends to improve soil characteristics like water retention and drainage, soil weight, and soil texture. Sludge is applied on land for various reasons. It is a good alternative to using fertilizes because it increases the yield of the soils while being less expensive than fertilizers. It also tends to retain nutrients in the soil better than fertilizers, and thus minimizes the leaching of pollutants like nitrates into the water table. Benefits of land application include a reduction of the adverse health effects of incineration, a reduction of emission associated with incineration that contribute to the greenhouse effect, and a decrease in the dependence on chemical fertilizers. Problems with land application of sludge arise if the EPA 40 CFR part 503 regulations are not met. Sludge must be treated in order to be eligible for land application. The most common hurdle to overcome is the presence of high levels of heavy metals. If a good monitoring system is in place, the sludge should pose no problem for both human health and the environment.

The most common application is to croplands, in order to improve their yields. It is basically used in place of fertilizers, and the sludge tends to work as well if not better than the chemicals. The nutrients in sludge tend to be in a water insoluble form, which means the nutrients are available to plants over longer periods of time. This also prevents leaching as was earlier mentioned. Sludge improves crop yield substantially, even by 20%. When used for agriculture, it can be difficult and costly to deliver the sludge to the rural areas where the farms are located, and one may not be able to apply the sludge if the crops are on the fields (Outwater, 1994). Puerto Rico has about 9% arable land, which includes permanent cropland (CIA, 2000). Applying sludge on lands that use fertilizers could improve crop yields and reduce surface water and groundwater contamination by nitrates and phosphorus.

Sludge can also be applied to forests in order to increase forest productivity, and to revegetate and stabilize harvested forestland. Forests are a good place for sludge application because they have fewer residents than farmlands and most forest products are not food chain crops, thus public health concerns and regulations tend to be less restrictive for these sites. Forests possess perennial root systems that allows year round uptake of nutrients from sludge, and permit yearlong sludge applications in temperate climates. Their soils tend to be well suited to sludge application because they have high rates of infiltration to reduce ponding and runoff. Studies seem to indicate that trees planted on sludge-amended land grow twice as fast, which improves economics of silviculture. Puerto Rico appears to have been involved in a sludge forest application project during the last 25 years, but it is not clear whether they are still running experiments on this type of land application (Nichols, 1989). Puerto Rico can be classified as 16% forests land, thus this technique for sludge disposal should be explored, especially in forests that are harvested for wood, or have water retention problems (CIA, 2000).

Land reclamation refers to the practice of turning unusable areas of land into productive properties by adding nutrients and organic matter to the soil. In the past, this practice has been carried out using fertilizer, soil conditioners, and/or topsoil covers. The types of places that can be reclaimed include collieries, eroded sand –dunes, and past mining areas. This is not highly applicable to Puerto Rico since there is no real mining in Puerto Rico, and there is great opposition to any mining happening in the future (Byrom and Bradshaw, 1989).

6.5.2.2 Energy Sources

The fact that sludge is mostly composed of organic matter gives it a potential fuel value. Its heat content tends to be around 5,500 kcal/kg of dry volatile solids, or 2, 500 to 3,000 kcal/kg of total dry matter. If we compare it to coal, which has a fuel value of 7,750 kcal/kg, one understands how much potential energy there is untapped in biosolids (Outwater, 1994).

6.5.2.2.1 Sludge to oil

German researchers discovered during the 1930's that heating biomass and treating it with alkali produced a scorched substance they labeled "artificial coal" (Outwater, 1994). Scientists from an Ohio based Battelle research facility decided in the 1980's to focus on the German research using sludge as the feedstock. Their research was funded by the EPA, the Department of Energy, and a Japanese company, and resulted in a process called sludge to oil reactor system, or STORS.

