Evaluation of a System for Residential Treatment and Reuse of Wastewater

Roger W. Babcock Jr., M.ASCE[1]; Daniel A. McNair[2]; Lance A. Edling[3]; and Harold Nagato[4]

Abstract: Approximately one-quarter of housing units in the United States are not connected to centralized, publicly owned wastewater treatment works and instead operate their own cesspools or septic tanks that provide only partial treatment. A study was conducted in which a commercially available, on-site, residential wastewater package unit was tested at its design capacity according to an established protocol to determine if it could produce a high-quality effluent. Additional pilot-scale sand filtration and ultraviolet disinfection units were fabricated and operated to determine the feasibility of producing recycled water suitable for residential reuse and which could meet strict water reuse regulations. The results indicate that the package unit can produce an effluent equivalent to secondary effluent when properly operated and maintained. In addition, using add-on sand filter and ultraviolet light disinfection units, it was possible to produce the highest quality of reclaimed water recognized by Hawaii regulations (oxidized, filtered, disinfected, unrestricted use). It was also possible and may be economically feasible to produce a slightly lower quality reclaimed water (oxidized, disinfected, R-2) suitable for residential subsurface irrigation.

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Introduction

According to the 1990 United States (US) Census, approximately one-quarter of housing units (25.7 million) are not provided service connections to publicly owned wastewater collection, treatment, and disposal systems (POTWs) (US Census 1990). Residents of these housing units must operate their own on-site, individual collection and/or treatment and disposal systems. Most of the existing systems are cesspools or septic tanks with leach fields that provide only partial treatment that can adversely impact groundwater and surface waters (Jones and Lee 1979; Leblanc 1985; Barber et al. 1988; Robertson et al. 1991; Wilhelm et al. 1994; Harman et al. 1996). In some cases, the same residences without wastewater service connections do not have connections to a public water supply or access to groundwater and rely on rainwater catchment for potable water supply. For these cases and perhaps others in areas where water supply is constrained, the idea of reclaiming treated wastewater at the point of generation for on-site use is appealing since it could potentially offset potable water needs and avoid costs associated with a dual distribution system. The US Environmental Protection Agency (EPA) estimates that 32% of average residential water use is for outdoor uses such as irrigation, while an additional 28% is used for toilet flushing which are both potential uses for recycled water (USEPA 1992).

The State Department of Health (DOH) regulates individual wastewater treatment systems in Hawaii (DOH 1991). The 1990 US Census found 72,940 cesspools and septic tanks in the State of Hawaii (USEPA 2000). This represents 18.7% of the households in the State. In 1988, the DOH established a goal to eliminate cesspools by the year 2000, which was not achieved. The cost of the infrastructure required to provide connections for all of the existing residences which do not currently have connections to new or existing centralized wastewater treatment facilities could be hundreds of millions of dollars. Replacement of cesspools and septic tanks with individual wastewater treatment systems which provide complete treatment of wastewater to "secondary" or higher quality levels is an alternative method to achieve the DOH objective of reducing potential groundwater pollution. Decentralized wastewater treatment can be a cost-effective method to provide treatment and protect the environment (Tchobanoglous 1996; Crites et al. 1997).

Because individual treatment units could be better for the environment than cesspools and septic tanks, it was desired to test an aerobic treatment package unit (consisting of a combination of anaerobic, aerobic, sedimentation, and disinfection processes) both "as delivered" and with additional processes needed to create a tertiary recyclable effluent. The OESIS-750 is the smallest unit in a series manufactured in Hawaii by Environmental Waste Management Systems, Inc. (EWMS). In order for the DOH to allow installation of an individual aerobic treatment unit in Hawaii, it must perform according to the National Sanitation Foundation (NSF) Standard 40 (1984). The NSF Standard 40 provides protocols for testing of individual treatment units as well as criteria for acceptable minimum performance. Minimum performance for production of a NSF Standard 40 Class I effluent re-

