APPENDIX U

Treatment Technologies

Appendix U provides additional details about the range of treatment technologies that were evaluated in support of the development of the Recommended Plan.

Primary Treatment

Increased Hydraulic Loading Rate

The traditional design standard is now considered to be conservative. Modern rectangular clarifier design allows peak surface overflow rates of up to 4,000 gpd/foot^2. This results in an approximately 35% reduction in tank footprint. This strategy also enables the expansion of the wet-weather capacity of existing facilities without building additional primary tanks.

Chemically Enhanced Primary Treatment

The addition of chemicals such as ferric chloride, alum, lime, and polymer to the primary process has been practiced to enhance TSS and BOD removal and increase the surface loading rate. This process had been applied at San Francisco facilities in the past and was found to perform poorly during wet–weather. This was possibly due to the rapidly changing influent condition during wet–weather—such as solids content, alkalinity, and ionic balance–that made it difficult to adjust to and maintain an optimum chemical dose. The process performance may benefit from reliable real-time water quality monitoring and automated control, which is yet to be demonstrated. The Oceanside Water Pollution Control Plant (OSP) essentially practices partial Chemically Enhanced Primary Treatment (CEPT), by adding ferric chloride to the plant influent for odor control. As a result, the primary tanks demonstrate higher TSS and BOD removal than conventional primary facilities. There is, however, no apparent incentive to implement CEPT for the purpose of improving TSS and BOD removal, as all dry-weather wastewater receives secondary treatment. It is recommended to consider chemical addition as an optional process for primary treatment since it provides multiple benefits.

Stacked Clarifiers

Stacked sedimentation tank designs have been used where land areas are limited (Osaka, Japan, and Singapore). In the U.S. the most notable installation is the Deer Island Wastewater Treatment Plant in Boston Harbor. The typical design involves stacking two tanks of parallel flow, each with individual sludge collection that discharges to a common sludge hopper. The effluent launders of the bottom tank are located at the end of the top tank. Existing installations have demonstrated performance similar to conventional sedimentation tanks. One disadvantage is more complicated maintenance work, because of restricted access to the lower tank. Equalizing flow distribution between upper and lower tanks also adds to the operating challenge. The stacked clarifier design can considered for treatment sites with limited area.

High-Rate Clarification

High-rate clarification accelerates the settling of particulate matter with the use of metal coagulants, polymer, and/or ballast particles, flocculation chambers, and inclined plate or tube settlers. The process has been used in Europe for over two decades and is beginning to be installed in the U.S. The peak hydraulic loading rate can be an order of magnitude higher than that of conventional primary sedimentation, dramatically increasing the flow capacity of a given facility footprint. The process also achieves higher TSS and BOD removal. Typical applications include advanced primary treatment, wet-weather treatment, and treatment of process side streams.

The SFPUC piloted several high-rate clarification designs and confirmed the performance and reliability of the process. The process however requires high chemical consumption. The process would be considered feasible if wet-weather treatment capacity needs to be significantly increased in a limited facility space, or if a higher primary effluent quality is desired during wet weather.

Secondary Treatment

Conventional Processes

Activated Sludge Processes

The activated sludge process involves the uptake and degradation of organic wastewater constituents by a suspended biomass of acclimated microorganisms (activated sludge) under aerobic condition, followed by sedimentation/clarification to separate the treated water from biomass. The process has been widely applied to treating municipal wastewater with well-established design and operating experience. Various process and reactor designs have been developed to improve treatment quality and optimize operating efficiency, such as reactor configuration, aeration method, and incorporation of anaerobic and anoxic stages. The clarification process is critical to producing a low-TSS effluent that meets secondary standards, and the clarifiers typically occupy a significant footprint. The process can also be designed for nutrients (nitrogen and phosphorus) removal.

The Southeast Water Pollution Control Plant (SEP) and OSP currently operate a high-purity oxygen (HPO) activated sludge system. The HPO process provides a compact aeration footprint, low off-gas emission, and high stability to load fluctuations. The disadvantages include high–energy consumption for onsite oxygen generation. If nitrification were to be required, the HPO process would not be compatible due to low mixed liquor pH—6.2 to 6.4 as opposed to 6.8 to 7.0 in air activated sludge. Alternatively, an air–activated sludge design with deeper (up to 30 foot) aeration tanks and fine bubble diffusers can achieve a compact footprint comparable to an HPO system with 15-foot tanks and operate in the requisite pH range to support nitrification.

