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Technical Memorandum

Prepared for: Sunnyvale, California

Project Title: Sunnyvale WPCP Strategic Infrastructure Plan

Project No: 135083

Technical Memorandum

Subject: Anaerobic Digestion of Algae at Sunnyvale WPCP

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1. EXECUTIVE SUMMARY

The anaerobic digestion of algae if executed properly can reduce the operating costs of the Sunnyvale WPCP and increase the overall renewable energy generated from the facility. Developing the recommended approach to the conversion of algal biomass to biogas, required two fundamental decision points.

First the configuration of the process equipment and the handling of the algae sludge was addressed. Four basic process configurations were defined and evaluated to determine if algae digestion could be economically executed at the Sunnyvale WPCP. The four alternatives were:

- Alternative 1-Current Operation with Discrete Solids Dewatering: This alternative would continue operation under the current solids handling/stabilization and dewatering configuration but with upgraded dissolved air flotation (DAF) and mechanical dewatering. Solids stabilization would consist of the mesophilic anaerobic digestion of primary sludge and continued deposition of thickened algae to the oxidation ponds. Dewatering would be discrete with separate dewatering of the digested primary biosolids and dredged biosolids from the pond.

- Alternative 2-Current Operation with Blended Solids Dewatering: This alternative would continue operation under the current solids handling/stabilization and dewatering configuration but with upgraded dissolved air flotation thickening (DAFT) and mechanical dewatering. Solids stabilization would consist of the mesophilic anaerobic digestion of primary sludge and continued deposition of thickened algae to the oxidation ponds. Dredged pond biosolids and digested primary biosolids would be blended and dewatered together to improve solids characteristics prior to disposal.

- Alternative 3-Co-digestion of Algae with Primary Sludge with Discrete Dewatering: The algae float from the DAF would be blended with the primary sludge and co-digested in the mesophilic anaerobic digesters. The additional biogas would be directed to the combine heat and power system (CHP) to off-set natural gas usage. The co-digested biosolids would be mechanically dewatered independent of the dredged biosolids generated during long-term pond maintenance.

- Alternative 4-Co-digestion of Algae with Primary Sludge with Extended Stabilization: The algae float from the DAF would be blended with the primary sludge and co-digested in the mesophilic anaerobic digesters. The additional biogas would be directed to the combine heat and power system (CHP) to off-set natural gas usage. The co-digested biosolids would be discharged to the oxidation pond for further stabilization. The stabilized biosolids would be removed from the pond, by dredging, and dewatered as part of the long-term pond maintenance program.

Based on an analysis of the operating costs alone, as the required infrastructure was assumed to be needed regardless of the handling of algae, it was determined that Alternative 4: Co-digestion of Algae with Primary Sludge with Extended Stabilization was the most cost effective means of handling the solids generated at the Sunnyvale WPCP. The most significant costs associated with the algae are those for dewatering and disposal which, without extended stabilization in the oxidation ponds (or eventually dedicated biosolids lagoons), become very high due to the high bound water content of the algae sludge.

Based on this process configuration further analyses were conducted to determine what impact anaerobic digestion process configuration has on the extraction of energy from the co-digesting sludges. The three processes evaluated were, mesophilic digestion, thermophilic digestion (TPAD) and the use of a sludge disintegration device with mesophilic digestion. TPAD, was found to increase the biogas production to the

greatest extent. Marginal biogas production from the conversion to TPAD may not produce a desirable payback due to the additional equipment and design costs that may be required to achieve TPAD operation. A separate on-going Strategic Infrastructure Plan evaluation is assessing the costs for conversion to TPAD operation and subsequent comparison of those costs to potential benefits described here may be used to evaluate the future economic sensibility of converting the digestion operations beyond the configuration recommended.

2. INTRODUCTION

The material presented in this technical memorandum is intended to provide a recommendation on the viability of the co-digestion of algae at the Sunnyvale WPCP.

2.1 Description of Sunnyvale WPCP Digestion System

Sunnyvale operates a total of 4 mesophilic anaerobic digesters to stabilize primary sludge and generate biogas for combustion in their combined heat and power (CHP) system. Digesters 1-3 serve as primary digesters, while Digester 4 is operated as a secondary, unheated digester and unmixed. Digested solids are dewatered on gravity drainage tiles followed by solar drying prior to ultimate removal from site for reuse. Figure 1 provides a basic schematic of the treatment process at Sunnyvale and Table 1 provides a summary of the average operating conditions of the anaerobic digesters.

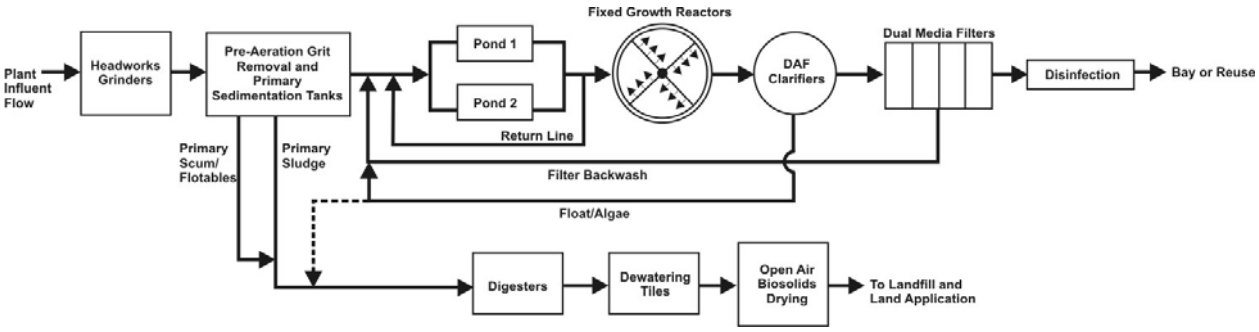

Figure 1: Basic Flow Schematic of the Sunnyvale Treatment Process

Table 1: Summary of Sunnyvale Digester Operating Conditions	
Parameter	Value
Volume (gallons, each)	
Digesters (1-3)	587,000
Digester (4)	950,000
Process Conditions[1]	
Operating Temperature (°F)	95
Solids Retention Time (Day)	44
Volatile Solids Reduction (percent)	68

1: average annual performance January 2003-December 2007

2.1.1 Assessment of Future Operating Conditions under the Current Process Configuration

The anaerobic digesters at Sunnyvale WPCP are operated in two stages with the three smaller digesters (Digester 1-3) serving as primary digesters and the larger (Digester 4) operating as a secondary digester, as shown in Figure 2. Digester 4, currently operates as a supernating digester, where the settled solids are sent to dewatering and the supernatant liquor is discharged to the secondary treatment system.

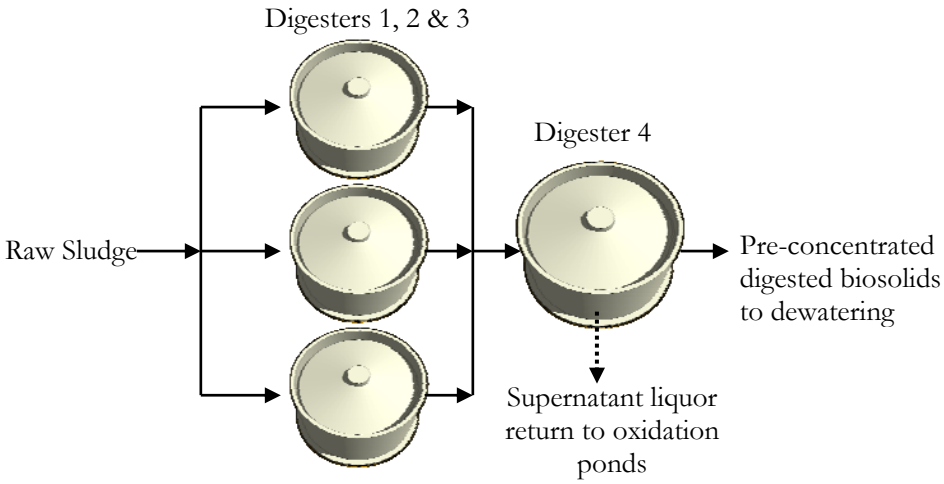

Figure 2: Basic flow schematic of Sunnyvale WPCP anaerobic digestion system

The projected capacity of the system was evaluated on a maximum month basis, rather than a peak week basis due to the extreme peaking and short duration of the peak week event. Typically a peak 2-week or 14-day flow and load are used to assess the limits of digestion, as it closely represents the limits for Class B digestion as defined by the US EPA 40CFR-503, for a process that significantly reduces pathogens (PSRP).

The two primary parameters used to assess remaining digester capacity are organic loading rate and hydraulic retention time. In the absence of stress testing to determine system specific limits for each parameter typical

values are used to define system capacity. An organic loading rate of 180 lbs-VS/1000-ft^3-d and a hydraulic retention time of 15 days, have historically produced a good quality biosolids product and stable digestion conditions, as such they are used in this assessment.

Assessing capacity not only depends upon the process limits but also the process configuration. As described previously Sunnyvale operates 3 primary digesters and 1 secondary digester, which is the largest digester. Assessing process conditions with the largest unit out of service would change the process configuration from 3 primary digesters and 1 secondary digester to 3 primary digesters, assuming a conversion to mechanical dewatering has occurred and the secondary digester thickening is not required. Figure 3 provides a basic flow schematic of the out of service condition at Sunnyvale with the largest unit out of service.

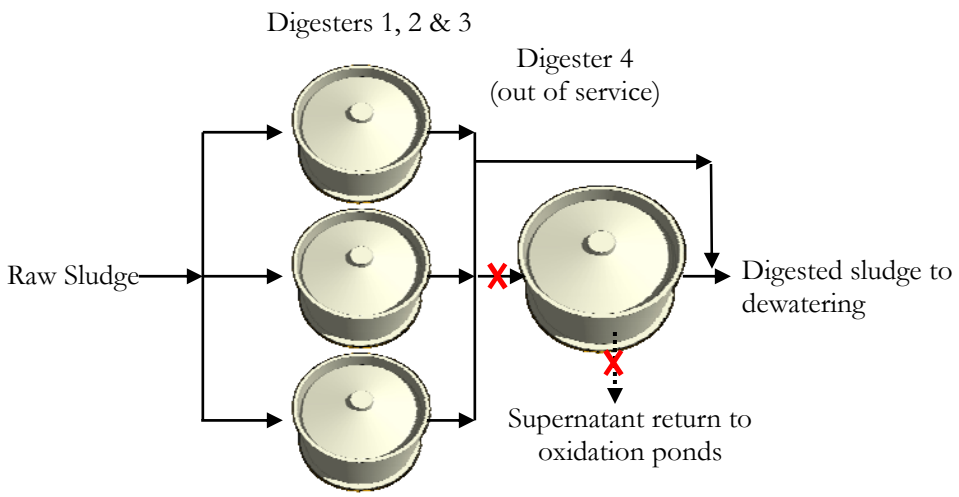

Figure 3: Basic flow schematic of alternative process flows with the largest digester out of service

Based on the out of service process condition the change in HRT and OLR were evaluated at the maximum month condition over the planning horizon, 2010 to 2035. It was further assumed that the primary sludge generated at the plant would be thickened in a process independent of the primary clarifiers, producing a total solids concentration of 5 percent. Figure 4 plots the remaining hydraulic capacity in digestion system, assuming that a 15 day SRT is maintained. Typically a 15 day SRT is maintained in digesters to meet the Processes to Significantly Reduce Pathogens (PSRP) requirements as well as provide a stable biosolids product for disposal, lower odor potential. What is apparent from Figure 4 is that there is significant hydraulic capacity remaining in the digestion system. At the maximum month condition, digesting only primary sludge, the system will operate a 32 day retention time, more than double the minimum recommended for mesophilic digestion, 15 days.