[1]Associate Professor, Civil and Environmental Engineering Dept., Univ. of Hawaii, 2540 Dole St., Honolulu, HI 96822. E-mail: rbabcock@hawaii.edu

[2]Graduate Student, Civil and Environmental Engineering Dept., Univ. of Hawaii, Honolulu, HI 96822. E-mail: dmcnair@hawaii.edu

[3]Graduate Student, Civil and Environmental Engineering Dept., Univ. of Hawaii, Honolulu, HI 96822. E-mail: ledling@hawaii.edu

[4]Environmental Waste Management Systems, Inc., P.O. Box 980, Waialua, HI 96791. E-mail: ewms@hawaii.rr.com

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quires that the 30-consecutive-day mean effluent concentration of biochemical oxygen demand (BOD_5) and total suspended solids (TSS) be no greater than 30 mg/L and that there be at least 85% total removal. At the same time, the mean values of BOD_5 and TSS for any 7-consecutive days cannot be greater than 45 mg/L. In addition, the effluent pH must always be between the limits of 6.0 and 9.0. These are the same requirements used by the EPA to define "secondary" treatment (Federal Register 1984).

Individual treatment systems that provide complete treatment have somewhat of a mixed reputation in the wastewater industry and poorly performing/failing systems due to mechanical problems and/or insufficient operator attention/maintenance have been used as a justification for regionalization of wastewater treatment (Marshall 1991). A 1981 evaluation of 20 operating individual treatment units from seven different manufacturers found that only four produced effluents comparable or better than the NSF Standard 40 requirements for Class I effluent (Mgou et al. 1981). A study of 51 aerobic treatment units in 1978 found poor effluent for 21 units in terms of turbidity, color, and odor (Brewer et al. 1978). The average effluent BOD_5 and TSS for all 51 systems were 30.9 and 49.2 mg/L, respectively. Lack of adequate operation and maintenance has been implicated for poor performance in several studies. Asbury and Hendrickson (1982) inspected 12 on-site aerobic treatment units and found that only four were operating properly. Hutzler et al. (1978) studied 36 aerobic treatment units and found 24% had mechanical failures. These studies indicate that while many aerobic treatment units are known to perform well under controlled test conditions, they tend toward failure when left to a homeowner to operate for many years. This is apparently why the EWMS units have few moving parts and include 2 years of maintenance service.

In the State of Hawaii, a Class I effluent is only suitable for disposal in an infiltration well or leach field. In order to reclaim the treated wastewater for beneficial reuse, additional treatment is required. The DOH has established a detailed set of "Guidelines for the treatment and use of recycled water" (DOH 2002). The Guidelines define three categories of recycled water; R-1, R-2, and R-3. The highest quality is R-1 water (essentially equivalent to California unrestricted reuse or "Title 22" water) which is suitable for many types of reuse including landscape irrigation and decorative impoundments. The lowest quality (R-3) corresponds to Class I effluent which is suitable for certain types of restricted agricultural irrigation but not for any uses that could apply to residential users. The additional treatment required to produce R-1 water from Class I water includes filtration and disinfection (R-2 requires disinfection only). The objectives of this investigation were to determine if the EWMS package treatment unit could produce a high-quality secondary effluent acceptable to the DOH for installation at residences in Hawaii and to determine the feasibility of producing recycled water suitable for residential reuse in accordance with the DOH's strict reuse regulations.

Materials and Methods

An OESIS-750 individual wastewater treatment unit was sited at the 75 million gallon per day Sand Island Wastewater Treatment Plant (SIWWTP) in Honolulu. The continuous-flow OESIS-750 unit consists of a first anaerobic chamber (0.84 m^3) containing submerged spherical plastic media, a second anaerobic chamber (0.71 m^3) containing submerged cylindrical plastic media, an aerobic chamber (1.03 m^3) containing submerged vertical trickling filter media, a clarification chamber (0.42 m^3), an overflow weir with an integral chlorine tablet holder, and a small final chlorine contact chamber (22 L) (McNair 1999). The total volume of the OESIS-750 is 3.0 m^3 (750 gallons) and is sized for a two-bedroom home with a design flow of 1,520 L/day (400 gallons/day, gpd). The overall dimensions of the unit are 1.32 m wide $\times$2.45 m long$\times$1.77 m tall (4.3 ft$\times$8 ft$\times$5.6 ft). A series of scaled-up OESIS units are available for flows up to 3,785 L/day (1,000 gpd). The only mechanical part of the OESIS unit is a small diaphragm air pump (60 L/h) which operates two fine-bubble diffusers, an aerobic chamber backwash feature, and an airlift recycle line to promote denitrification.