The STORS process consist of taking wet sludge at 4% solids, centrifuging it to 20% solids, and the adding about 5% of a sodium carbonate alkali as a catalyst to assist molecular rearrangement. This organic mixture is then pumped into a thermochemical reactor. Here it is heated to 300°C, and maintained under its own steam pressure (about 2000 psi) for less than 1 hour. This causes the carbon to release the oxygen, which rearranges the hydrogen and carbon molecules to form hydrocarbons. Once this process is complete, the product is decanted into letdown vessels so that the sludge can cool and separate into four components. These components are: wastewater, a sludgy char made up of organic matter used as a fuel to heat the reactor, an off-gas that is 90% carbon dioxide, and an odoriferous black oil that resembles car oil after being used for 3,000 miles, which floats on top of the water. This oil possesses 80 to 90% the heating value of diesel fuel and is not heavily contaminated (Outwater ,1994).

The characteristics of this oil are not all good. It has the unfortunate property of being a thick black gunk that is difficult to pump through feed lines, and has a smell very similar to that of sludge. This can be fixed by adding an addictive that cuts its viscosity and masks the smell. After this process is finished, the oil looks and pours like diesel fuel # 4. If it is furthered deodorized, the oil can be used in ship and industrial boilers, and it can even be distilled and upgraded for car use. The patent of the STORS process is owned and controlled by ThermoEnergy Corporation of Little Rock, AR .

STORS has several attractive attributes including the enormous reduction it effects on sludge volume. If a sludge possessing 20 % solids is used as feed, 500 tons of sludge are turned into 30 tons of ash, which reduces the volume of residuals to be disposed (Outwater, 1994). Another attractive feature of this process is that the energy it requires to extract oil from sludge is only one third of the energy value of the products. This sets STORS apart from the other sludge to oil developers. This favorable energy balance can be attributed to in part to using a wet feedstock, and in part to the spontaneous separation of the products.

Another process that turns sludge into oil is called oil from sludge or OFS. It is different from STORS in various ways. First, it uses dried sludge pellets as the feed for the procedure instead of dewatered sludge. Second, OFS is a low temperature-atmospheric pressure process compared to STORS's high temperature-high pressure method. They are similar in that both use technology that thermally converts the volatile organic matter in sludge to a liquid fuel composed essentially of straight chain alkanes and alkenes. This makes the fuel very similar to diesel fuel by composition.

The oil from sludge process was developed by German researchers at Tubingen University at around the same time the STORS process was created, as described in the above section (Outwater, 1994). It appears that catalyzed vapor-phase reactions convert the lipids and proteins in sludge into hydrocarbons forming straight chains. The product tends to be mostly alkanes, but all pyrolysis processes produce some amounts of cyclic and aromatic compounds, independent of what substrate is used. The process, when used with sludge, seems to be catalyzed by the aluminosilicates and heavy metals present in the biosolids, which provides a “solution” to the problem of sludge contamination.

The OFS process starts with sludge that has been dried to 95% solids, and heats it anaerobically for 30 minutes to 350°C at mainly atmospheric pressure. This first steps vaporizes 40 to 50% of the sludge. These vapors are then sent to a second stage in the reactor, where they are exposed to the char, or residue of the sludge. There the organics are turned into straight-chain hydrocarbons (the main ingredient of crude oil) by catalyzed vapor-phase reactions. OFS’s main products are char, a noncombustible gas, reaction water, and on average 230 liters of oil per ton of sludge used. The by-products---char, gas, and oil---are combusted to produce enough energy to dry the sludge and heat the reactor (Outwater, 1994).

The type of sludge used in the OFS process has an impact on the amount and type of oil that’s produced. If raw sludge is used, the oil yield tends to be greater, and the oil has a higher viscosity than if one utilizes digested sludge. Energy conversion efficiencies of 95% and higher are common. The residuals from this type of technology tend to be relatively benign since heavy metals are trapped in the ash, pathogens are destroyed, and air emissions are minimal and controlled.

6.5.2.2.2 Sludge to Energy

Hyperion energy recovery system (HERS) was developed at the Los Angeles Hyperion treatment plant when they had to stop their ocean dumping of sludge (illegal since 1992) by 1985 due to a court order. It involves an advanced sludge incineration process that uses sludge as a fuel and generates more energy than it uses, and all this takes place on site at the plant. The system was completed in 1987 (Outwater, 1994).

The process removes every kilowatt possible from the sludge. Its average power production so far is 20 MW. Most of this energy is used to power the plant, while any excess is sold to a local utility plant.