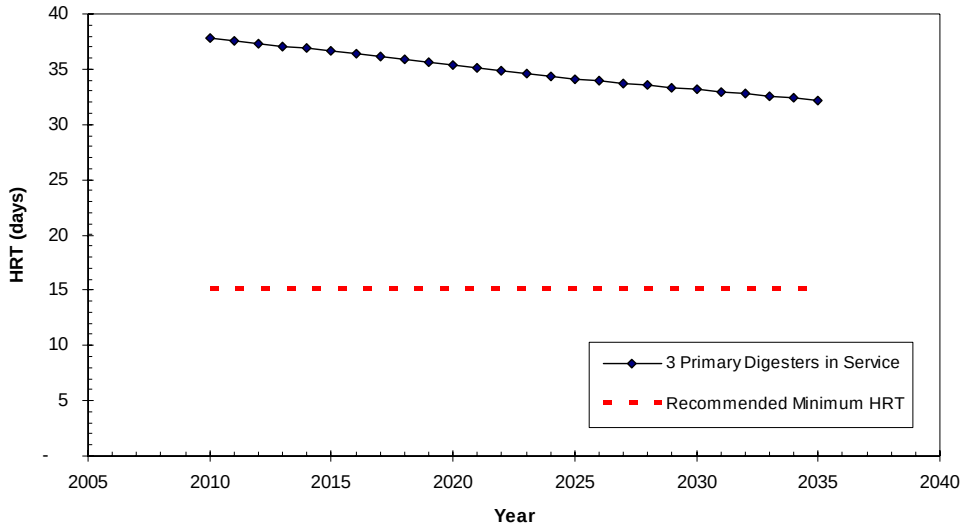

Figure 4: Projected hydraulic retention time for the Sunnyvale WPCP digesters with the largest unit out of service at maximum month flow and load.

As was observed with hydraulic capacity, the projected organic load at 2035 (85 lb-VS/1000-ft^3-d) is approximately 50% of the recommended allowable load for mesophilic digestion (180 lb-VS/1000-ft^3-d), as shown in Figure 5. Based on the HRT and OLR results and if Sunnyvale WPCP continues to digest only primary sludge for the next 25 years, the system will be heavily under utilized.

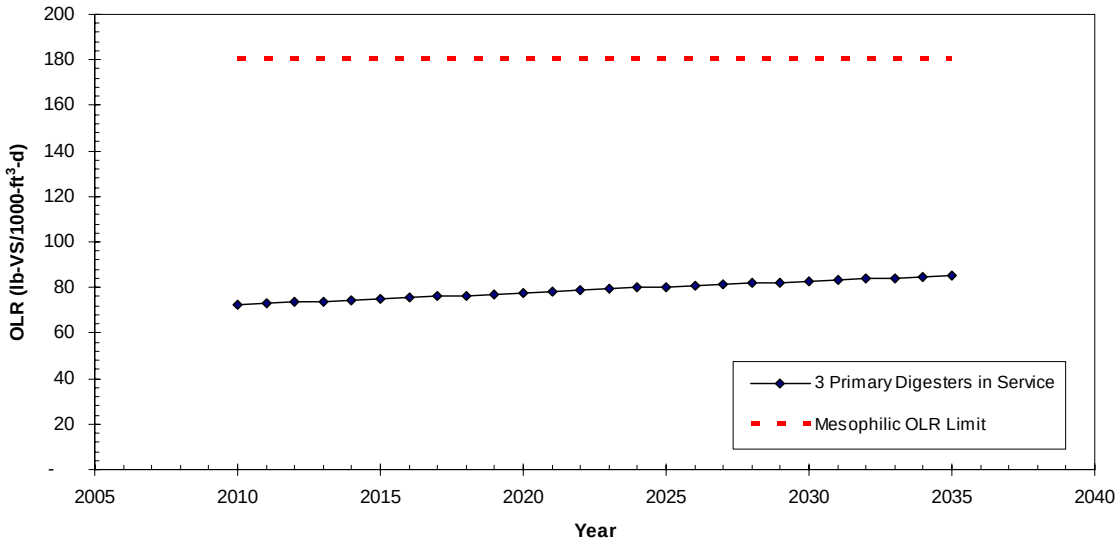

Figure 5: Projected organic loading rate to Sunnyvale WPCP digesters with the largest unit out of service

2.1.2 Digester Capacity Utilization

Evaluation of the digestion system capacity, as currently configured, indicates that approximately half available system capacity will be used when the planning horizon, 2035, is reached. The excess capacity at Sunnyvale can be used in one of the following three ways:

- Reserve capacity for future population growth or service area expansion.
- Digestion of algae float from the secondary treatment lagoons.
- Digestion of exogenous substrates such as FOG, food waste and hauled liquid wastes.

The allocation of digester capacity for purposes other than the primary objective of the treatment plant, stabilizing wastewater solids, should be done judiciously. Capital costs, environmental impacts and overall process stability must be considered when expanding the role of digestion.

Sunnyvale, WPCP currently produces significant quantities of algae from its pond system. The algae are continuously harvested from the oxidation pond effluent and returned to the ponds for sedimentation, digestion and storage. While simple and effective, the practice of direct lagooning of algal solids misses an opportunity to salvage additional biofuel generated energy from the waste treatment system. The following sections review the state of knowledge on algae digestion, the environmental, operational and capital merits of digesting algae under different operating regimes and a recommend system and approach for implementation at Sunnyvale.

3. STATE OF KNOWLEDGE: ANAEROBIC DIGESTION OF ALGAE

This section reviews the experiences of Sunnyvale WPCP in digesting algae generated in its wastewater treatment lagoons as well as those experiences reported in the literature by other utilities and researchers.

3.1 Sunnyvale WPCP: Algae Digestion Experience

Sunnyvale WPCP over the years has either directly or indirectly participated in studies of the anaerobic digestibility of algae. Summarizing past experience and reported impacts of algae on the digestion process will lay the foundation for future implementation, while reducing the potential for repeated or unnecessary capital expenditures. In the following subsection a summary of the primary findings of Sunnyvale associated digestion studies are reported.

3.1.1 EOA: Sunnyvale Algae Digestion Study, 1988

In 1988 a study of algae co-digestion at the Sunnyvale WPCP was conducted. Based on the information provided in the final EOA report the test conditions were as outlined below:

- Digester 2 and Digester 3 served as the control and experimental digesters (receiving algae float), respectively.
- Digester 3, received on average 21 percent of its total solids load and 28 percent of the hydraulic load as thickened algae solids, over the course of the study.
- Digester 2 and Digester 3 were loaded at an average OLR of 50 lb-VS/1000ft^3-d and 61 lb-VS/1000-ft^3-d, respectively, over the period of May 1986 through December 1987.

- Digester 2 and Digester 3 operated at an average hydraulic retention time of 49 and 36 days, respectively.
- Both digesters were operated at mesophilic conditions.

The primary findings and recommendations made in the EOA authored report are summarized below. It should be noted that some of these recommendations are dated and may no longer be representative of current operating conditions. The primary findings of the study on the digestibility of algae in the anaerobic digesters at Sunnyvale WPCP have been reproduced below:

- The algae/polymer sludge from the present dissolved air floatation (DAF) operation is effectively stabilized in the anaerobic digester
- All of the chemical parameters available for judging anaerobic digestion efficiency indicate a degree of stabilization of the mixed primary and algal/polymer sludge that is equivalent to that observed for primary sludge alone.
- The observed COD and TS reductions in all three digesters were virtually identical. (67-70% for COD, 58-66% for TS)
- Gas production measurements have been improved during the study period, but even with these improvements, they do not appear to be reliable enough to make comparisons of gas production between digesters.
- Because of the historical, and perhaps continuing, gas measurement problems, it is also not possible to compare present gas production with historical performance.
- Based on the COD and TS destruction, and on the energy balance estimates, it appears that the actual total digester gas production is in the range of 100,000 to 120,000 cu.ft./day. Measured total digester gas volumes, based on the gas meters, have generally been in the range of 120,000 to 140,000 cu.ft./day.
- Based on all of the above it is concluded that Action Statement 974 A.3, "convert algae solids to energy through the use of anaerobic digestion for methane gas production" has been accomplished n a full-scale basis and that there is every reason to go ahead with feeding additional algae harvested with polymer to the digesters, once the necessary modifications are made for dewatering the sludge and pumping it into the digesters.

Based on these primary findings the following recommendations were made.

- The quantity of algal/polymer sludge fed to the digesters should be increased, within the limits of "standard" digester operating parameters. This translates to an upper limit of 0.1 lb VS/cu ft/day or 0.12 lb TS/cu ft /day corresponding to 28,300 lb TS for 3 digesters and 44,200 lbTS for 4 digesters. At 5% solids these volumetric loading rates provide a detention time of about 26 days compared to a minimum required detention time of 25 days. (B&C recommends a lower SRT limit of 15 days and an upper organic loading limit of 180 lb-VS/1000-ft^3-day, for peak 2-week loading.)
- The increase in algae digestion should be accomplished in stages, beginning with an increase to 50% in one digester, and proceeding until each of the three digesters if fed at capacity (no more thant 9,400 lbs of TS <u>and</u> no more than 70,000 gallons of combined sludge.

- Installation of appropriate thickening equipment should be implemented prior to any significant increase, because the present low concentrations make detention time the limiting factor. To be cost-effective, this thickening equipment should be design to be easily expanded to handle the entire projected DAF float production.

- When digesters, 1, 2, and 3 are fed at their capacity, the City should evaluate the following options: 1) converting digester 4 back to a primary digester to provide capacity to treatment more of the algae sludge available during the summer months; 2) converting digester 4 to primary service for the peak algal production periods and then back to secondary service the remainder of the year; 3) operating the existing primary digesters as high rate digester; and 4) returning the excess algae float directly to the ponds under peak DAF production periods.

3.1.2 Algae Digestion Testing 2005

Sunnyvale over the years has continued to periodically investigate the digestion of algae in its mesophilic digesters. In the recent 2005 effort, a significant operating constraint was noted with the co-digestion of the algae. When the digesters were co-digesting algae, with sewage sludge, it was noted that the supernatant quality was noticeably degraded. The operational concerns associated with the nature of supernatant quality and the subsequent impacts on sludge dewatering operations were likely more important in the 2005 trial because the plant now actively dewaters digested sludge whereas, in the prior 1980's study, digested sludge was discharged back to the Oxidation Ponds where there would be little concern about the dewatering characteristics of the dewatered sludge.

3.2 Research on the Anaerobic Digestion of Algae

The anaerobic digestion of algae for the purpose of generating biogas as an energy source has received interest in the wastewater industry over the past 50 years. The energy associated with algae digestion comes from two sources, that imparted by the utility to convey the wastewater to the facility and the solar energy used by the photosynthetic organisms to consume the carbon and nutrients in the liquid to form biomass. The digestion of algae, unlike sewage sludge, results in the indirect conversion of solar energy to biogas energy. However, the efficient digestion of algae presents its own set of challenges in handling and processing the material. Based on a limited review of the literature available on algae several process and handling questions have become apparent. These include:

- Limited digestibility of algal cells
- Reduced biogas production relative to sludge digestion
- Process toxicity, ammonia-N and hydrogen sulfide
- Dewatering impacts

Each of these subjects are covered in the following subsections and where appropriate, the degree of correlation between the current digestion experience at Sunnyvale and that of other facilities will be addressed.

3.2.1 Limited Digestibility of Algal Cell Mass

Algae, like many bacterial/archeal cells found within secondary sludge, have evolved to be resistant to bacterial attack to increase the probability of survival in the environment. This resistance to attack manifests itself as a low degree of degradability in an anaerobic digester, relative to digestion of mixed primary and

secondary sludge. Cell mass, in general, typically exhibits a lower degree of degradability than primary sludge as such most digestion enhancement technologies, shear, sonication, electric pulse, chemical treatment etc.., have focused on treating secondary solids only. Table 2, provides a summary of reported values for different substrates associated with anaerobic digestion as well as algal biomass.