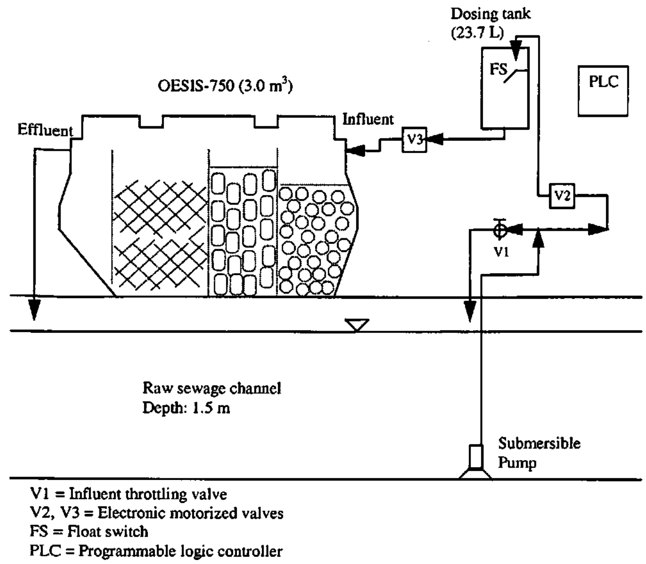

Fig. 1. Schematic diagram of piping system for OESIS-750 performance testing

A submersible pump, plumbing, electronic valves, a 23.7 L (6.25 gallon) dosing tank with float switch, and a programmable logic controller (the "test system") were fitted to the OESIS-750 to provide raw wastewater to the unit (Fig. 1 is a schematic of the system). The test system (described in detail in McNair 1999) withdrew screened raw wastewater from the SIWWTP influent channel and was designed in order to provide a total flow of 1,520 L/day (400 gal/day) to the OESIS-750 in a manner prescribed by the NSF Standard 40 test protocol. The NSF Standard 40 protocol calls for 35% of the daily flow to enter between 6 and 9 a.m., 25% to enter between 11 a.m. and 2 p.m., and 40% to enter between 5 and 8 p.m. The NSF Standard 40 calls for a 6-month continuous standard performance period followed by a series of four stress tests. The four stress tests are called "wash day" (three wash loads of 35 gallons each added to the tank for three mornings in a row; wash loads contain detergent and bleach), "working mother" (no flow midday, and one wash load each evening for 5 days), "power failure" (power and flow off for 48 h), and "return from vacation" (no flow for 1 week followed by high flows and three wash loads). Each stress test required approximately 1 week plus an additional week of monitoring following the stress test to observe effects.

During the 6-month standard performance period, programmable samplers (ISCO Model 3700, Lincoln, Neb.) were utilized to collect influent and effluent samples 5-days-per-week each hour during those times when the unit received influent. Influent and effluent samples were composited in proportion to the influent flow pattern. Grab samples from the aeration tank were also collected 5-days-per-week. All analytical measurements were ac-