The sludge that is used in the HERS process must be dehydrated. It was initially just centrifuged to a solids content of 20-to 22% solids, but now they use the Carver-Greenfield multiple effect evaporation process with turns sludge into pellets with 99% solids content. During this process, dewatered sludge is placed inside a series of chambers, where heat is applied, which drives off the water as vapor. This heat from the water vapor is then applied to the next chamber in the series, and consequently more water vapor is produced. When the sludge has passed through all four chambers, it has been dewatered in a very efficient manner.

The electricity generated by HERS is mainly produced in four gas turbines, which are run by digester gas and by two turbines, which are run by steam. The heat generated by the gas turbines in the process of making electricity is fed to generators that produce steam, which is fed to the steam turbines. This uses a by-product (heat) that would normally go to waste. This “cogeneration” tends to double the net generation of electricity (Outwater,1994). HERS also has the advantage of lowering emissions from the treatment plant, through technology like internal combustion engines, scrubbers, and bag houses, among other methods.

6.5.2.3 Construction Materials

The use of sludge in manufacturing ceramic products, and other construction materials dates back to 1889 and a man named Thomas Shaw, who had a patent for such a process (Outwater, 1994.). It most recent revival happened in 1982 when the Maryland Clay Products, Ins, used 20 tons sludge to produce 35,000 bricks. Japan uses thermal melting to turn 100 percent sludge ash into bricks.

The process in Japan for turning ash into bricks uses high pressure molding (98 MPa) of the ash and then fires up the molds in a roller hearth kiln using natural gas. The temperature reaches 1000 °C and stay there for an hour to assure complete oxidation of organic matter. Then, the bricks are cooled to room temperature, which takes four hours in order to inhibit breaking of the bricks from thermal strain. No heavy metals leach out of the bricks even under highly acidic conditions. A fluidized bed incinerator works well for this process since a fine ash is needed to prevent cracking of the bricks. In addition, organic matter, and moisture should be low in the ash to again prevent cracking during firing process. Lime conditioning of sludge is undesirable if this method for ash disposal is going to be used since it causes hair cracks in final product (Okuno et al. 1997). End products from this process are widely accepted for public works such as pedestrian walkways. This could be an interesting application for the ash that Puerto Rico will produce once it starts incinerating some of its sludge again. Puerto Rico has many development projects that could use these sludge bricks, and the municipalities could employ them in public works.

6.6 Recommendations

Puerto Rico does not have a significant sludge problem at this time. However, as Puerto Rico improves the efficiency of its wastewater treatment, the amount of sludge produced by its 67 plants will increase considerably. This will be added to by a growing population, and by increased development projects on the island. A passive attitude to this problem will result in increased costs, and ineffective solutions. In order to safeguard against a considerable sludge management problem in the future, a proactive approach needs to be implemented while there is time to study different alternatives, and find the best solution for Puerto Rico's sludge management. Sludge management consists of two steps: treatment and disposal, and the recommendations are divided as such.

Currently, Puerto Rico treats its sludge primarily through digestion and then dewatering. Digestion can be either an aerobic or an anaerobic process. It would be to Puerto Rico's benefit to try to harness the digester gas produced in anaerobic digesters in order to produce energy as is done by Orange County. They could use this energy to run their plants, and sell any excess power to local utilities. Dewatering methods are mainly sand drying beds and belt filter presses. The sand drying beds are slightly old methods that could be improved upon with slight alterations. One such alteration could be applying the reed bed system to existing sand beds in Puerto Rico. This would entail finding a similar reed to *Phragmites communis* that does not need a dormancy period. This could result in a low cost, low maintenance system that could improve their dewatering efficiency compared to existing sand beds and cut on their handling costs since the sludge can remain on the beds for at least seven years. If they prefer to stop using natural dewatering, they can just employ belt-filter presses at all their plants, since they have upgraded some plants with this and have some experience with it. They may want to investigate some of the other mechanical methods like the centrifuges used by Point Loma on their sludge.