Inspection of the data in Table 2 indicates that algae exhibit a digestibility similar to that of waste activated sludge. Golueke et al (1957) noted that following digestion the biosolids had a noticeable green color to it, indicating the survival of chlorophyll, which as an intracellular material, suggesting cellular lysis was not complete during digestion. The same effort by Golueke et al. noted that solids destruction increased with increasing process temperature. Increasing from mesophilic to thermophilic (50 °C) conditions increased the volatile solids destruction approximately 10 to 18 percentage points and changed the biosolids color to a darker brown (i.e. less green).

Honglay (1987) also reported that the overall degradability of algae was dependent upon the species being digested. Therefore, seasonal fluctuations could affect the observed performance of the digesters.

Table 2: Summary of the anaerobic degradability of sludges as measured by Volatile Solids Reduction (VSr)

Substrate	Digester Condition	HRT (days)	VSr (percent)	Notes	Source
Primary Sludge Only	Mesophilic	44	68		Sunnyvale WPCP
Primary Sludge and Scum	Mesophilic	22.7	59.5		Zhao and Viraraghavan (2004)
Waste Activated Sludge	Mesophilic	15	23.2	conventional activated sludge with nitrification, bench scale study	Muller et al. (2009)
Sewage Sludge and Algae	Mesophilic	11.7	26.1	sewage sludge alone had a VSr of 28.7 at HRT of 14.5 days	Cecchi et al (1996)
Algae Only	Mesophilic	30	36-44		Golueke et al (1957)
Algae Only	Thermophilic	30	54	Temperature = 50 °C	Golueke et al (1957)
"Raw Sludge"	Mesophilic	30	57-60	composition undefined	Golueke et al (1957)

3.2.2 Reduced Biogas Production

The generation of biogas from the mineralization of organic matter is dependent upon several factors including; digester operating and environmental conditions, the degradability of the substrate and the composition of the substrate as well. Table 3, summarizes reported biogas yields from variety of studies investigation the anaerobic digestion of algae.

The data in Table 3 indicate that stable digestion of algae can occur under a variety of conditions and the yield of biogas from a mass of substrate varies. However, the data suggest that the yield of biogas relative to sewage sludge is not vastly different, and the biogas composition is similar. It is therefore likely that any reduced total biogas production is associated with overall substrate degradability rather than the composition of the algae itself.

Algae, has been reported to be rich in nitrogen, Chen (1987). High nitrogen, typically measured as TKN can be indicative of high protein content in the sludge. Based on observations by Li et al (2002), protein stoichiometicrically should produce a good quality and quantity of biogas, as shown in Table 4. The proteins in any substrate, during the mineralization process, will be converted to ammonium through the process of ammonification; which results in an increase in solution ammonium concentrations in the digesters. Elevated

ammonium concentrations have been linked to toxicity and reduced performance of digesters. Toxicity will be discussed in later sections.

Table 3: Summary of Biogas Yields from Different Algae Digestion Studies

	HRT days	Biogas[1] Yield ft^3/lb-VSin	Methane Content percent	OLR lb-VS/1000-ft^3-d	Source
Mesophilic Digestion					
Algae Only	28	6.7	73	N/A	Chen (1987)
Sewage Sludge	28	7.1	63	N/A	Chen (1987)
Algae Only	30	6.6	61.1	N/A	Golueke et al (1957)
Raw Sludge	30	9.6	62	N/A	Golueke et al (1957)
Sewage Sludge	14.5	3.8	61.4	105	Cecchi et al (1996)
Sewage Sludge + 18.9 % Algae	14.7	5.0	71.1	161	Cecchi et al (1996)
50/50 Sludge/Algae (35 °C)	28	4.66	64	N/A	Chen (1987)
Sewage Sludge + 40 % Algae	11.7	3.85	69.4	261	Cecchi et al (1996)
Thermophilic Digestion					
Algae Only (50 °C)	30	7.9	62.1	N/A	Golueke et al (1957)
60/40 Sludge/Algae	11.2	0.64	25	N/A	Cecchi et al (1996)
50/50 Sludge/Algae (40 °C)	28	7.2	66	N/A	Chen (1987)
50/50 Sludge/Algae (55 °C)	28	4.8	62	N/A	Chen (1987)

1 Yield in literature is based on Volatile Solids Loading (VSin). Engineering practice typically measures yield on basis of Volatile Solids Reduction (VSr), typical range being 13 – 18 ft^3 biogas / lb VSr. These literature values are generally within that range assuming the VSr is typically in the 50% - 60% range for HRTs > 15 days.

Table 4: Theoretical Gas Production from Different Organic Waste Components (Li et. al. (2002))			
Component	Reaction of Methane Fermentation	Gas Production m^3-biogas/kg	CH_4 % in Biogas
Lipids (Fats)	$C_{15}H_{90}O_6 + 24.5\ H_2O \rightarrow 34.75\ CH_4 + 15.25\ CO_2$	22.9	69.5
Carbohydrates	$(C_6H_{10}O_5) + nH_2O \rightarrow 3n\ CH_4 + 3nCO_2$	13.3	50
Proteins	$C_{11}H_{24}O_5N_4 + 14.5\ H_2O \rightarrow 8.25\ CH_4 + 3.75\ CO_2 + 4\ NH_4^+ + 4HCO_3$	14.8	68.8

3.2.3 Toxicity Impacts on Digestion

Anaerobic digesters are susceptible to toxicity from a variety of sources. However, for algae digestion two predominant sources were identified in the literature. Cecchi et al (1996) reported hydrogen sulfide toxicity when anaerobically digesting algae. The author attributed the toxicity to the high concentrations of sulfate associated with the liquor of the algae.

The other predominant mechanism of toxicity likely associated with algae is ammonia toxicity. Ammonium, as previously stated is released during the digestion process as proteins are degraded. Ammonium fluctuates between its ionized state (NH_4^+) and its unionized state (NH_3, ammonia) in solution. Ammonia is considered to be the more toxic of the pair. References within Speece (2008) report unionized ammonia concentrations of 150 mg/L and above as toxic.

The work done by Chen (1987) reported that micro-algae used in that study had a carbon to nitrogen ratio (C/N) of 5, with optimum fermentation at a C/N ratio of 25-45. Typical wastewater sludges are rich in protein as well. Monitoring the ammonium production in a digester will be critical to ensure that ammonium toxicity does not occur. High temperature processes, such as thermophilic digestion, shift the ammonium/ammonia equilibrium towards the unionized species along with increasing pH. In such cases additional care should used when operating the system.

3.2.4 Dewatering Impacts

The reported impacts of algal cell mass on the dewatered sludge cake properties are limited at this time. Golueke et al (1957) reported that unlysed algal cells were present in the sludge following digestion, even at thermophilic temperatures. The added cell mass resulted in a deterioration in the dewatered cake properties, manifesting as a wetter cake product.

Unstabilized biomass, depending on the dewatering process and ultimate disposal of method of the facility, can result in off-site odor issues. High shear processes, such as centrifuges, can lead to increased odors from dewatered cake through increasing the bioavailability of proteins in the dewatered cakes. Proteins, not only contain nitrogen as previously discussed, but also sulfur based amino acids which degrade to volatile compounds such as methanethiol and hydrogen sulfide, which both have a distinct foul odor. While the literature is silent on the impact of undegraded algal biomass on biosolids odors, a reduction in this material in the final product should mitigate potential issues associated with the algal biomass.

4. ALTERNATIVE PROCESS CONFIGURATIONS FOR HANDLING AND DISPOSAL OF ALGAE

The intent of the material presented in this section is to evaluate the best method of handling algae solids at the Sunnyvale WPCP. Based on an initial analysis 4 basic process configuration alternatives are evaluated; which include:

- **Alternative 1-Current Operation with Discrete Solids Dewatering:** This alternative would continue operation under the current solids handling/stabilization and dewatering configuration but with upgraded dissolved air flotation (DAF) and mechanical dewatering. Solids stabilization would consist of the mesophilic anaerobic digestion of primary sludge and continued deposition of thickened algae to the oxidation ponds. Dewatering would be discrete with separate dewatering of the digested primary biosolids and dredged biosolids from the pond.

- **Alternative 2-Current Operation with Blended Solids Dewatering:** This alternative would continue operation under the current solids handling/stabilization and dewatering configuration but with upgraded dissolved air flotation thickening (DAFT) and mechanical dewatering. Solids stabilization would consist of the mesophilic anaerobic digestion of primary sludge and continued deposition of thickened algae to the oxidation ponds. Dredged pond biosolids and digested primary biosolids would be blended and dewatered together to improve solids characteristics prior to disposal.

- **Alternative 3-Co-digestion of Algae with Primary Sludge with Discrete Dewatering:** The algae float from the DAF would be blended with the primary sludge and co-digested in the mesophilic anaerobic digesters. The additional biogas would be directed to the combine heat and power system (CHP) to off-set natural gas usage. The co-digested biosolids would be mechanically dewatered independent of the dredged biosolids generated during long-term pond maintenance.

- **Alternative 4-Co-digestion of Algae with Primary Sludge with Extended Stabilization:** The algae float from the DAF would be blended with the primary sludge and co-digested in the mesophilic anaerobic digesters. The additional biogas would be directed to the combine heat and power system (CHP) to off-set natural gas usage. The co-digested biosolids would be discharged to the oxidation pond for further stabilization. The stabilized biosolids would be removed from the pond, by dredging, and dewatered as part of the long-term pond maintenance program.

Based on the results of this analysis, further recommendations for process optimization and long term operation will be made in later sections.

4.1 Baseline Conditions and Assumptions for Alternatives Evaluation

Sunnyvale WPCP is going to implement a series of process/mechanical upgrades to improve overall system performance and capacity. Some of these upgrades have a direct impact on the evaluation of the alternatives for algae handling at Sunnyvale. Listed below are the conditions, upgrades to other systems and assumptions that will be common to all alternatives reviewed:

- Sludge and Algae Thickening:

- The dissolved air floatation process will be upgraded to improve the capture and thickness of the algal cell sludge harvested from the oxidation ponds.
- The thickening of primary sludge will be improved through the use of gravity thickeners.

- Oxidation Pond Dredging:
  - The oxidation ponds will be dredged, using the same dredge used in the pilot study, to maintain a mass of solids in the system of 47 tons. Maintenance dredging will continue beyond the initial removal of the approximate 26 tons of material scheduled for removal.
  - It is assumed that the 500 gpm diesel powered pump on the dredge is equivalent to a 30 HP electric motor.
  - It is assumed that there is 1 hour of start-up and 1 hour shut down and cleaning of the dredge for each day of operation.
  - The dredge requires 2 personnel to operate and maintain safe working conditions.
  - The hourly rate of the operating staff is $100 per hour.
- Dewatering and Handing of Digested Sludge/Dredge Material:
  - A recommended mechanical dewatering process has not been identified for sludge dewatering, it is assumed that mechanical dewatering will be implemented and the drainage system will be abandoned. For this analysis it is assumed that belt filter presses will be used, as this technology was used for the dredging pilot study and provides the most verifiable and relevant data available.
  - Cost of operation and maintenance of the belt filter presses will be $66 per dry ton, based on the information provided by BDP.
  - It is assumed that polymer used for dredge dewatering and sludge dewatering costs $2.25 per lb-polymer.
  - It is assumed that the current cost of disposal of solids from the plant will remain $44.69 per wet ton for both biosolids and dredge material or any mixture of those materials.
- Algal Solids Destruction:
  - EOA reported that algae sludge deposited in the oxidation pond achieved approximately 83 percent volatile solids destruction due to the extreme detention time in the pond system, using the Van Kleeck equation.
  - It is assumed that any biological sludge material, that does not contain any inhibitory compounds, would degrade to a similar extent in the ponds.
- Sludge Cake Concentrations:
  - The EOA pilot study reported that material dredged and dewatered using a belt filter press achieved a cake solids concentration of 18.8 percent total solids, based on the average value reported by Synagro and Sunnyvale's laboratory.