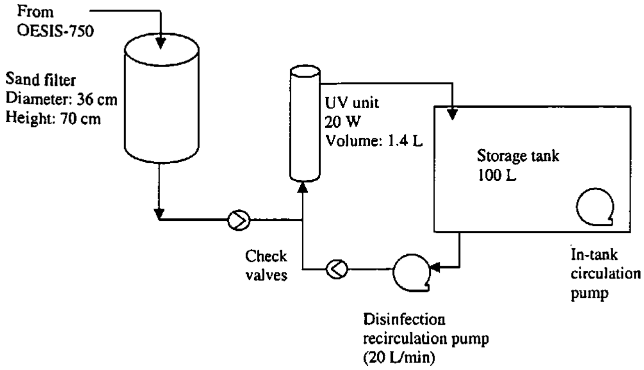

Fig. 2. Schematic diagram of pilot water reclamation system

cording to procedures detailed in the 19th edition of *Standard methods for the examination of water and wastewater* (APHA 1995) and method numbers appear below in parentheses. Influent, effluent, and grab samples were monitored for BOD_5 (5210 B) and TSS (2540 D). In addition, the dissolved oxygen (DO) (4500-O G), temperature (using thermistor on DO probe), and pH (4500-H) within the aeration tank portion of the system were measured 5-days-per-week. Aeration tank grab samples were also analyzed for settleable solids (2540 F). Additional samples were obtained at various intervals from each chamber of the treatment unit and analyzed for organic nitrogen (4500-Norg C), ammonia (4500-NH_3 D), nitrate/nitrite (4500-NO_3 E), orthophosphorus (4500-P C), and total phosphorus (4500-P C). Influent and effluent grab samples were also monitored periodically for tubidity (2130 B), ultraviolet transmittance at 254 nm (UVT_{254}) (5910 B), fecal coliforms (9222 D), and oil and grease (5520 B). Additionally, on three (3) occasions during the 6 month standard performance evaluation period, a grab sample of the effluent was diluted 1:1,000 with distilled water and evaluated for color, threshold odor, presence of oily film, and presence of foam.

A sand filter and a tubular UV disinfection unit were added-on to the unit in order to produce recycled water. A schematic of the recycled water production system is shown in Fig. 2 and described in detail in Edling (1999). Effluent from the OESIS-750 was directed to a simply constructed gravity sand filter with a diameter of 36 cm containing a 10-cm gravel underdrain and a 30-cm bed of silica sand (50% 0.5 mm and 50% 0.1 mm). The filtered water was passed through a UV disinfection unit (Capitol Controls Group Model 8101) with a single low-intensity mercury vapor lamp (20 W), a water volume of 1.4 L, and a contact time of 5.8 s at the tested flow rate of 14 L/min (Edling 1999). The filtered water was pumped through the disinfection unit multiple passes in order to achieve the required reduction of fecal coliform bacteria.

Dose response curves were created by irradiating small samples (50 mL) of wastewater at known doses and measuring the number of fecal coliforms before (No) and after (N) irradiation (laboratory collimated beam tests). Four sets of collimated beam experiments were conducted using a Trojan Technologies unit (Ontario, Canada). All experimentation was completed within 6 h of sample collection. For each experiment, a radiometer (Model P254UV Trojan Technologies, Ontario, Canada) was used to position the collimated beam at a distance from the sample surface corresponding to an intensity of 240 mW/cm^2. Using a correction factor to correct for the absorbance of the light in the water sample, an average intensity throughout the 2.2 cm depth of the 50 mL water sample was determined (average intensity $=$ surface intensity $\times$ correction factor; where surface intensity was 240 mW/cm^2). The correction factor used was

$$C=(1-e^{-\alpha L})/\alpha L$$

where $C=$correction factor, $\alpha=$absorbance (/cm), and L $=$sample depth (cm), 2.2 in these tests.

Table 1. Summary Data for OESIS-750 during 6-Month Standard Performance Period

Parameter	Number of samples	Average value	Standard deviation
BOD			
Influent BOD_5 (mg/L)	130	146.4	20.3
Effluent BOD_5 (mg/L)	130	13.9	6.0
BOD removal (%)		91.0	
Solids			
Influent TSS (mg/L)	130	128.0	27.6
Effluent TSS (mg/L)	130	13.1	6.9
TSS removal (%)		89.7	
Aeration tank			
DO (mg/L)	130	3.4	1.3
pH	130	7.4	0.2
Temperature (°C)	130	25.4	

Exposure times were calculated to obtain doses of 5, 10, 20, 30, 40, 50, and 75 $mW\,s/cm^2$. Samples were placed under the collimated beam at the correct distance and covered with a cardboard plate prior to and following the carefully timed exposure period. Following exposure, the samples were immediately processed for fecal coliforms.