Attached Growth Processes

In the attached growth process, wastewater is treated as it flows through biofilm attached onto a packing material, followed by a sedimentation stage. The most common examples include trickling filters and rotating biological contactors (RBCs). Trickling filters have been in use for over a century. The reactor, also termed biotower, is filled with packing and wastewater is distributed to the top of the reactor. The RBC process involves a series of tightly spaced plastic discs that rotate through wastewater. The processes are generally of simple design and operation and require less energy.

Submerged attached growth processes, a newer type of attached growth processes, are discussed in the Compact Technologies section.

Anaerobic Processes

Anaerobic degradation of wastewater organic material can be highly energy efficient, since aeration is not required and methane gas is produced as a byproduct. The processes can be suspended or attached growth. One noted example is the upflow anaerobic sludge blanket (UASB) process. The processes allow for high organic loading and are more commonly applied to high-strength wastes. Treatment performance is also sensitive to temperature. To comply with secondary discharge standards, a subsequent aerobic process would be required.

Green Technologies

Constructed Wetlands

Constructed wetlands are engineered wastewater treatment systems that are based on the use of emergent wetland vegetation, such as cattails, rushes, or reeds. They can be further divided into three types, free water surface, subsurface flow, and vertical flow systems.

In free water surface wetlands, the emergent vegetation is flooded to a depth of 4 to 18 inches. The wastewater is treated as it flows through the wetland by bacteria attached to the submerged vegetation, as well as by physical and chemical processes. Typical vegetation in free water surface wetlands includes cattails, reeds, sedges, and rushes. A free water surface wetland system usually consists of multiple channels constructed over an impermeable liner or low-permeability compacted soil. Mosquito management is required to prevent nuisance conditions (Crites and Tchobanoglous 1998). Free water surface wetlands can be designed for tertiary effluent polishing while providing a community amenity for activities such as bird watching and hiking. Constructed wetlands designed for these purposes generally have a greater percentage of open–water areas to attract waterfowl and to create a visually appealing environment.

In subsurface flow wetlands, wastewater is treated as it flows through gravel or sand media planted with emergent wetland vegetation. The water surface is maintained below the media surface. The vegetation transports oxygen to the plant roots, supporting aerobic bacteria in the media. Treatment also occurs through physical and chemical processes. Subsurface flow wetlands are usually planted with bulrush or reeds because of the deeper rooting depths of these plants. Mosquito breeding is prevented with the absence of free water surface. Subsurface flow wetlands have been operating on a small scale for the last 15 years (Crites, et al. 2006). The typical flow is less than 0.5 mgd due to the cost of the media.

Vertical flow wetlands are a variant of intermittent packed-bed filter technology. The wetland consists of a pea-gravel media bed planted with emergent vegetation. Influent is intermittently distributed to the surface and percolates through the media. Wetland vegetation improves the aesthetics of the media bed while supplying a small amount of oxygen to bacteria in the media via the plant roots. Part of the effluent collected at the bottom of the wetland is mixed with influent and recirculated. Vertical wetlands are more effective at nitrification than free water surface and subsurface flow wetlands due to the intermittent dosing of water and continuously drained media.

Tidal Flow Wetlands Living Machine

The Tidal Flow Wetland Living Machine System is a proprietary integrated treatment system consisting of a series of aerated and vegetated reactors, clarifier, and fluidized beds. The Living Machine® represents the company's latest and most advanced system. It is a variation of the vertical flow subsurface flow wetlands and operates on a fill-and-draw basis. It consists of four to six tidal flow cells that operate in series, connected by small basins with integral pump stations. Each tidal flow cell is filled with engineered media and covered with aquatic plants. The cells are flooded and drained via pumping several times daily to simulate tidal cycle. Influent step feed and recycle of final effluent are integral to the design (Living Designs Group 2005). The system developer reports that the technology can achieve excellent effluent quality and nitrogen removal. The system is designed to be an attractive facility and can be viewed as an amenity.

An earlier version of the Living Machine was pilot tested at the OSP, not as a secondary treatment process but for treating secondary effluent to Title 22 level and for nutrient removal (Ocean Arks International 1996). The Living Classroom, an environmental education and demonstration center under construction at Heron's Head Park in San Francisco, will operate a Living Machine system.