- It is assumed any material deposited in the pond, due to the high degree of stabilization, would achieve a similar solids concentration during dewatering.

- Economic Analysis
  - It is assumed all upgrades will proceed regardless of the manner in which the algae sludge is handled. Therefore, the relative cost of each alternative is based on the operating costs only.
  - Operating costs will be evaluated as the means of comparison between alternatives in this memorandum. As operating costs are a function of solids production, for this effort, all alternatives were evaluated for operation in the the planning year of 2035, as this single year will likely provide the largest magnitude change in operating cost between each alternative. Therefore all costs presented are those for the year 2035 and not an annualized present value. The costs are intended to allow for the reader compare and contrast the listed alternatives within the structure of this memorandum only and do not represent full lifecycle costs and benefits, unless otherwise stated.

4.2 Alternative 1: Current Operation

Alternative 1, assumes that there are no changes to the current practices at the plant, in terms of the handling of the algae solids. Figure 6, provides a basic process flow schematic of Alternative 1.

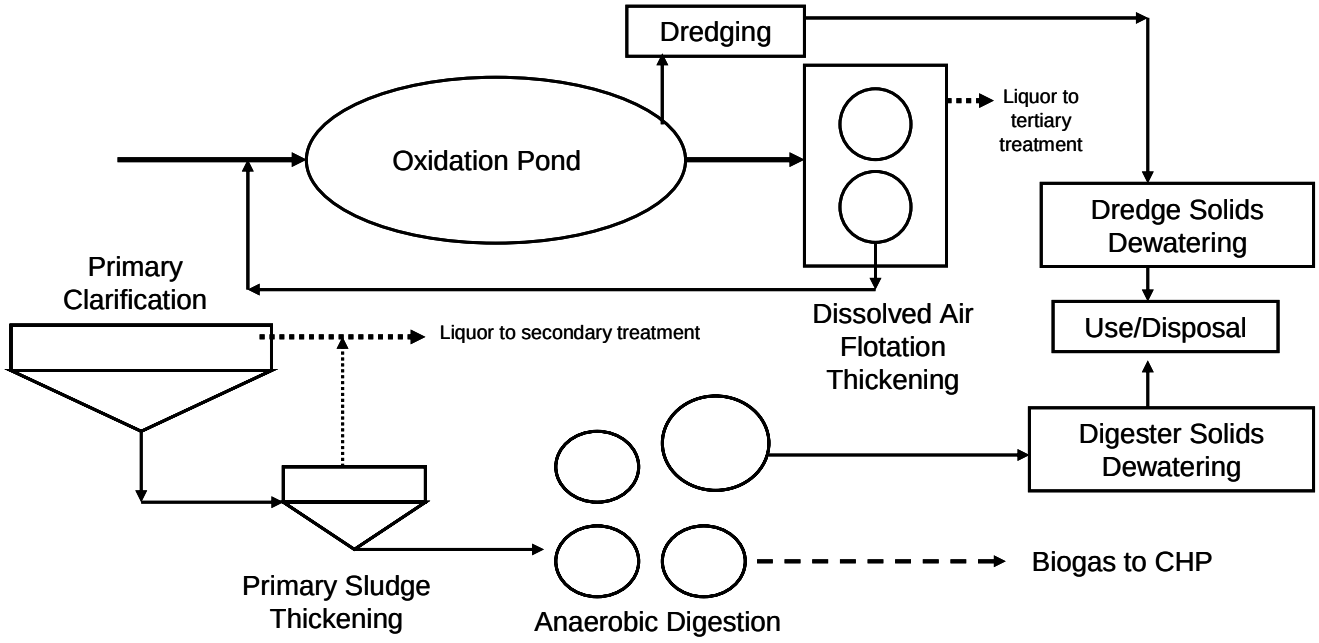

Figure 6: Basic process flow schematic for Alternative 1: Current Configuration

Under Alternative 1, algae would be harvested from the ponds by the upgraded DAF units and thickened. The thickened sludge product would be reintroduced to the oxidation pond for stabilization and eventual removal through the dredging process. Under this operating scenario the organic loading rate to the ponds from the algae solids and those endogenous to the system would be 0.9 lb-VS/1000-ft^2-day, of which 0.681 lb-VS/1000-ft^2-day is associated with the algae. Assuming that 47,000 tons of material remains in the pond at all times the average solids retention time would be 30 years in the oxidation pond. Primary sludge, would be

thickened in the primary clarifiers and stabilized in the anaerobic digesters then dewatered for final disposal. No additional biogas would be generated from this process thus the energy production facility would not be impacted under this alternative. Table 5, presents the operating costs under Alternative 1 for the design year of 2035.

Table 5: Estimated Operating Costs for Alternative 1 in Year 2035

Cost Element	Costs or (Revenue) $/year
Oxidation Pond Maintenance Operations	
Dredging and Dewatering	211,000
Hauling and Disposal	372,400
Digester Solids Dewatering and Disposal Operations	
Polymer Usage	11,400
Dewatering O&M	67,100
Hauling and Disposal	181,700
Total Operating Costs and Revenues from Biogas Production	
Total Operating Costs	843,600
Revenue from added biogas	(0)
Net Operating Cost	843,600

Based on the information in Table 5, it is estimated that it would cost $843,600 dollars in 2035 annually to operate the system in this manner. Under this operating regime, no additional biogas will be produced to offset natural gas usage at the energy facility, as well.

4.3 Alternative 2: Current Operation with Blended Sludge Dewatering

Under Alternative 2 it is assumed that the handling of the algae and primary solids would be the same as in Alternative 1, but the stabilized solids from each process would be blended prior to dewatering to improve the solids concentration of the final product. The organic loading rate of solids to the pond (algae and endogenous solids) would be the same as Alternative 1, 0.9 lb-VS/1000-ft^2-d) Figure 7, provides a basic flow schematic of Alternative 2. An increase in the overall blended solids concentration should reduce haul costs of the final product, which under Alternative 1 represented the greatest cost to Sunnyvale, as shown in Table 5. Table 6, reevaluates the data with this process modification and assumes that the blended solids will achieve a cake solids concentration of 22.5 percent following dewatering, assuming the blended product results in overall improvement proportional to the mass load of each sludge type to the dewatering device.

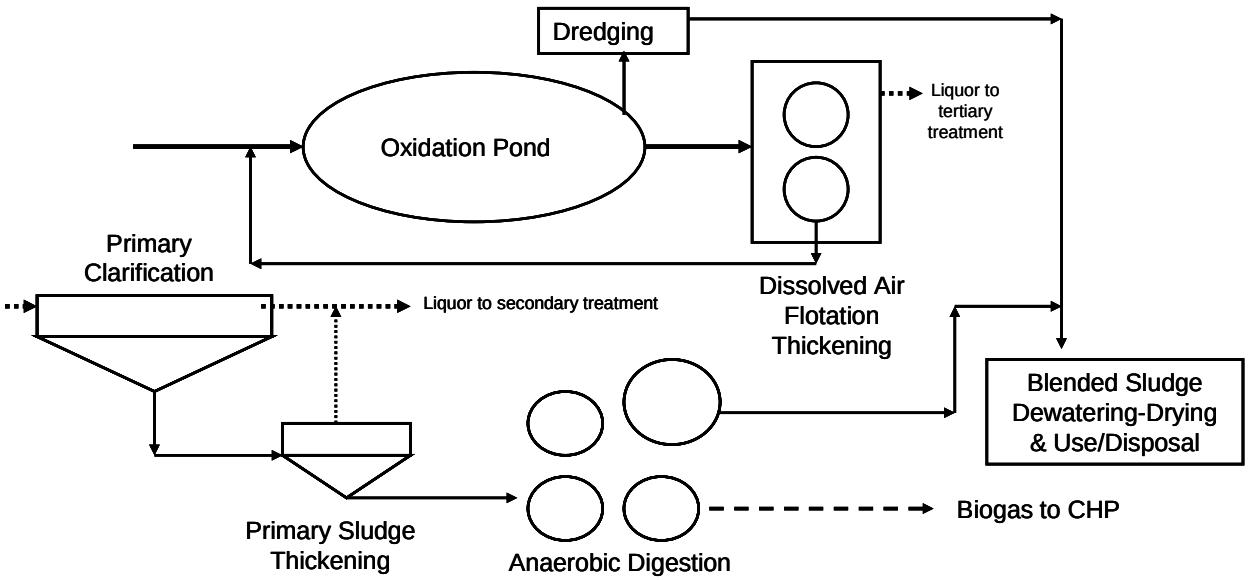

Figure 7: Basic process flow schematic of Alternative 2: Current Operation with Blended Solids Dewatering

Table 6: Estimated Operating Costs for Alternative 2 in Year 2035

Cost Element	Costs or (Revenue) $/year
Oxidation Pond Maintenance Operations	
Dredging and Dewatering	211,000
Hauling and Disposal	311,000
Digester Solids Dewatering and Disposal Operations	
Polymer Usage	11,400
Dewatering O&M	67,100
Hauling and Disposal	202,000
Total Operating Costs and Revenues from Biogas Production	
Total Operating Costs	802,500
Revenue from added biogas	(0)
Net Operating Cost	802,500

Based on the data presented in Table 6, it would appear that blending of solids would have a marginal impact on the annual operating costs associated with continued operation under the current solids processing regime.

The approximate $42,000 reduction in costs is heavily dependent the assumption that the cake solids improvement would be proportional to the relative ratio of the primary sludge to the algae sludge.

4.4 Alternative 3: Co-digestion of Algae with Discrete Dewatering

Alternative 3, diverts the algae float from the upgraded DAF system to the anaerobic digesters, to utilize the excess capacity existing in the system to stabilize the solids and generate methane for use in the cogeneration process. Under this operating condition it is assumed that the solids from the digester and the solids dredged from the lagoon are dewatered discretely, as the lagoon solids have been reduced to only the deposition of material from the influent and the minimal amount of sludge from the trickling filters. The removal of algae solids from the pond system would reduce the organic loading to 0.219 lb-VS/1000-ft^2-day, or to 24 percent if current practices were continued. Figure 8, provides a process flow schematic of the process.