Presently, Puerto Rico employs three disposal methods, with a fourth one available in the near future. These methods are landfilling, composting, land application, and incineration. The major sludge disposal method used by Puerto Rico is landfilling, which will soon stop being a practical option since more than half the landfills in Puerto Rico will close by 2005. This means the other three methods are going to have to expand their operations to handle the sludge now landfilled. Composting requires space, but produces a marketable product that is publicly well accepted. This makes it an attractive option for disposal, and should definitely be explored at other facilities besides the one in Arecibo. Puerto Rico might want to invest in storage basins that can keep the sludge at the plant until the composting facility can accept it. Land application should definitely be considered and further studied, especially in places were soil conditions are not favorable to agriculture. Incineration is an expensive option that should be expanded carefully considering the many strict environmental regulations that apply to it and that these will probably become prohibitive in the future. Puerto Rico could make incineration more attractive by retrofitting their new incinerators with technology to harness the energy from its heat and emission gases. This is similar to the process that harnesses digester gases to produce electricity. They may also want to consider employing the ash that results from incineration into making bricks or tiles, which can then be applied towards public works and construction.

Puerto Rico is undergoing some major changes to its wastewater treatment infrastructure. The island is also expanding in population and development. This indicates a future growth in the amount of sludge the island will have to manage. Sludge management is a difficult and costly task that can be made easier by upgrading to newer technologies. By improving the treatment of sludge, one can reduce its volume, and make it an easier product to handle and dispose of. Disposal methods can safely dispose of sludge in manners that safeguard both human health and the environment if performed correctly. Sludge may also be used to produce various serviceable products. Puerto Rico does not have to fall into the traps of costly sludge problems if it invests the time and energy today to find the best solutions for tomorrow.

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Appendix A – MSDS

AguaKem

PAX-XL19

Aluminum Chlorohydrate

*AguaKem PAX-XL19 is a high performance liquid Aluminum Chlorohydrate coagulant that generally offers superior clarification in either potable or waste water. The aluminum in PAX-XL19 is highly charged, enabling less of it to do more. Advantages available to many end users are **Reduced Sludge, Minimized pH Adjustment, Longer Filter Runs, Superior Finished Water Quality, and Optimized Cold Water Performance**. PAX-XL19 is especially designed to achieve extremely high levels of turbidity removal.*

PRODUCT SPECIFICATION

Appearance	Clear Liquid
Aluminum (Al)	12.4 ± 0.3%
Aluminum Chlorohydrate	50% Solution
Al_2O_3	23.5 ± 0.5%
Iron (Fe)	< 0.03%
Specific Gravity (25°C)	1.34 ± 0.02
pH	4.2 ± 0.2
Basicity	80 ± 3%
Active Material	4.59 moles/kg
Freezing Point	-5° C / 23° F

METALS ANALYSIS - Typical

METAL	SYM.	LEVEL
Antimony	Sb	< 0.5 mg/kg
Arsenic	As	< 0.1 mg/kg
Cadmium	Cd	< 2 mg/kg
Copper	Cu	< 2 mg/kg
Chromium	Cr	< 1 mg/kg
Lead	Pb	< 2 mg/kg
Manganese	Mn	< 2 mg/kg
Mercury	Hg	< 0.05 mg/kg
Nickel	Ni	< 1 mg/kg
Selenium	Se	< 0.1 mg/kg
Silver	Ag	< 1 mg/kg
Zinc	Zn	< 15 mg/kg

CUSTOMER SERVICE

AguaKem **787 841-6669**

CERTIFICATION / APPROVAL

PAX-XL19 meets or exceeds all **AWWA** standards for Aluminum Chlorohydrate. PAX-XL19 is **ANSI/NSF Standard 60** certified for use in potable water treatment up to 250 mg/l.

DOSING

PAX-XL19 should be fed straight without dilution. A diaphragm metering pump of non-corrosive material is suitable.

STORAGE

Storage tanks and piping should be constructed of suitable non corrosive material such as fiberglass or cross linked polyethylene. PAX-XL19 is mildly corrosive and will attack most metals over a period of time. PAX-XL19 has a recommended shelf life of 8 months. As with any chemical, it is recommended to clean the storage tank every 1-2 years.

HANDLING / SAFETY

The handling of any chemical requires care. Anyone responsible for using or handling PAX-XL19 should familiarize themselves with the full safety precautions outlined in our Material Safety Data Sheet.