Algal Ponds

Algal ponds use algae as a major source of oxygen to support pollutants degradation by aerobic bacteria. Algal ponds have low energy consumption compared with systems using mechanical aeration, but require large surface areas to support algae photosynthesis. Advanced algal pond systems incorporate different types of ponds, including facultative ponds with anaerobic digestion pits at the bottom and a high algae population in the upper layer to support aerobic treatment and odor removal.

Due to algal biomass carried over to the effluent, an algae removal process such as dissolved air flotation is required downstream in order to meet secondary standards. There is always a meaningful decline in pathogenic bacteria across algal ponds, although this does not eliminate the need for disinfection.

Floating Aquatic Plant Systems

The floating aquatic plant systems include water hyacinth systems and duckweed systems. Water hyacinth systems are similar in concept to free water surface wetlands, but are based on using water hyacinths rather than emergent wetlands vegetation. The water hyacinth (*Eichhornia crassipes*) is a perennial freshwater macrophyte that is native to the Amazon region of South America. They now populate the Sacramento–San Joaquin River Delta, where they are considered to be an invasive aquatic weed. Water hyacinth wastewater treatment systems consist of wastewater ponds containing floating water hyacinths. The water hyacinths transmit oxygen to the water through the roots. Bacterial growth attached to the plant roots accomplishes much of the pollutant removal, in addition to physical and chemical processes. The water hyacinth multiplies rapidly under proper conditions (presence of warm water and nutrients) and must be regularly harvested and disposed. Mosquito control measures are required to prevent nuisance conditions.

Water hyacinth systems are able to produce secondary quality effluents. Nitrification can also be achieved if the system is aerated (Tchobanoglous, et al. 1989). There are relatively few water hyacinth systems still in operation.

Duckweed systems are typically used for effluent polishing downstream of algal ponds. Lemna Corporation, the proprietor of the process, no longer advocates for the floating duckweed technology. This system is not considered further.

Compact Technologies

Activated Sludge with Fixed-Film Packing

This type of process is also commonly described as Integrated Fixed-Film Activated Sludge (IFAS) and is designed to enhance the activated sludge process with attached-growth biomass on packing material placed in the mixed liquor. Several types of synthetic packing materials have been developed that can either be suspended or fixed in the aeration tank. Because of the complexity of the processes and issues related to understanding the biofilm activity, IFAS process designs are usually based on pilot-plant or demonstration-scale results. Two available systems, one with suspended packing and one fixed, are given below as examples.

Among the more than 10 existing suspended IFAS processes, the HYBAS process, developed by the Norwegian company Anox Kaldnes, is currently a market leader. The process combines activated sludge with the moving-bed biofilm reactor technology, which uses small cylindrical polyethylene carriers as fix-film packing. The carriers have a specific surface area of about 500 m^2/m^3 and may occupy 25% to 50% of the reactor volume. They are retained and continuously circulated in the reactor. The process also provides a compact option for nitrification applications.

The Ringlace process is one example of fixed IFAS processes. The packing are looped strands of polyvinyl chloride. The strands are wrapped onto racks or frames to form packing modules that provide 120 to 500 m^2/m^3 specific surface area. The modules occupy 25% to 35% of reactor volume. The process performance is sensitive to the BOD level and optimal performance may be difficult to achieve.

Aerobic Submerged Fixed-Film Processes

In these processes, the biofilm packing is submerged and the reactor is operated similarly to a filtration unit. They are also referred to as biological aerated filters (BAFs). They include downflow packed-bed reactors, upflow packed-bed reactors and upflow fluidized-bed reactors. Oxygen is supplied by diffused aeration into the packing or predissolved into the influent. The type and size of packing is a major factor for performance and operating characteristics. Clarification is not required. Excess solids from biomass growth and influent suspended solids removal are trapped in the system and must be periodically removed, most often by a backwashing system similar to one used in a water filtration plant, usually on a daily basis. Such fixed-film systems have hydraulic retention times of 1.0 to 1.5 hours based on empty tank volumes. Many processes can produce a high-quality effluent with filtration integrated in the system, although not at Title 22 level. Two proprietary systems are described below.

Biofor is an upflow system using expanded clay particles for packing and has a typical bed depth of 2 to 4 meters with installed packing porosity of 40%. Fine influent screening is needed to protect the inlet nozzles. Backwashing is undertaken once per day. In applications for BOD removal only, organic loading ranges from 3.5 to 4.5 kg BOD/m^3–d, and for combined BOD removal and nitrification the organic loading is reduced to 2.0 to 2.7 kg BOD/m^3–d.