Jar tests were performed to determine a range of aluminum sulfate doses necessary to reduce the OESIS-750 effluent turbidity below 5 NTU. The AWWA (1977) procedure was followed using a six-paddle jar test stirrer unit (Phipps and Bird, Richmond, Va.). Samples were subjected to rapid mix for one (1) min (70 rpm), gentle mix (30 rpm) for 15 min, and settling (0 rpm) for 20 min prior to sampling the supernatant for turbidity.

Near the end of the field testing period, turbidity removal was augmented by the addition of aluminum sulfate coagulation/flocculation/sedimentation prior to sand filtration. This chemical treatment was performed in 5 gallon buckets using a paddle mixer and the same timing as the jar tests. Following sedimentation, the supernatant was pumped into the top of the sand filter.

Results and Discussion

During the 6-month standard performance period, the OESIS-750 unit was operated at its design capacity treating 1,520 L/day which gave an overall hydraulic retention time (HRT) of 45 h. The average HRT was 23 and 15.5 h in the anaerobic chambers (combined) and the aerobic chamber, respectively. Since sludge was not removed from the fixed-film aerobic chamber, the solids retention time (SRT) was 180 day. Table 1 indicates that the average influent BOD_5 concentration was 146.4 mg/L which equates to an overall system loading rate of 0.074 kg $BOD_5/day\,m^3$ (4.6 lb/day 1,000 ft^3). Data collected during the 6-month standard performance period for influent and effluent BOD_5 and TSS are presented in Figs. 3 and 4. The overall average effluent values and their standard deviations for this period were 13.9 ± 6.0 and 13.1 ± 6.9 mg/L for BOD_5 and TSS, respec-

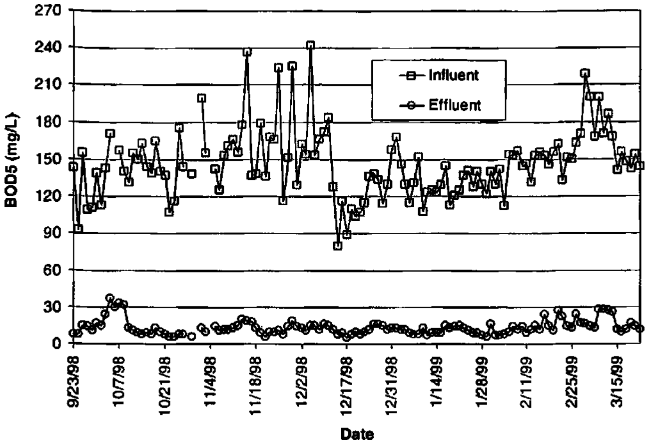

Fig. 3. Biochemical oxygen demand (BOD_5) during 6-month standard performance period

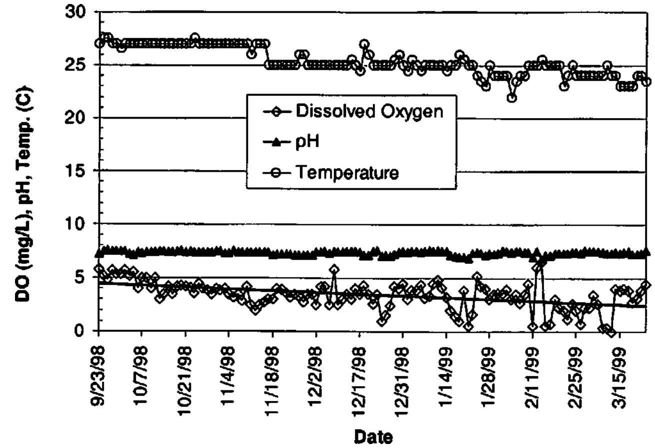

Fig. 5. Temperature, dissolved oxygen, and pH during 6-month standard performance period

tively (Table 1). The data in Figs. 3 and 4 and Table 1 indicate that the OESIS-750 unit performed very well (approximately 90% removal of BOD_5 and TSS) and easily met the requirements for a NSF Standard 40 Class I effluent.