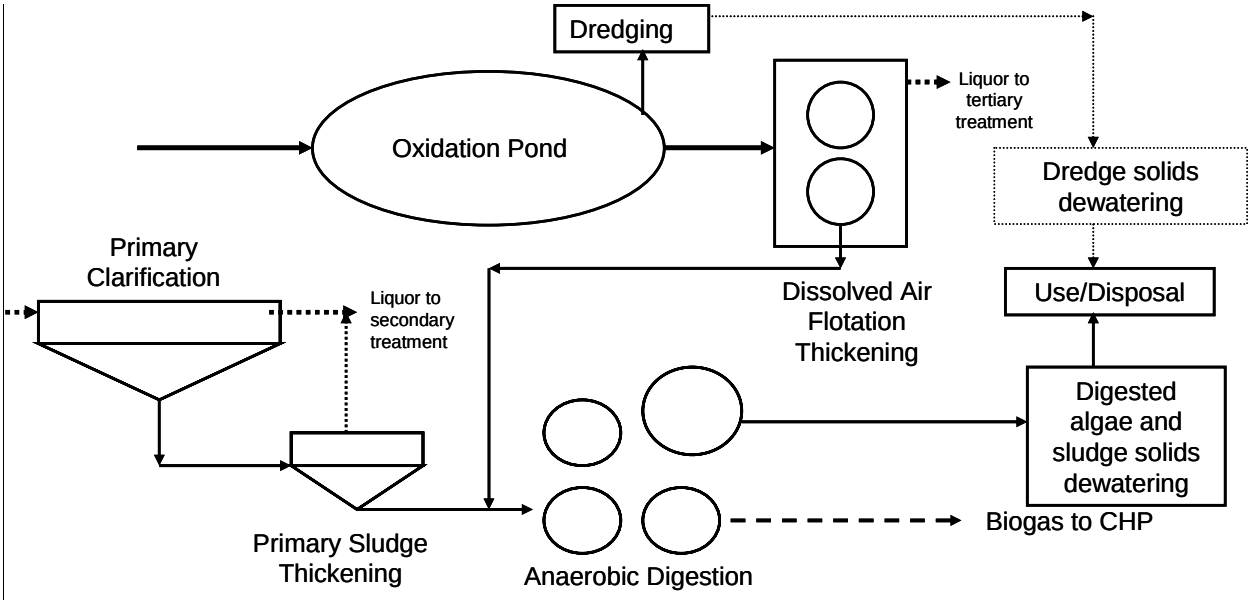

Figure 8: Basic process flow schematic of Alternative 3: Co-digestion of Algae with Discrete Dewatering

Table 7, provides a summary of the annual operating cost for operation of the system at the planning horizon, under this configuration. Unlike Alternative 1 and 2, this configuration does provide some added benefit in that the additional biogas generated from the digestion of the algae solids can offset the use of natural gas at the cogeneration facility. However, unlike digestion in the lagoon sediments, the extent of algae float digestion in the digester is much less, 40 percent VSr relative to 83 percent VSr, which results in significantly more biosolids requiring mechanical dewatering processing and off-site transport to reuse locations.

The relatively low degradability of the algae sludge, as has been reported by Gouleke et al (1957), can have a negative impact on dewatering as well as gas production. The survival of algal cells through the digestion process will increase the bound water content of the sludge resulting in a much wetter cake product, as noted in previous sections. The added water will reduce the cake solids concentration from the belt filter presses resulting in more material for disposal. It is estimated that the addition of undegraded algae sludge to primary sludge would result in a cake solids concentration of approximately 15 percent total solids. The impact of this deterioration of cake properties, along with the greater mass quantities requiring processing, is considerably more significant than the revenue gain from the biogas production, as shown in Table 7.

Table 7: Estimated Operating Costs for Alternative 3 in Year 2035

Cost Element	Costs or (Revenue) $/year
Oxidation Pond Maintenance Operations	
Dredging and Dewatering	145,200
Hauling and Disposal	213,900
Digester Solids Dewatering and Disposal Operations	
Polymer Usage	240,600
Dewatering O&M	176,500
Hauling and Disposal	796,600
Total Operating Costs and Revenues from Biogas Production	
Total Operating Costs	1,572,700
Revenue from added biogas	(148,800)
Net Operating Cost	1,423,900

Relative to the current operating regime, co-digestion of algae and the dewatering mixed solids from the digester is significantly more expensive. The added revenue associated with offsetting natural gas is marginal relative to the added hauling and disposal costs. Based on this analysis this mode of operation can not be recommended.

4.5 Alternative 4: Co-digestion of Algae with Extended Stabilization

As was indicated in the review of Alternative 3, the relatively low degradability of the algal cells in the digester and the subsequent deterioration of sludge cake properties significantly increases the operating costs of the facility. As noted in the EOA Dredging Pilot Report, the extreme detention time of the oxidation pond sludges allowed for a high degree of stabilization of the algae solids in the pond, resulting in improved dewatering performance. Alternative 4, takes advantage of the high SRT of the oxidation pond by reintroducing solids from the digester to the pond, as shown in Figure 9. The addition of stabilized primary solids along with the stabilized algae solids will increase the solids loading rate to the pond to 1.05 lb-VS/1000-ft^2-day or 17 percent more than would be loaded if current practices were continued. Maintaining a sludge inventory of 47,000 ton will result in a SRT of 21 years. It is assumed that even at this relatively reduced retention time the primary solids and algae solids will continue to be stabilized until the full 83 percent reduction in volatile solids is achieved.

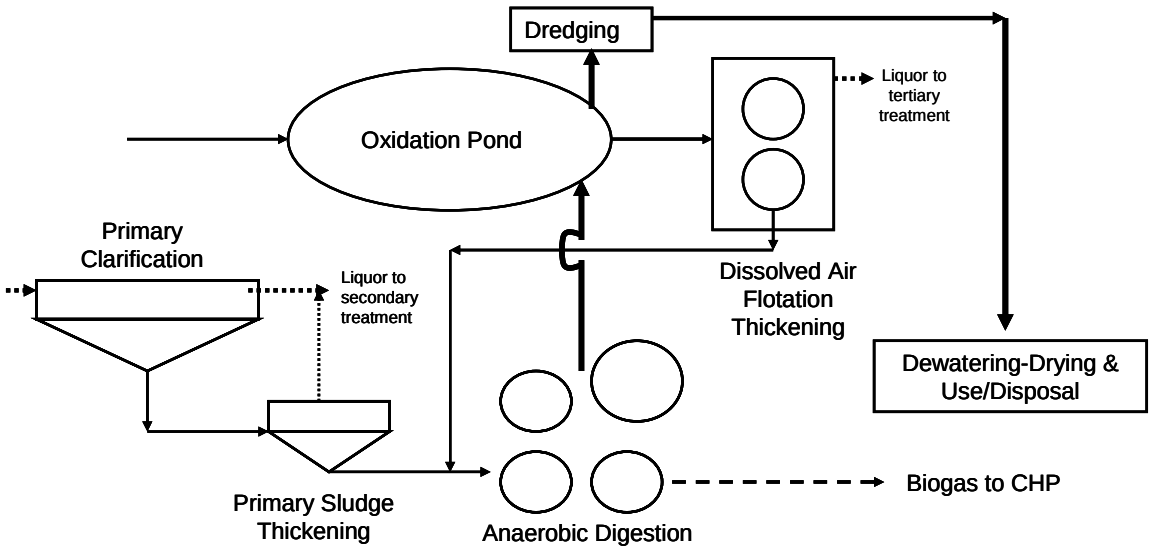

Figure 9: Basic flow schematic of Alternative 4: Co-digestion of Algae with Extended Stabilization

Table 8: Estimated Operating Costs for Alternative 4 in Year 2035	
Cost Element	Costs or (Revenue) $/year
Oxidation Pond Maintenance Operations	
Dredging and Dewatering	281,000
Hauling and Disposal	541,000
Digester Solids Dewatering and Disposal Operations	
Polymer Usage	--
Dewatering O&M	--
Hauling and Disposal	--
Total Operating Costs and Revenues from Biogas Production	
Total Operating Costs	822,000
Revenue from added biogas	(148,800)
Net Operating Cost	673,000

Based on this operating regime the annual operating costs were calculated, as shown in Table 8. The recovery of sludge cake properties through continued stabilization results in large reduction in the overall operating costs of the facility, making the additional biogas generated a significant cost savings. Alternative 4 is by far the least costly mode of operation, for Sunnyvale and the most sustainable as it further extracts energy from the process, which was once lost.

4.6 Recommended Process Configuration

Table 9: Summary of Sunnyvale WPCP Algae Handling and Stabilization Alternatives

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Operations and Process Considerations (average annual conditions at 2035)				
Organic Loading Rate to Pond System (lb-VS/1000-ft^2-day)	0.219	0.219	0.9	1.05
Estimated daily dredging time (hours)	1.5	1.5	0.87	2.2
Total mass of solids from dewatering (2035) (wet tons)	12,400	11,480	22,600	12,110
Additional Energy from the digestion of algae (therms)	--	--	143,000	143,000
Economic Considerations (average annual conditions at 2035)				
Oxidation pond solids dredging, conditioning and dewatering ($)	211,000	211,000	145,200	281,000
Oxidation pond solids hauling and disposal ($)	372,400	311,000	213,900	541,000
Digester sludge conditioning costs ($)	11,400	11,400	240,600	--
Digester sludge dewatering costs (O&M) ($)	67,100	67,100	176,500	--
Digester sludge hauling and disposal ($)	181,700	202,000	796,600	--
Revenue from additional biogas production ($)	--	--	148,800	148,800
Net annual operating cost ($)	843,600	802,500	1,423,900	673,000
Recommended?	No	No	No	Yes

From the evaluation of each of the alternative process configurations, which are summarized in Table 9, it was determined that Alternative 4, co-digestion with extended stabilization is the most cost effective configuration. The additional solids stabilization achieved in the oxidation pond system improves the dewatering characteristics to such an extent that disposal costs are significantly reduced. A reduction in dewatering costs allows for a overall reduction in operating costs as the offset of natural gas by biogas from algae digestion becomes significant. While Alternative 4, is economically attractive the long term use of the oxidation ponds as sludge stabilization ponds is not recommended. As an interim solution the ponds will serve adequately but it is recommended that the City of Sunnyvale ultimately investigate the construction of dedicated biosolids lagoons for the purpose of extended stabilization. Dedicated biosolids lagoons could be designed with more depth than the oxidation ponds and, as such, could be configured to accommodate dredging operations with greater efficiency. Approximately 20 acres of dedicated sludge lagoons would be required to accommodate projected loads. In the short term, the City is already committed to a program of dredging the oxidation ponds to catch up with nearly 50 years of biosolids accumulation that has gone without removal operations. Discharging digested biosolids to the oxidation ponds during the several year (5 – 20 year) time period anticipated for catch-up dredging in the ponds seems to be an efficient near term management approach.

5. ALTERNATIVES FOR ENHANCING ALGAE DIGESTION

Literature discussed earlier in this memorandum noted that algae digestion in the anaerobic digestion vessels may be accomplishing only a partial level of degradation of the algae. The dewatering and off-site transportation consequences of the partial degradation favored the recommended configuration that achieved more complete biosolids degradation in an extended stabilization lagoon.

Figure 10 illustrates the typical pattern of organic solids degradation in an anaerobic digester, though the rate and extent may vary from facility to facility. Common to all digestion systems is the he phenomena of diminishing returns on volatile solids destruction with extended solids retention time. As the detention time increases the marginal increase in solids destruction and biogas production decreases. This essentially sets a maximum retention time at which the degree of solids stabilization and biogas production relative to capital investments in tankage and equipment make fiscal sense, if energy recovery and solids destruction were to be maximized. The data in Figure 10 also indicates that for retention times typical to digestion systems, increasing temperature will increase the observed rate and extent of solids destruction, though other methods of increasing rate and extent are also available.