Biostyr is an upflow system that uses polystyrene beads for packing. Typical depth is 1.5 to 3.0 m with packing porosity of about 40%, providing an effective specific area of 400 m^2/m^3 for biofilm growth. The floating packing is compressed as wastewater flows upward to provide filtration. Typical organic loadings are similar to those used for the Biofor systems.

Membrane Bioreactors

Membrane biological reactors or membrane bioreactors (MBR) consist of a biological reactor with suspended biomass and solids separation by microfiltration membranes with nominal pore sizes ranging from 0.1 to 0.4 μm, thereby replacing the functions of secondary clarification and tertiary filtration. Hollow-fiber membrane systems have been developed as well as sheet configurations. MBRs have two basic configurations; the integrated MBR has the membrane modules mounted in the bioreactor, and the recirculated MBR has the membrane separation unit external to the bioreactor. Currently, most large MBR facilities are of the integrated type. Treated effluent is withdrawn with the application of a vacuum (less than 50 kPa) on the filtrate side of the membrane.

Membrane fouling control is critical to MBR performance. The causes and mechanism of fouling is not completely understood.

Continuous membrane cleaning is provided by the shearing action of air bubbles from the aeration system. More aggressive cleaning such as chemical soak is conducted periodically to maintain the filtration capacity of the membrane. In an MBR pilot study at the SEP, rapid membrane fouling was observed in wet-weather conditions, possibly caused by stressed biomass due to diluted influent or other factors. The feasibility of MBR application at San Francisco thus requires further investigation.

By replacing secondary clarifiers, membranes avoid issues of sludge bulking and other floc settling problems, and the system MLSS concentration is no longer limited by secondary clarifier solids loading capacities and can be as high as 20,000 mg/L (around 10,000 mg/L is more typical). The effluent quality is ideal for reuse applications, with turbidity typically less than 0.5 NTU.

Disinfection Technologies

Ultraviolet Radiation

The ultraviolet radiation (UV) process was considered for the Southeast Water Pollution Control Plant secondary effluent as part of the SEP 250-mgd expansion plan in the early 1990s. Available UV technologies at the time would require significant redundancies and result in a large facility with an excessive number of lamps. The estimated costs were considered unacceptable, and chlorination was not replaced. Since that time, however, the technology has experienced considerable improvements and UV disinfection of wastewater has become an increasingly popular alternative.

The UV lamps contain mercury or mercury amalgam, which, as electrons flow through and excite the mercury vapor, emits UV light. As UV light penetrates through the cell wall and cytoplasmic membrane, it causes a molecular rearrangement of the microorganism's DNA and RNA. The damage prevents normal DNA and RNA replication and the microorganism is inactivated. Comparing the disinfection effectiveness of chlorination and UV (WERF 2004), the performances on fecal coliform deactivation are similar, but UV is more effective at inactivating total bacteria, viruses, and protozoa. At a dose of 20mJ/cm^2, UV is highly effective against chlorine–resistant protozoan cysts such as Cryptosporidium parvum and Giardia lamblia. UV does not experience a reduction in disinfection efficiency in the presence of ammonia as is the case with chlorination. The UV process does not generate chlorinated DBPs and does not leave a residual.

UV systems fall into three basic categories: low pressure, low intensity; low pressure, high intensity; and medium pressure, high intensity. Low-pressure, low-intensity systems are generally considered applicable for smaller systems with higher quality (e.g., filtered) effluents and are not feasible for large-scale secondary effluents. Medium-pressure, high-intensity systems deliver the highest UV dosage per unit and are the most commonly selected UV systems for larger municipalities. Low-pressure, high-intensity systems have evolved considerably in recent years. Use of a mercury amalgam instead of mercury in the UV lamps provides two to four times the output of a low-pressure, low-intensity system. While these systems cannot necessarily match the output of a medium-pressure, high-intensity system, they have the advantage of using considerably less power. Both the medium-pressure, high-intensity and low-pressure, high-intensity systems have installations greater than 300 mgd and many recent large installations are in the low-pressure, high-intensity category.

Ozone

Ozone, an unstable gas produced when oxygen molecules are reacted with an electrical discharge, is the strongest oxidant of the disinfectants discussed here. Ozone is typically produced on site, diffused into a reactor in contact with wastewater, and achieves bacterial kill through cell wall disintegration. It produces no residual, and the off-gas oxygen can be reused in the secondary process. The primary disadvantage of ozonation is its tremendous power consumption. Ozonation systems also tend to have very high capital costs and have the potential to produce harmful DBPs. Historically, ozone has been used as a disinfectant at water treatment plants, but some wastewater applications were also reported. Preliminary cost estimates for secondary effluent disinfection show that the operating cost for ozone would be an order of magnitude greater than the cost for chlorination or UV.