DELIVERY

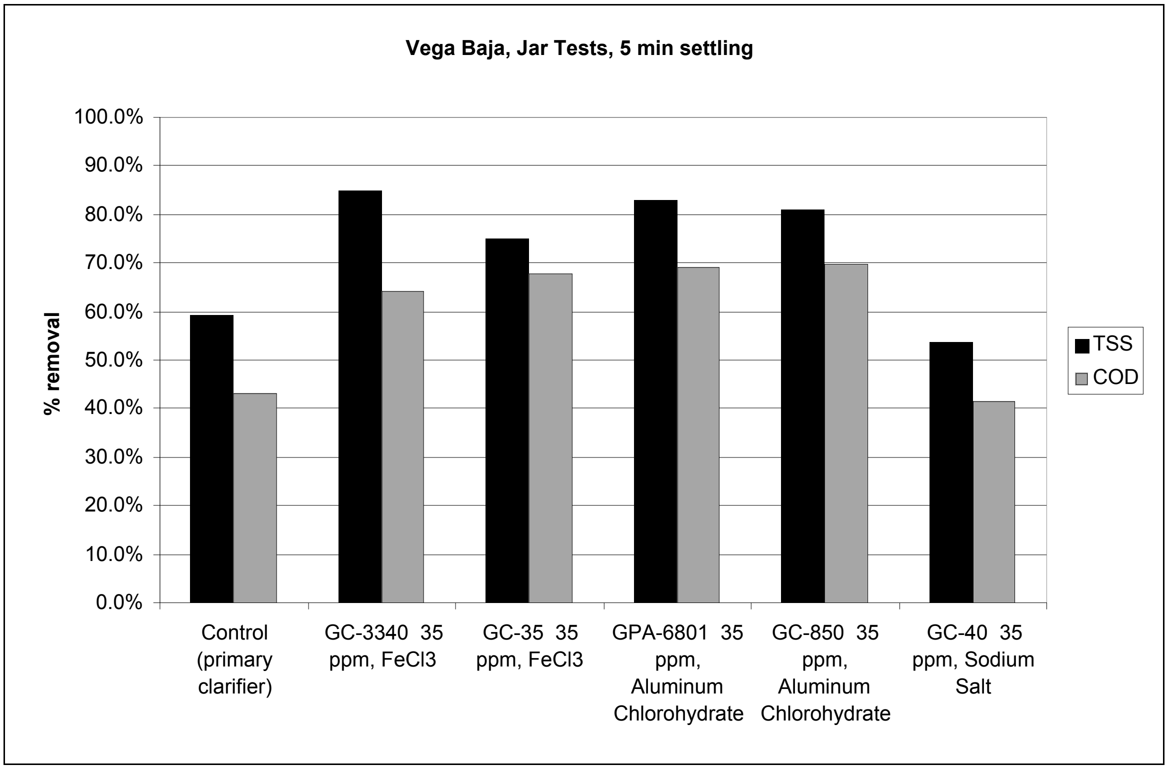
55 gal. plastic drums / 300 gal. tote bin
Bulk tank trucks, Rail Car
Corrosive Liquid, Acidic, Inorganic, n.o.s.
8, UN 3264, P.G. II