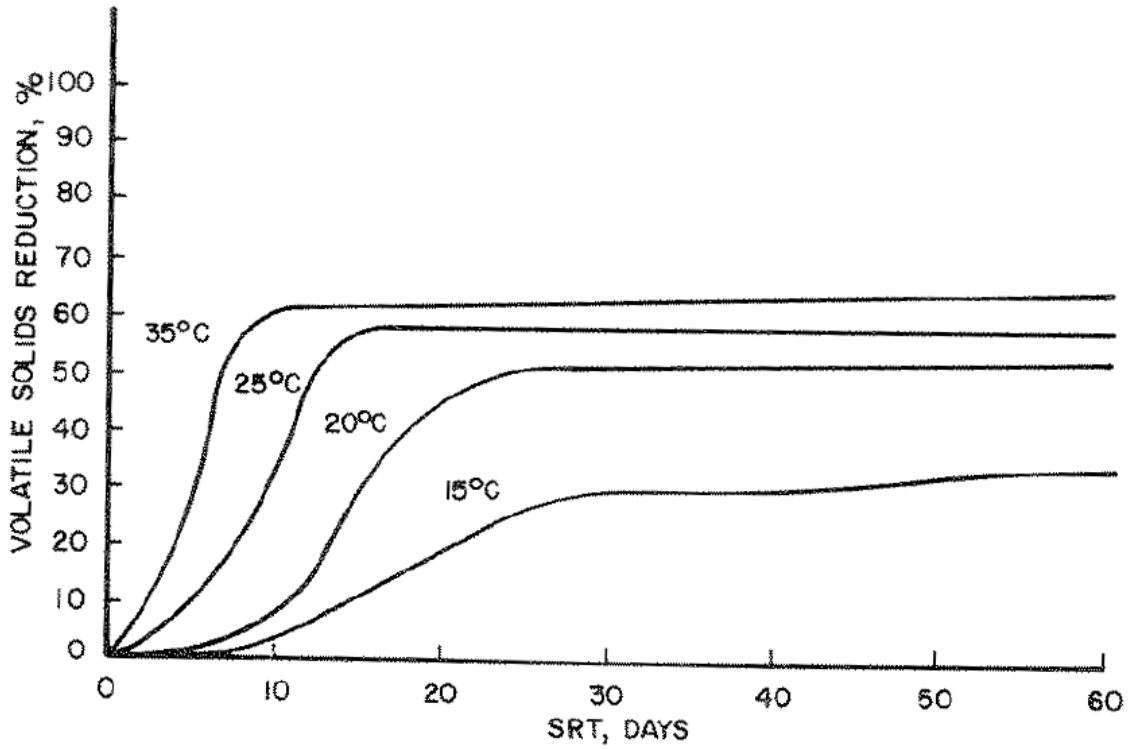

Figure 10: Volatile solids destruction as a function of temperature and solids retention time [O'Rourke, (1968)]

The data in Figure 10 provides a fundamental understanding of the behavior of solids degradation in anaerobic digesters, but extending these relationships to sludge lagoons is more complex. There is little doubt that some degree of additional stabilization of biosolids in extended stabilization lagoons will occur, as the microorganisms associated with the solids will continue to respire, though likely at a much lower rate. Sludge lagoons operate at far longer retention times and at lower temperatures than tank based digestion systems. Furthermore, the relative contributions to extended solids stabilization associated with anaerobic versus aerobic digestion mechanisms is currently not well known. Energy recovery from extended stabilization (post-anaerobic digestion) lagoons is virtually unknown in the industry, as such is not addressed

in the Technical Memorandum. Also not well known, from a greenhouse gas (GHG) perspective, is the overall rate of methane emissions from these types of lagoons. Methane generation may be mitigated by biological methane oxidation processes occurring in the upper partially aerobic sediments, or in the water column. Thus making claims of GHG reductions associated with lagoon operations would be purely speculative at this time.

As the literature discussed earlier and emerging practices in the wastewater solids stabilization industry indicate, modifications to the anaerobic digestion phase of the stabilization process may result in greater VSr within the digester vessels; which could lead to an optimal configuration for energy recovery.

The following sections will review current operation, mesophilic digestion, and two process enhancement approaches, thermophilic digestion and sludge disintegration. The intent of this analysis is to provide a review of potentially viable digester process enhancements to increase biogas recovery, if and when the extended stabilization mode of algae digestion operation is applied.

5.1 Mesophilic Anaerobic Digestion of Algae

Mesophilic anaerobic digestion of algae is approximately equivalent to the digestion of waste activated sludge. The reported resistance of algal cells to microbial degradation (Gouleke et al (1957)) results in an overall poor volatile solids destruction, even at retention times as high as 30 days. While the degree of degradability of algae it variable, having been shown to be species dependent (Honglay (1987)) it is typically low, and is assumed to be around 40 percent (VSr) for this analysis. Based on this observation the predicted performance of the mesophilic co-digestion of algae can be predicted. Table 10 summarizes the predicted performance of the system at the planning horizon, 2035.

Table 10: Summary of Digestion Performance and Energy Recovery of Mesophilic Co-Digestion of Algae and Primary Sludge for Year 2035

Parameter	Value	Units	Notes and Assumptions
Operating Conditions at 2035			
Algae Load (lb-TS/day)	12,397	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Algae Load (lb-VS/day)	10,538	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-TS/day)	13,200	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-VS/day)	11,220	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge VSr	60%	percent	Source: TM: Solids Load Technical Memorandum
Algae Sludge VSr	40%	percent	Source: TM: Solids Load Technical Memorandum
Anaerobic Digester Operation: Biogas Production			
Primary Sludge Volatile Load (lb-VS/day)	11,220	lb-VS/day	
Algae Volatile Solids Load (lb-VS/day)	10,538	lb-VS/day	
Biogas Yield	15	ft^3-biogas/lb-VSr	Assumed equivalent biogas yield from algae and primary sludge
Total Annual Biogas Production from Primary Sludge	36,857,700	ft^3-biogas/year	

Table 10: Summary of Digestion Performance and Energy Recovery of Mesophilic Co-Digestion of Algae and Primary Sludge for Year 2035

Parameter	Value	Units	Notes and Assumptions
Total Annual Biogas Production from Algae	23,077,669	ft^3-biogas/year	
Lower Heating Value of Biogas	620	BTU/ft^3	Lower heating value of biogas
Total Energy from Primary Sludge	228,518	therm/year	
Total Energy from Algae	143,082	therm/year	
Value of Biogas	$1.04	$/therm	Average price of natural gas, Sunnyvale Data
Market Value of Biogas from Primary Sludge	$237,658	annually	
Market Value of Biogas from Algae	$148,805	annually	
Total Value of Biogas From Digestion	$386,463	annually	

5.2 Sludge Disintegration with Mesophilic Digestion

The pretreatment of sludges to increase the overall biodegradability of the substrate has been the focus of many technologies. Typically these technologies apply some external energy or force to physically, in some cases chemically, change the nature of substrates prior to, or during, digestion resulting in increased biodegradability. The resistance of the algal cell wall to microbial attack and subsequent cell lysis has been suggested as the primary impediment to efficient algae digestion. Many of these digestion enhancement technologies (sludge disintegration technologies) claim to induce cellular lysis, though quantifiable results of these claims are limited. Given the larger size of an algal cell relative to a bacterial cell (~1 μm) cell disruption is likely to be more efficient, though testing and verification are recommended. Figure 11, provides a process schematic of an anaerobic digestion system and the possible locations for cell disruption (i.e. disintegration) technologies. By far the most common location of such technologies is isolation on the waste activated sludge line, prior to digestion, as it is commonly thought that WAS is significantly less degradable than primary sludge. Pretreatment, would likely be the model system used for treating the DAF algae float at Sunnyvale; as primary sludge treatment is typically not needed and the application of these technologies is very limited on the sludge heating recirculation line.

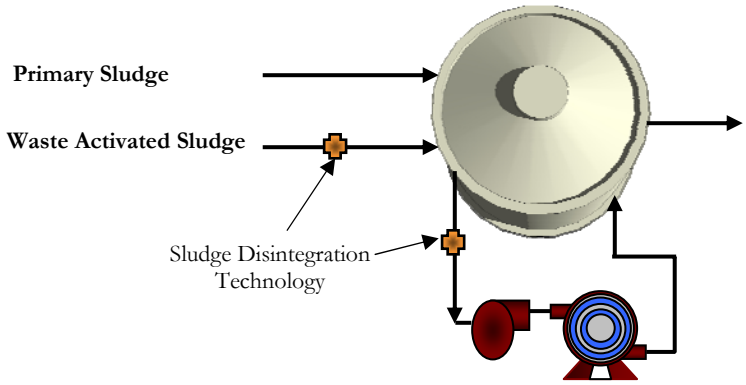

Figure 11: Common configurations of sludge disintegration technologies for the enhancement of anaerobic digestion

Table 11: Example Technologies for the Pretreatment of Sludge Prior to Digestion[1]

Generic Technology Description	Energy/Force Applied	Notes	Vendor Cost ($)
High pressure homogenization	hydrodynamic cavitation (12,000 psi) following chemical pretreatment (NaOH)	no U.S. installations, 1 planned installation in Canada	2,000,000
Ultrasonics	acoustic cavitation	no U.S. installations, several European installations	N/A
Pulsed-electric field	electroporation of cells by application of high voltage current	single U.S. installation	1,500,000
Hydrodynamic Cavitation	forcing solids through a high pressure nozzle to induce cavitation	several European installations	750,000
Thermal hydrolysis	high pressure vessel, high heat (170 ºC)	no current U.S. installations, several global installations	N/A

Note: 1: no current applications for algal cell disintegration, at the time of this report

Table 11, provides a partial listing of types of technologies that are currently being used to increase the degradability of waste activated sludge prior to digestion. Assuming that the addition of a sludge minimization technology will improve the VSr of the algae by 20 percent, a value typical to most processes, the observed VSr would increase from 40 percent to 48 percent. Table 12, evaluates the impact of the addition of a sludge disintegration technology to the mesophilic co-digestion of algae solids at Sunnyvale.

Table 12: Summary of Digestion Performance and Energy Recovery of Mesophilic Co-Digestion of Algae and Primary Sludge Enhanced with a Sludge Disintegration Process for Year 2035

Parameter	Value	Units	Notes and Assumptions
Operating Conditions at 2035			
Algae Load (lb-TS/day)	12,397	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Algae Load (lb-VS/day)	10,538	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-TS/day)	13,200	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-VS/day)	11,220	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge VSr	60%	percent	Source: TM: Solids Load Technical Memorandum
Algae Sludge VSr	48%	percent	Assumed a 20 percent increase in VSr
Anaerobic Digester Operation: Biogas Production			

Table 12: Summary of Digestion Performance and Energy Recovery of Mesophilic Co-Digestion of Algae and Primary Sludge Enhanced with a Sludge Disintegration Process for Year 2035

Parameter	Value	Units	Notes and Assumptions
Primary Sludge Volatile Load (lb-VS/day)	11,220	lb-VS/day	
Algae Volatile Solids Load (lb-VS/day)	10,538	lb-VS/day	
Biogas Yield	15	ft^3-biogas/lb-VSr	Assumed equivalent biogas yield from algae and primary sludge
Total Annual Biogas Production from Primary Sludge	3,6857,700	ft^3-biogas/year	
Total Annual Biogas Production from Algae	2,7693,203	ft^3-biogas/year	
Lower Heating Value of Biogas	620	BTU/ft^3	Lower heating value of biogas
Total Energy from Primary Sludge	228,518	therm/year	
Total Energy from Algae	171,698	therm/year	
Value of Biogas	$1.04	$/therm	Average price of natural gas, Sunnyvale Data
Market Value of Biogas from Primary Sludge	$237,658	annually	
Market Value of Biogas from Algae	$178,566	annually	
Total Value of Biogas From Digestion	$416,224	annually	

5.2.1 Thermophilic Anaerobic Digestion

Thermophilic anaerobic digestion operates at temperature ranges between 50 and 55 ºC and at retention typically around 5 days or greater, though some processes have reported 3 day detention times. The primary advantages of thermophilic processes are the greater pathogen kill, increased solids destruction and increased biogas production. The elevated temperatures associated with thermophilic digestion typically increase the rate and extent of the biological mineralization of sewage sludges. However, thermophilic digestion while effective does have its drawbacks. Table 13, summarizes some of the common benefits and drawbacks of thermophilic digestion, using mesophilic digestion as the base line condition of comparison. It should be noted, that while thermophilic digesters commonly report enhanced pathogen reduction the process is not considered a process that further reduces pathogens (PFRP) under EPA 503 regulations.

There are a variety of thermophilic digestion configurations that can be used to effectively treat sewage sludge. Single stage and series thermophilic, have been successfully used. Temperature phased anaerobic digestion (TPAD) has also be successfully used. If thermophilic digestion is pursued it is recommended that Sunnyvale utilize the temperature phased digestion process configuration. Figure 12, provides a schematic of the TPAD process. The incorporation of the mesophilic stage serves mitigate some odors associated with thermophilic sludge dewatering by consumption of excess volatile acids and a reduction in ammonia release through a reduction in operating temperature. Analysis, provided in Appendix B, indicate there is sufficient process capacity to operate in this manner.