Peracetic Acid

Peracetic acid (PAA) has long been used as a bactericide and fungicide in the food–processing industry. Produced from acetic acid and hydrogen peroxide, PAA has an oxidation capacity somewhere between that of ozone and sodium hypochlorite. PAA is considered a desirable disinfectant because it does not produce trihalomethanes (THMs) or other DBPs, but is as simple to use as sodium hypochlorite. The main disadvantage of PAA is its high cost. As a result, there are no known wastewater installations of PAA in North America and very little experimental work has been performed on PAA as a disinfectant for secondary effluent. Some experimental work has shown that it is effective at similar concentrations and contact times as sodium hypochlorite (Zacheis et al., 2003; Atasi et al., 2001). According to a California PAA manufacturer, aquatic toxicology work on PAA has been completed for both saltwater and freshwater, but the intended use of PAA at this time is for CSO disinfection and for enhancement of UV disinfection. It is currently considered cost prohibitive for secondary effluent disinfection based on typical dose and contact time. A study conducted by the Orange County Sanitation District also found that PAA did not perform significantly better than sodium hypochlorite, but costs considerably more.

BCDMH

1-bromo-3-chloro-5,5-dimethylhydantoin, also known as BCDMH, is a strong chemical disinfectant, currently in use to treat CSOs in Japan. BCDMH breaks down into hypobromous acid (HOBr) and hypochlorous acid (HOCl), both of which are strong oxidants. Compared to sodium hypochlorite, the dose of BCDMH required to achieve comparable disinfection is about half, and disinfection is achieved in one-fifth of the contact time. The use of BCDMH does, however, produce DBPs, including THMs. In addition, BCDMH produces chlorine and bromine residual, both of which would need to be treated with sodium bisulfite. There are no known installations of BCDMH disinfection systems in the United States and little toxicity information is available comparing the aquatic toxicity of bromine to that of chlorine. One study indicated that different test organisms might be more or less sensitive to bromine as compared to chlorine, but overall, bromine seems to be at least as toxic as chlorine. Thus, the use of BCDMH poses little potential environmental advantage over the current use of sodium hypochlorite. Furthermore, there is currently only one supplier of BCDMH in the United States, which could lead to supply problems.

Pasteurization

A novel patented technology integrates disinfection and power generation processes. Exhaust from a gas turbine (that drives a generator) is used to heat the effluent through a heat exchanger to pasteurization temperature (70° to 80°C). A second heat exchanger recovers heat from treated flow and preheats the feedwater. The process is claimed to achieve much higher energy effectiveness than conventional pasteurization. The California Department of Health Services accepted the process for Title 22 reclaimed water disinfection. The technology is relatively new and there are no known full-scale installations.

Class A Stabilization Technologies

Pasteurization/Mesophilic Anaerobic Digestion

Pasteurization consists of heating sludge to 70°C (158°F) or greater for 30 minutes or longer to reduce pathogens. This satisfies the Class A requirement as one of the Processes to Further Reduce Pathogens (PFRPs) defined in EPA 40 CFR Part 503. Pasteurization is almost always accomplished in batches to prevent short circuiting of pathogens through the process. As required by the 503 Rule, pasteurization must take place before mesophilic digestion, the vector attraction reduction (stabilization) process. Implementation of pasteurization is more common in Europe but fairly limited in North America.

Thermophilic Anaerobic Digestion

Thermophilic anaerobic digestion is similar to mesophilic digestion except that the reactors are operated at temperatures ranging from 50 to 57°C, resulting in the predominance of thermophilic microorganisms. The major advantages are faster reaction rates, additional volatile solids reduction and gas production, and the potential to meet Class A pathogen density requirements. At present, there are at least a dozen full-scale wastewater plants using thermophilic digestion in the U.S. and Canada. California installations include the City of Los Angeles Hyperion and Terminal Island treatment plants and one of the Inland Empire Utilities Agency plants. Themophilic digestion may also be arranged in combination with (typically in front of) mesophilic digestion in systems termed Temperature Phased Anaerobic Digestion to achieve the benefits of thermophilic digestion while reducing the volatile acids levels, and thereby the odor potential of the digested product.