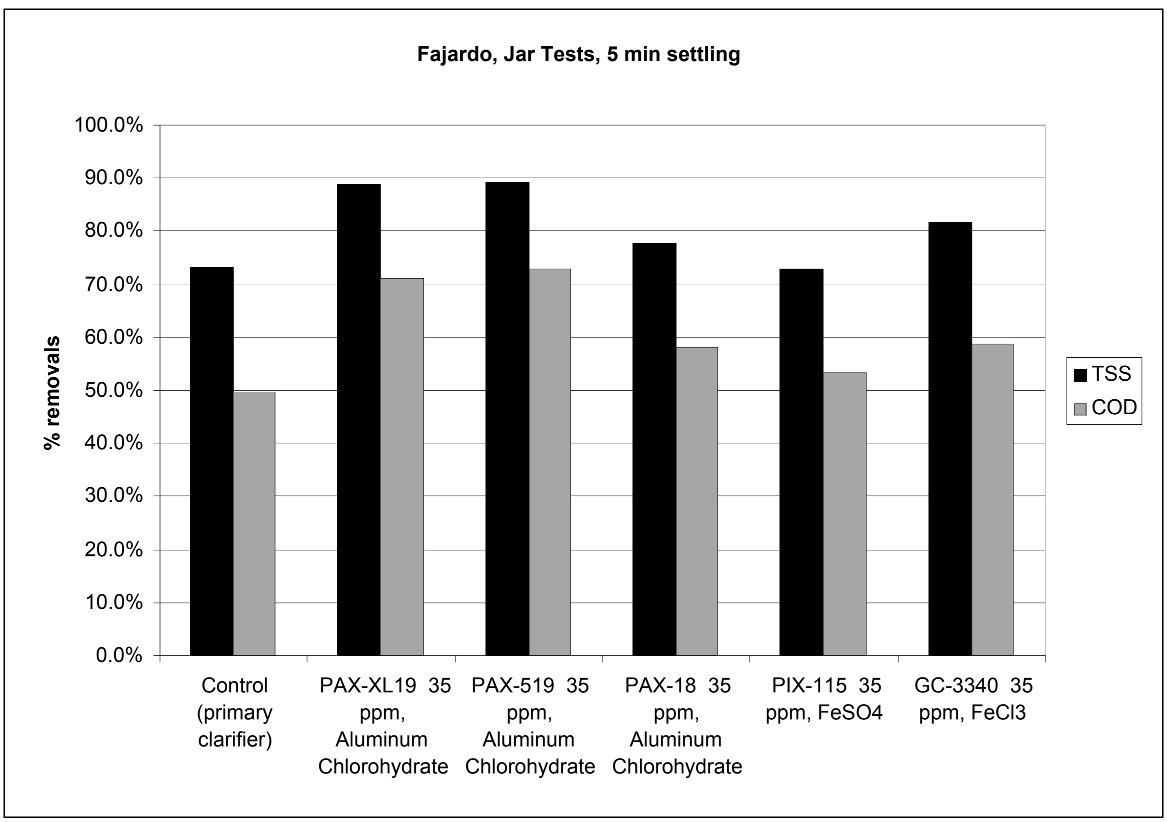
PRODUCTION

Coagulant production plants world-wide

AguaKem - **P.O. Box 177, Mercedita, PR 00715 - Phone: 787 841-6669 - Fax: 787 841-6662**

Appendix B – Chemical selection jar test results





Appendix C- Calculations of Puerto Rico Sludge Data for 1999

Appendix D- EPA 40 CFR Part 503 regulations: regulated chemicals and their limits

Table A-1: Ceiling Concentration for Pollutants in Sludge	
Pollutant	**Ceiling Concentration (mg/kg)[1]**
Arsenic	75
Cadmium	85
Copper	4300
Lead	840
Mercury	57
Molybdenum	75
Nickel	420
Selenium	100
Zinc	7500

[1] Dry Weight Basis

Table A-2: Cumulative Pollutant Loading Rate	
Pollutant	**Cumulative Pollutant Loading Rate (kg/hectare)**
Arsenic	**41**
Cadmium	**39**
Copper	**1500**
Lead	**300**
Mercury	**17**
Nickel	**420**
Selenium	**100**
Zinc	**2800**

Table A-3: Pollutant Concentration

Pollutant	Monthly Average Concentration (mg/kg)[1]
Arsenic	41
Cadmium	39
Copper	1500
Lead	300
Mercury	17
Nickel	420
Selenium	100
Zinc	2800

1 Dry Weight Basis

Table A-4: Annual Pollutant Loading Rates

Pollutant	Monthly Average Concentration (kg/hectare/365 day period)
Arsenic	2.0
Cadmium	1.9
Copper	75
Lead	15
Mercury	0.85
Nickel	21
Selenium	5.0
Zinc	140