Table 13: Summary of the benefits and drawback of thermophilic digestion relative to a base case of mesophilic digestion

Benefits	Drawbacks
additional solids destruction	additional heating requirements
additional biogas production	increased ammonia in the return liquor
increased pathogen kill	increased volatile acids in return liquor resulting in odors during dewatering
potential to create a Class A product	typically increased polymer dose to achieve optimum conditioning
	changes in gas system associated with enhanced gas production (volume and rate)

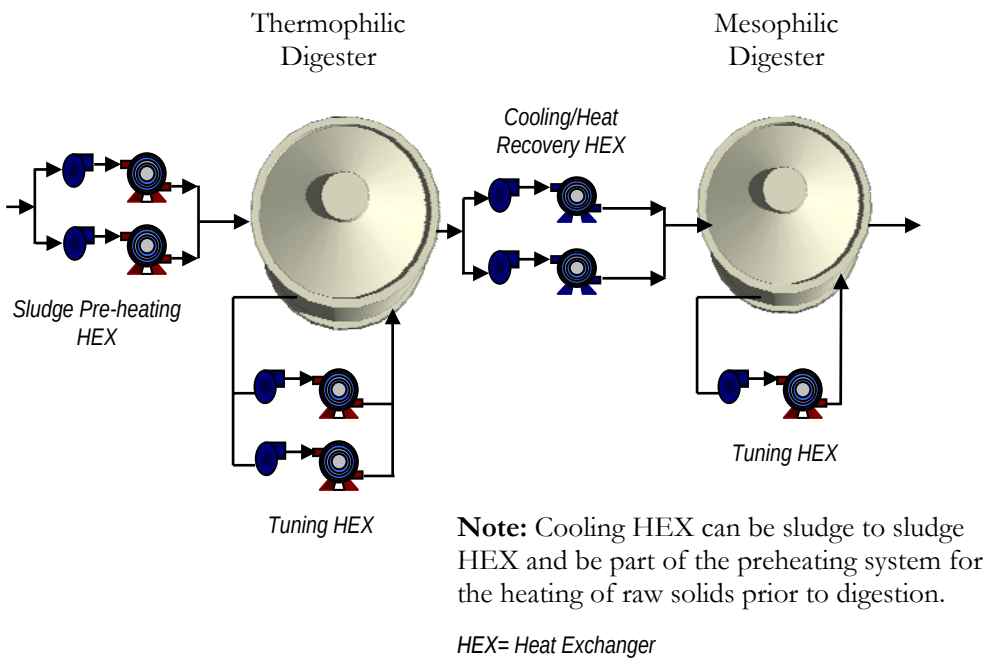

Figure 12: Basic flow schematic of a temperature phased anaerobic digestion system (TPAD)

The impact of conversion to thermophilic digestion not only impacts the degradability of the algae but the primary sludge as well. The study by Gouleke et al (1957) reported an approximately 10 percentage point increase in algae VSr when the process temperature was increased from 95 °F to 122 °F, most thermophilic processes today operate at 131 °F. Assuming that a similar improvement algae VSr would occur at Sunnyvale and the primary sludge VSr would increase to 65 percent, just below it current annual average of 68 percent, the performance changes in the system can be predicted. Table 14, summarizes the performance change associated with the thermophilic co-digestion of algae with primary sludge.

Table 14: Summary of Digestion Performance and Energy Recovery with the Thermophilic Co-Digestion of Algae and Primary Sludge for Year 2035

Parameter	Value	Units	Notes and Assumptions
Operating Conditions at 2035			
Algae Load (lb-TS/day)	12,397	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Algae Load (lb-VS/day)	10,538	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-TS/day)	13,200	lb-TS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge Load (lb-VS/day)	11,220	lb-VS/day	Source: TM: Solids Load Technical Memorandum
Primary Sludge VSr	65%	percent	Assumed a 5 percentage point increase with conversion to thermophilic
Algae Sludge VSr	50%	percent	Assumed a 10 percentage point increase base on Gouleke et al (1957)
Anaerobic Digester Operation: Biogas Production			
Primary Sludge Volatile Load (lb-VS/day)	11,220	lb-VS/day	
Algae Volatile Solids Load (lb-VS/day)	10,538	lb-VS/day	
Biogas Yield	15	ft^3-biogas/lb-VSr	Assumed equivalent biogas yield from algae and primary sludge
Total Annual Biogas Production from Primary Sludge	39,929,175	ft^3-biogas/year	
Total Annual Biogas Production from Algae	28,847,086	ft^3-biogas/year	
Lower Heating Value of Biogas	620	BTU/ft^3	Lower heating value of biogas
Total Energy from Primary Sludge	247561	therm/year	
Total Energy from Algae	178852	therm/year	
Value of Biogas	$1.04	$/therm	Average price of natural gas, Sunnyvale Data
Market Value of Biogas from Primary Sludge	$257,463	annually	
Market Value of Biogas from Algae	$186,006	annually	
Total Value of Biogas From Digestion	$443,469	annually	

5.3 Recommended Digestion Enhancement Approach

Assuming that the ultimate degradability of the solids in the digester is 83 percent and stabilization in the pond makes a uniform product, regardless of digestion process the benefit of each digestion process is a function of energy recovery and capital costs. Table 15, provides a summary of the energy recovery using mesophilic digestion, thermophilic digestion and disintegration enhanced digestion.

Table 15: Summary of Energy Recovery and Equivalent Value of Biogas for Co-digestion Process Alternatives

Co-Digestion Process	Value of Recovered Biogas ($ / year)	Marginal Value of Recovered Biogas over Basic Mesophilic Digestion ($ / year)	Limiting Capital Investment for 10 year Payback ($)[1]
Mesophilic Digestion	386,463	NA	NA
Mesophilic with Sludge Disintegration	416,224	29,761	230,000
Thermophilic Digestion	443,469	57,006	440,000

[1] Assuming 5% discount rate, (P/A, 10 yrs, 5% = 7.722)

Table 15 suggests that an investment in sludge disintegration of greater than $230,000 would not pay itself back in less than 10 years. Current information on costs for sludge disintegration technologies indicate that it would be unlikely to acquire this improvement within that limiting price range. Similarly, to achieve a 10 year payback with thermophilic digestion, the capital investment should be less than $440,000.

A cost analysis for thermophilic digestion is being conducted in another on-going Strategic Infrastructure Plan evaluation (associated with the new treatment plant major approach). The results of that effort will provide better information on the advisability of investing in thermophilic digestion to achieve enhanced algae digestion in the major approach of rehabilitating the existing plant processes.

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APPENDIX A: IMPACT OF ALGAE ADDIITON TO MESOPHILIC DIGESTER CAPACITY

Capacity Impacts of Algae Co-Digestion under the Recommended Configuration-Mesophilic

A revaluation of the capacity assessment adding in maximum month algae loads, as noted in Table A-1, was conducted. It was also assumed that not only was the primary sludge thickening upgraded to produce a 5 percent total solids sludge but the dissolved air floatation was either rehabilitated or replaced producing a 5 percent total solids algae float.

Table A-1: Projected Maximum Month Primary Sludge and Algae Production from Sunnyvale WPCP[1]

	Total Solids Load (lb-TS/d)		Hydraulic Load (gpd)	
Year	Primary Sludge	Algae Float	Primary Sludge	Algae Float
2010	20,080	14,407	46,523	32,884
2015	20,759	14,613	48,097	33,354
2020	21,511	14,751	49,839	33,667
2025	22,263	14,888	51,581	33,981
2030	22,913	14,888	53,088	33,981
2035	23,608	15,368	54,696	35,077

1: assumes algae float and primary sludge are both at 5 percent total solids and have a 85 percent volatile solids content

Figure A-1, plots the change in solids retention time in the digesters associated with the addition of algae float over the planning window, with primary sludge only digestion as a reference to current operations. What is apparent in Figure A-1 is that even when adding the entire maximum month load to the digesters, with the largest unit out of service, there is more than sufficient hydraulic residence time in the digester to accommodate the addition of algae. At the planning horizon the system would be operating at an HRT of 20 days under maximum month conditions, an HRT thought by many to be ideal of mesophilic digestion.

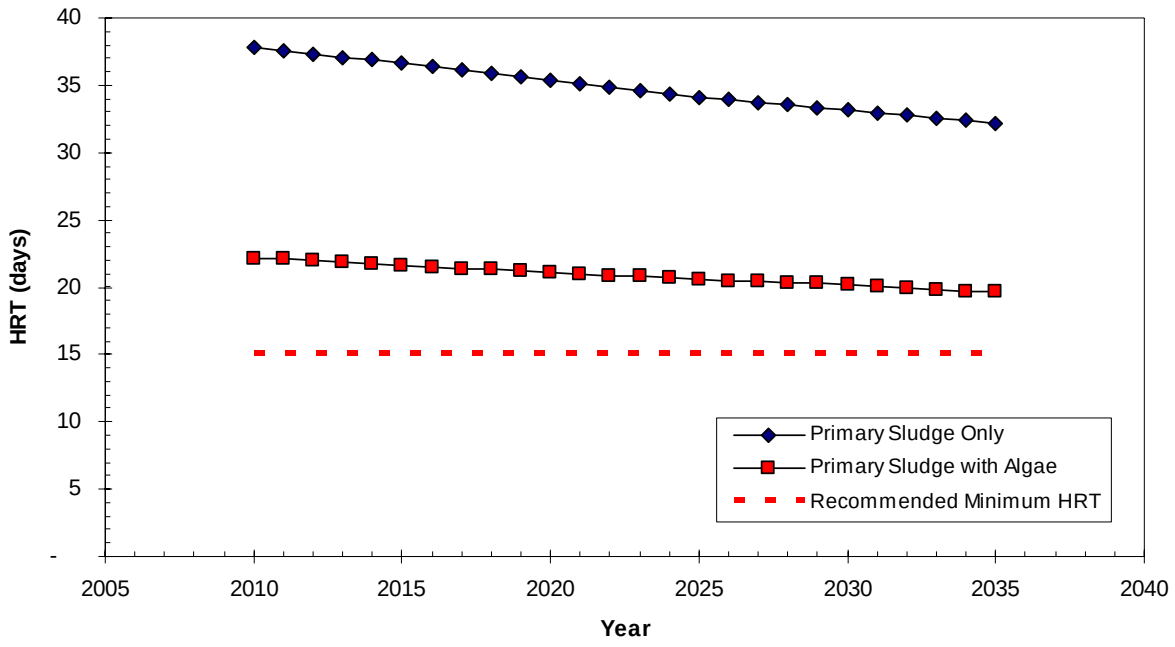

Figure A-1: The influence of algae addition on digester HRT at Sunnyvale WPCP, under maximum month flow and load