Thermophilic anaerobic digestion does not necessarily produce Class A products. However, since the sludge is heated to 50°C or above, a batch process can be added to satisfy the time-temperature regimes of Class A requirements. The scheme is similar to the pasteurization process and requires multiple tanks operating in a fill/hold/draw cycle. Alternatively, continuous flow systems may demonstrate performance as PFRP equivalent. These systems usually involve efforts to minimize short circuiting in the process train, such as the plug flow process developed at Columbus, Georgia.

Acid/Gas Phased Digestion

This process separates the hydrolysis/acidification and methanogenesis phases of anaerobic digestion in order to optimize the operating conditions of each. The process achieves greater volatile solids reduction and biogas production. Either phase can be at mesophilic or thermophilic temperature. The Woodridge-Greene Valley Plant in DuPage County, Illinois, has operated this process for over 10 years. More recent examples include the Regional Plant 1 of Inland Empire Utilities Agency. Gas generated from the acid phase is extremely odorous and any leakage would likely create a significant odor problem.

Thermal Hydrolysis/ Anaerobic Digestion

Thermal hydrolysis is a sludge pretreatment process aimed at achieving more efficient anaerobic digestion and producing a highly dewaterable Class A biosolids. An example of thermal hydrolysis process is the Cambi® process that was developed by a Norwegian company and has been implemented full scale at several Northern European plants such as Denmark, Ireland, Norway, and the United Kingdom. In the process, the dewatered sludge is fed into a batch hydrolysis vessel, where high-pressure steam is introduced to bring the vessel temperature to 160°C and pressure to 100 psi. After a preset holding time, the pressurized sludge is rapidly released to a flash tank, and the cell structures of the sludge biomass are broken down (hydrolyzed) and pathogens are destroyed in the process. The processed sludge also has much lower viscosity and can be fed to the digesters at higher solids concentrations, typically about 9%. This significantly reduces the digestion volume requirements, which is one of the key advantages of the process. Other key advantages are a very well-dewatered product (typically 30% to 35% solids) and increased gas production. The Cambi® process was pilot tested successfully at the SEP in 2001.

Auto-Thermal Thermophilic Aerobic Digestion

The Auto-Thermal Thermophilic Aerobic Digestion (ATAD) process is a variation of aerobic digestion processes that utilizes the energy released from the oxidation process to raise the reactor temperature above 50˚ to 55˚C to achieve higher digestion rate. The ATAD process typically consists of at least two covered reactors in series that are mixed and aerated vigorously. The detention time is typically eight to ten days. The process is effective in volatile solids reduction and is a PFRP process (at 55˚ to 60˚C and 10-day detention time). The ATAD process has been used primarily at small plants; it is rarely used at plants over a 5- to 10-mgd capacity. There are also significant odor issues to overcome in the design and operation of ATAD facilities.

Dual Digestion

Dual digestion is a combination of aerobic and anaerobic digestion processes. The first stage consists of high-purity oxygen aerobic digestion with about a one-day detention time, which heats the sludge to thermophilic temperatures. This provides a high degree of pathogen reduction and conditions the sludge for more effective anaerobic digestion. The second stage consists of anaerobic digestion with typically 15 days of detention time. The dual digestion process can meet the Class A requirement through demonstration. This process can be implemented more readily at plants that already produce high-purity oxygen. The only West Coast example is at Tacoma, Washington.

Technologies for Producing Advanced Biosolids Products

Cake Mixture

Dewatered Class A can be blended with other materials to produce a more appealing product. One example is the Tagro product produced in Tacoma. Dewatered Class A biosolids are mixed with sand and sawdust in varying percentages and sold directly for landscaping and related uses in the Tacoma area. This option would require the minimum of capital investment. However, its feasibility depends on public acceptance and the capacity of local demands. This option can be further evaluated.

Heat Drying

Heat drying technologies use thermal energy to evaporate almost all moisture from biosolids. A wide variety of dryer technologies are available, which can be generally divided into direct and indirect drying. In direct dryers, moisture removal is achieved predominantly by convective heat transfer, with supply of hot air/gas in direct contact with dewatered sludge. Direct dryers currently have a larger market share in the United States. Indirect dryers achieve moisture removal predominantly by conductive heat transfer. The sludge is kept separate from the primary heating medium (typically oil or steam), which circulates inside the mechanisms and casing that come into contact with the sludge. The appearance and characteristics of the dried products depend on the type of feed solids and drying technology. The dried products can be either graded or ungraded. Graded products are more uniformly sized and appear more similar to commercial fertilizer products. They are therefore easier to market as fertilizer. Ungraded products tend to have wider variations in particle size and shape and contain more fines that result in a dustier product. Heat drying processes produce odorous exhaust that needs to be properly treated. Safety is also a concern with respect to fire and explosion risks. The dried products can be flammable and must be stored in properly designed and monitored facilities.