Appendix E-Table of pathogenic organisms and potential diseases

Bacteria and Actinomycetes		
Organism	**Disease**	**Mode of Transmission Comments**
Coliform Species	• Internal Infections • Gastroenteritis • Diarrhea	Contaminated food and water
Vibrio cholera	• Cholera	Contaminated water, food
Salmonella species	• Salmonellosis	Food and water Common in biosolids
Salmonella typhi	• Typhoid fever	Water Found in biosolids
Shigella	• Shigellosis (bacillary dysentery)	Polluted water
Bacillus Anthracis	• Anthrax	Disease of animals, rare in humans
Brucella	• Brucellosis	Infected milk or meat Found in biosolids
Mycyobacterium tuberculosis	• Tuberculosis	Found in biosolids
Leptospira interohaemorrhagiae	• Leptospirosis	Contaminated food and drink Found in biosolids
Yersinia entercolitica	• Gastroenteritis	Contaminated food and water
Esherichia coli (usually nonpathogenic)	• Gastroenteritis	Contaminated water and food Common in biosolids
Clostridium tetani	• Tetanus	Wound contact Found in biosolids
Nocardia spp.	• Lung disease (nocardiosis)	Inhalation and contact with skin Found in biosolids
Actinomycates israelii	• Actinomycosis (meningitis, endocarditis, genital infections)	Inhalation and contact with skin Found in biosolids
Camphlobacter spp.	• Acute enteritis	Contaminated food and drink Found in biosolids

Protozoa		
Organism	**Disease**	**Mode of Transmission Comments**
Entamoeba histolitica	• Amoebic dysentery	In untreated biosolids used as a fertilizer, resistant to disinfection
Giardia lamblia	• Giardiosis	Cysts are not destroyed by disinfection Found in biosolids
Criptosporidium	• Gastroenteritis	Found in biosolids
Balantidium coli	• Dysentery	Found in biosolids
Isospora belli	• Isosporosis	Digestion of viable cysts

Enteric Viruses		
Organism	**Disease**	**Mode of Transmission Comments**
Polio Virus	• Poliomyelitis	Found in biosolids Polio vaccine eliminates disease
Virus	• Hepatitis A	Found in biosolids
Coxsackievirus, echovirus	• Mild infections • Meningitis • Diarrhea in infants • Heart disease • Conjunctivitis	Inhalation, water Found in biosolids
Adenovirus, reovirus	• Respiratory infections • Influenza • Colds • Bronchitis • Diarrhea	Inhalation, water Found in biosolids
Rotavirus, calicivirus	• Viral gastroenteritis	Inhalation, water

Helminths & Nematodes

Organism	Disease	Mode of Transmission Comments
Ascaris lumbricoides; ascaris suum	• Ascariasis (large intestinal roundworm) • Abdominal pain • Digestive disturbances • Fever • Chest Pain	Ingestion of eggs in food or drink Found in biosolids wet and dry Most common of helminth
Ancyclostoma duodenale, Necator americanus	• Hookworm • Abdominal pain • Digestive disturbances	Ingestion of eggs Found in biosolids
Enterobius vermicularis	• Pinworm (enterobiasis)	Ingestion of eggs Easily curable with drugs
Trichuris trichiura	• Whipworm (trichuriasis) • Abdominal pain • Diarrhea	Ingestion of eggs Easily curable with drugs Found in biosolids
Taenia saginato	• Abdominal pain • Digestive disturbances	Found in biosolids
Cat, dog, beef, and pork worms	• Worm infections in humans	Ingestion of eggs
Various trematodes (flukes)	• Intestinal flukes • Lung flukes • Liver flukes	Ingestion of eggs Found in biosolids

Fungi		
Organism	**Disease**	**Mode of Transmission Comments**

Aspergillus fumigatus	• Aspergillosis • Lung infection	Inhalation of pores Found in biosolids and compost Most common and serious of fungal infections
Candida albicans	• Candidiasis (infection of lungs, skin, intestinal tract)	Inhalation of spores
Coccidioides immitis and *Histo-plasma capsulatum*	• Lung infection	Inhalation of spores Fungus grows on biosolids in warm and moist conditions
Blastomyces dermatitides	• Blastomycosis (lung infection)	Inhalation of spores
Crytococcus neoformans	• Cryptococcosis (lung infection)	Inhalation of spores
Sporothrix schenkii	• Sporotrichosis	Broken skin contact

Appendix D -Calculation of Point Loma Sludge for 1999