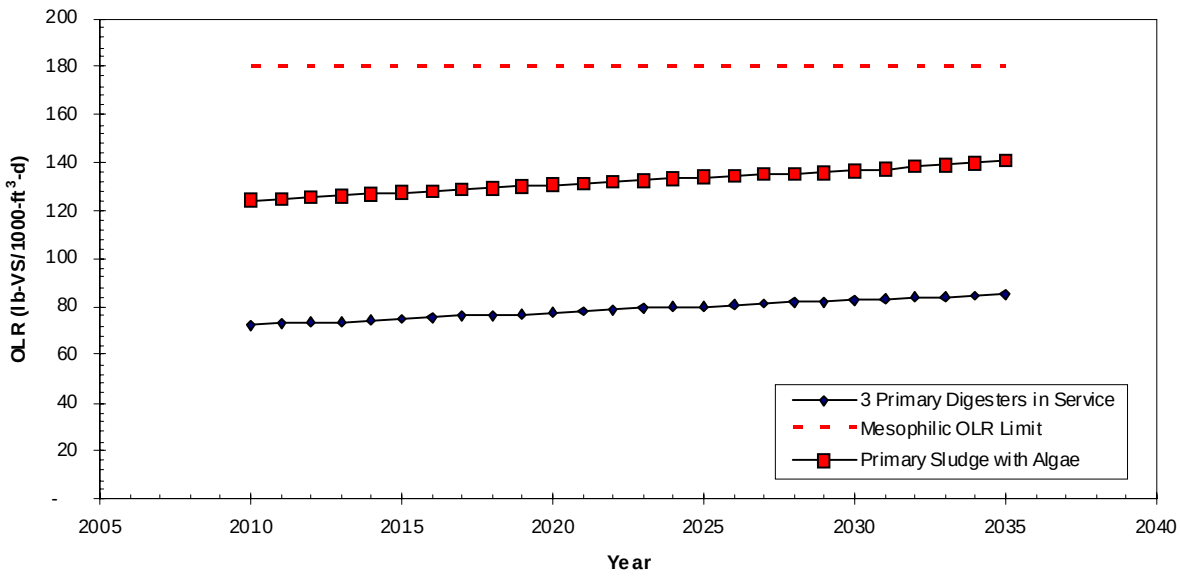

Figure A-2: The influence of algae addition on digester OLR at Sunnyvale WPCP, under maximum month flow and load

Figure A-2, presents the impact of algae addition on the organic loading rate to the anaerobic digesters under maximum month conditions. As with the HRT data the OLR data indicate that the addition of algae will consume a portion of the existing capacity, 141 lb-VS/1000-ft^3-d, at the planning horizon, but still remain within the maximum recommended loading rate, 180 lb-VS/1000-ft^3-d. Based on these findings, and assuming that both primary sludge and algae thickening are upgraded, there is more than sufficient remaining capacity in the digesters to accept algae.

Base on the data presented in Figures A-1 and A-2 there is sufficient process capacity to co-digest algae with primary sludge, up to the planning horizon, under mesophilic conditions.

APPENDIX B: IMPACT OF ALGAE ADDIITON TO THERMOPHILIC

DIGESTER CAPACITY-TEMPERATURE PHASED

Impact of Co-digestion of Algae on the Capacity of a Temperature Phased Anaerobic Digestion system

Thermophilic digestion capacity was evaluated with one unit out of service, the largest, Digester 4. Assuming that upgraded DAF operation and primary sludge thickening perform the same there is no added hydraulic capacity associated with the system. Given the recommended system configuration is temperature phased the process flow schematic for the system would have two thermophilic and 1 mesophilic digester, as shown in Figure B-1. Under this configuration the cooling rate between the thermophilic and mesophilic digesters would increase as there is only one tank to receive the solids. By leaving two thermophilic digesters in operation the most heavily loaded portion of the system would remain unaffected, by the out of service condition.

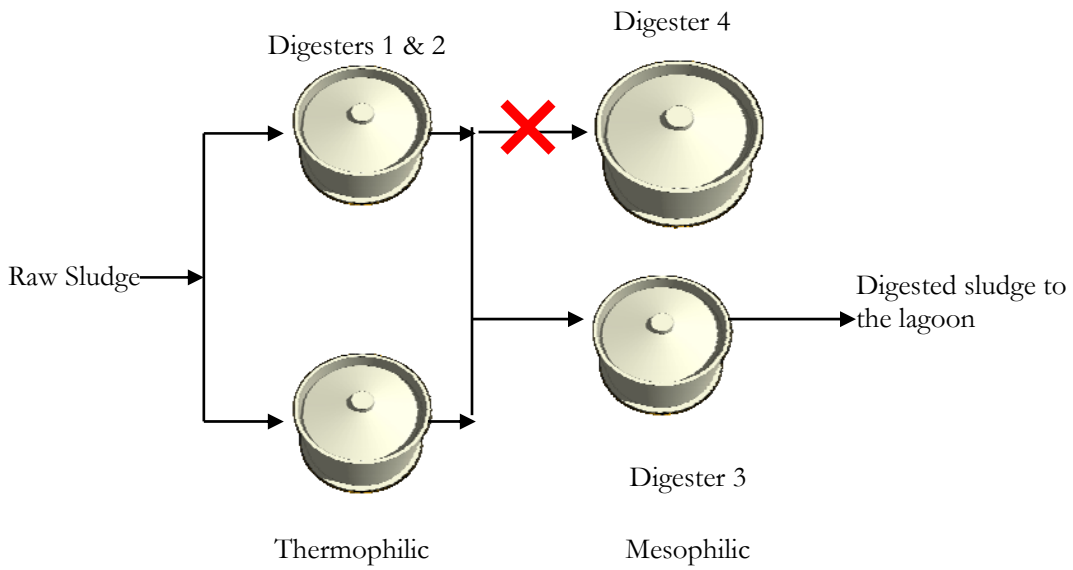

Figure B-1: Basic flow schematic of TPAD operation at Sunnyvale with the largest unit out of service

Thermophilic digestion is still a Class B process and it is typically accepted that a residence time of 15 days produces a stable biosolids product, therefore by setting the minimum system HRT at 15 days regulatory and aesthetic requirements can be met. It should be noted that the thermophilic digestion lower limit for HRT should be approximately 5 days to ensure sufficient process stability. If there is significant peaking in the sludge loading a longer HRT may be warranted.

Figure B-2, plots the total system and the thermophilic phase HRT as a function of time for the recommended system. What is apparent in the data is that there is sufficient hydraulic capacity in both the thermophilic phase and the entire system to maintain adequate retention time for stable, Class B biosolids digestion.

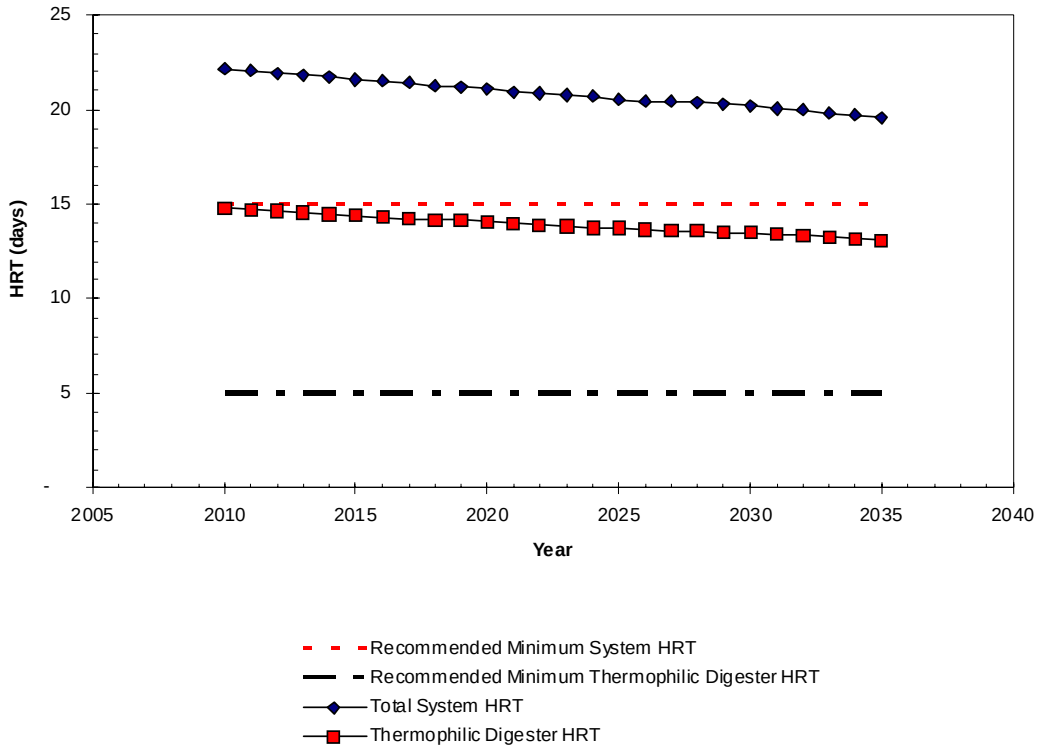

Figure B-2: Influence of Algae co-digestion on the operating HRT of a TPAD system at Sunnyvale WPCP

The organic loading capacity of thermophilic systems is significantly higher than that of mesophilic systems. Thermophilic digestion processes have achieved stable operation at organic loading rates of 350-450 lb-VS/1000-ft3-day and higher. Even at the lower range, which is the recommended limit, the process has approximately double the organic loading capacity of a similarly sized mesophilic digester. Figure B-3 plots the organic loading rate to the thermophilic phase of the TPAD process, 2 primary digesters, over the planning period. The mesophilic phase is typically not considered in this portion of the analysis as approximately 89 percent of the solids degradation occurs in the first stage of TPAD, making the degradable organic load to the mesophilic stage very low.

What is apparent from the data in Figure B-3, is that the is more than sufficient organic loading capacity in the Sunnyvale digesters under a TPAD configuration. The peak loading achieved by 2035 is 211 lbs-VS/1000-ft3-day, well below the state limits of thermophilic digestion.

Based on this analysis, and assuming all digester upgrades proceed, there is sufficient process capacity to operate a TPAD system with the largest unit out of service at the Sunnyvale WPCP.

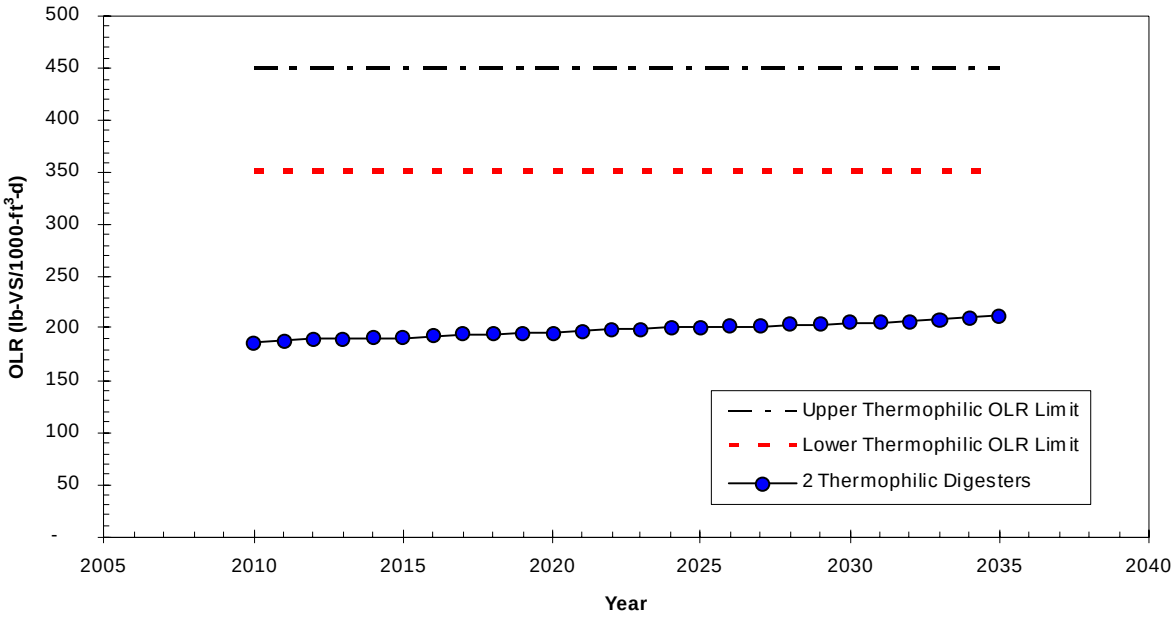

Figure B-3: Influence of Algae co-digestion on the operating OLR of a TPAD system at Sunnyvale WPCP