There is a long history of dried biosolids reuse in the U.S., dating back over 80 years ago when Milwaukee, Wisconsin, began producing Milorganite. The dried biosolids can be further blended with additional materials to produce more appealing and nutrient- balanced products. They can also be used as alternative, renewable fuel. Therefore, heat drying appears to be a technology that can provide more reliable and versatile reuse outlets.

Air/Solar Drying

Air/solar drying is a low-energy option to produce dried product. Traditional uncovered drying beds would not be feasible for San Francisco due to space requirement and neighborhood impacts. Recent innovations involve containing the drying process within a greenhouse or hot-house structure equipped with forced air ventilation and automatic mechanical mixing. The mechanical mixing systems vary in type and complexity, one example being a mobile "mole" that agitates the drying biosolids continuously. Exterior and interior humidity and air temperature are monitored and ventilation fans are energized as needed to maintain optimized drying conditions. Additional heat sources, such as the waste hot water stream from the cogeneration facility, may be applied to enhance the drying process. These systems are able to produce pelletized products of up to 90% solids. Treatment of the discharged airstream is required for sites with neighbors in close proximity. One small system has been successfully implemented at the town of Discovery Bay in Northern California.

The application of contained air/solar drying is still constrained by its intensive space requirement. However, the utilization of natural solar energy is an attractive feature and the drying efficiency continues to improve with technological advancements. This technology deserves further evaluation, and may be considered for drying a portion of the city's biosolids depending on space availability.

Innovative Drying Technologies

Several innovative drying technologies have been developed, often in an attempt to reduce the energy requirements. Examples include Belt Drying, which operates at lower temperatures than typical heat drying processes, and Microwave Drying, which heats the material from within. These technologies have been largely developed and applied in Europe and are currently geared toward smaller operations. They can be carried forward for future consideration as they continue to evolve and mature. As discussed in Air/Solar Drying, the utilization of the waste hot water stream from the cogeneration facility in combination with these technologies should be explored to minimize fuel/energy use.

Composting

Composting is the controlled aerobic decomposition of organic matter to produce a humuslike material. Bulking agents are mixed with dewatered cake to increase the porosity of the mixture and to supplement carbon. Typical bulking agents include wood chips and sawdust. In co-composting operations, the bulking agent is municipal green waste. Unconfined composting is conducted in the open air, while confined composting takes place within an enclosed building or vessel. Due to vigorous aeration and mixing requirements, composting processes tend to have high odor potential. The acreage demands are also very high. Thus, composting is not considered a viable option within the city, although the possibility of sending material to an offsite composting facility does exist.

Vermiculture

Vermiculture is the process of converting biosolids into soil conditioner material using earthworms. The earthworms consume the biosolids and produce castings (earthworm feces), which have a mild odor and are similar in appearance to high-quality topsoil. Biosolids are mixed with a bulking agent, such as green waste or wood chips, to increase porosity and create an ideal aerobic environment suitable for the earthworms. The mixture is typically spread in low windrows on top of a mixture of castings and earthworms. Space requirements are significant and odor control issues need to be resolved. In addition, the biosolids must be processed in batch, and the process can be very labor intensive. Work to date has been on smaller-scale facilities. For these reasons, vermiculture is not recommended for further consideration.

Slurry-Carb® Process

This is a patented process developed by EnerTech Environmental, Inc. that creates renewable fuel from biosolids. Dewatered biosolids are subjected to high heat and pressure (250° to 350°C and 1200 to 2100 psi) to break down the cellular structure, releasing carbon dioxide. After depressurization and partial cooling, the resulting slurry is dewatered with centrifuges to about 50% solids, and then dried to over 90% solids. The dried product, called E-Fuel®, is carbon rich and is considered a renewable fuel in California, and can be used in cement kilns and coal-fired processes. The process is claimed to be more energy efficient than heat drying. The first full-scale Slurry-Carb facility is being constructed at Rialto, California, to process about 883 wet tons of biosolids into 167 dry tons of E-Fuel daily. The facility is expected to be operating fully by early 2009. The Slurry-Carb process is considered a future possibility for the SFPUC, and the performance of the Rialto facility, as it comes online, will be reviewed.

Thermal Depolymerization and Thermal Conversion Process

This is a patented process developed by Changing World Technologies, Inc. that converts complex organic materials into a light crude oil. Potential feedstock materials include food-processing wastes, wastewater solids, mixed plastics, and old tires. The feedstock is subjected to high temperature and pressure (250°C and 600 psi) for about 15 minutes. The pressure is then rapidly reduced to boil off most of the water. This produces a mixture of crude hydrocarbons and solid minerals that are separated out. The hydrocarbons are refined further in a second reactor that is heated to 500°C. The oil product is suitable for electrical generation equipment. The first full-scale facility is in Carthage, Missouri, which processes turkey offal. The facility has experienced odor complaints since its startup in February 2005. There are currently no full-scale facilities that process sewage sludge. Further development and performance demonstration are required for this process to be a viable option for the City.

Thermal Processing with Energy Recovery

As the most direct method of exploiting the energy value of biosolids, this process consists of the complete combustion of biosolids in fluidized bed or multiple hearth incinerators. Heat is recovered by passing combustion exhaust through heat exchangers and is usually directed back to the combustion process to reduce supplemental fuel requirements. Digested sludge has lower energy value and would need to be dewatered to higher solids content to avoid supplemental fuel needs. Air pollution control devices, such as wet scrubbers, dry and wet electrostatic precipitators, fabric filters, and afterburners are used to reduce emissions to acceptable levels. The EPA estimates that approximately 20% of the biosolids generated in the United States are combusted for disposal. In California, biosolids incinerators are operated by the

City of Palo Alto and the Central Contra Costa Sanitary District. This option is not recommended for the city, as air and other permitting issues, along with negative public perception, potentially make such a facility impossible to site within the city limits.

Bio-Brick Production

Bio-bricks are produced by mixing dewatered biosolids with the conventional brick ingredients of clay and shale. The mixture is formed, dried, and then fired in the conventional brick-making manner. The kiln temperatures reach 1,100°C during the firing process, causing the combustion of the organic matter in the biosolids. Therefore, the biosolids provide some energy value to the kiln. The interstitial voids in the bio-bricks add to the freeze-thaw durability and improve mortar adhesion. Pilot testing is required to determine the acceptable quantity of biosolids that can be incorporated into a brick mixture while maintaining compressive strength, water absorption, and freeze-thaw resistance criteria. Upgraded emission control equipment may be required for the bio-brick kiln. In addition, there is very limited large-scale experience with this technology. The current feasibility of this option is therefore low for the City. The SFPUC may monitor its development for future consideration.

Supercritical Water Oxidation

Supercritical water oxidation (SCWO) oxidizes organic and biological materials virtually complete to benign products without the need for stack gas scrubbing. An additional potential benefit of this technology is the possibility of direct recovery of energy from sludges. While this technology holds promise, there have been major obstacles to commercialization, such as the development of reactors that cannot be clogged by inorganic solids deposits. This technology is currently in a pilot-scale level of development and is testing for wastewater treatment plant sludges.

References

Atasi, K. et al. Alternative Disinfectants Evaluation for Combined Sewage Overflow (CSO): Detroit Baby Creek CSO Case Study. WEFTEC, Atlanta, GA. Water Environment Federation. 2001.

Crites, R.W., E.J. Middlebrooks and S.C. Reed. Natural Wastewater Treatment Systems. CRC Press, Boca Raton, FL. 2006.

Crites, Ron, and George Tchobanoglous. Small and Decentralized Wastewater Management Systems. WCB McGraw-Hill. 1998.

Living Designs Group, LLC. Tidal Flow Wetland Living Machine® System. 2005.

Ocean Arks International. Interim Performance Report for the San Francisco Living Machine: March 1995-September 1996. 1996.

Tchobanoglous, G., F. Maitski, K. Thompson, and T.H. Chadwick. Evolution and Performance of City of San Diego Pilot-Scale Aquatic Wastewater Treatment System Using Water Hyacinths. Research Journal of the Water Pollution Control Federation, Vol. 61, No. 11/12, pp 1625-1635. 1989.

Zacheis, G.A. et al. Laboratory Analysis of Disinfection Options for Orange County Sanitation District. WEFTEC, Los Angeles, CA. Water Environment Federation. 2003.