Some general observations regarding the operation of the OESIS-750 unit during the 6-month standard performance period are as follows. (1) The OESIS-750 needed very little maintenance and essentially ran unattended without any problems for a period of 6 months. Every 2 months, the air inlet filter for the air pump was dusted-off (the only maintenance performed). The effluent was observed to have good clarity and no odor. Within the unit, there was no accumulation of scum. (2) Despite fairly large fluctuations in influent BOD_5 (from 80 to 242) and TSS (from 80 to 277), effluent values were quite stable (see Figs. 3 and 4). (3) Aeration tank pH values were nearly constant (at 7.4) and it can be assumed that the effluent pH was equivalent (see Fig. 5). (4) Aeration tank DO combined with visual water clarity observations seem to be good measurements for routine performance monitoring. If the aeration tank water becomes cloudy and the DO decreases to less than 1.0 mg/L, this is a good indicator that BOD_5 removal performance is being adversely impacted by buildup of biomass on the air diffusers or in the packing media and/or accumulation of sludge. It may be necessary to remove excess sludge every 6 months if the system is operated continuously at its design capacity as can be seen in Fig. 5. DO was measured above 5 mg/L at the start of the test period. The trend line shown in Fig. 5 shows a decrease in DO in the aerobic chamber as a function of time. The tank was taken off line after 5.5 months for cleaning. Cleaning was accomplished by completely removing the sludge in anaerobic chamber No. 1 and about half of the sludge in anaerobic chamber No. 2. A sump pump was used to remove the sludge from both anaerobic chambers by submerging the pump through vertical access channels (designed for a 4 in. vacuum-truck hose). When the filter media were exposed by partially dewatering each chamber, the biomass was cleaned with a water spray and also removed by the sump pump. The DO quickly recovered following the cleaning and started to increase, approaching 5.0 mg/L. The data indicate that the tank requires cleaning about every 6 months in order to maintain the DO above 1.0 mg/L.

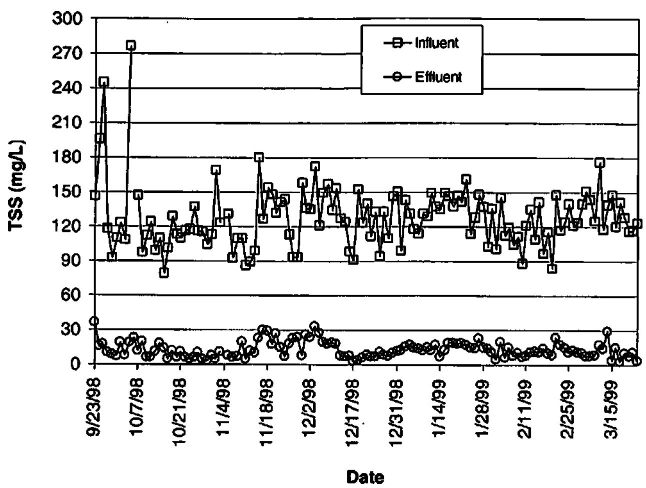

Fig. 4. Total suspended solids (TSS) during 6-month standard performance period

Additional data were collected during the 6-month standard performance period. These included BOD_5 and TSS after the first and second anaerobic chambers, influent and effluent nitrogen and phosphorus species (Table 2), aeration tank settleable solids, and influent and effluent turbidity. The average BOD_5 concentration entering the aerobic chamber was 20 mg/L which equates to an average loading of 0.029 kg BOD_5/day m^3 (1.8 lb/day 1,000 ft^3) to the aerobic chamber. This very low loading rate indicates that most of the BOD_5 removal (86%) occurred in the initial anaerobic sections and the aerobic chamber was basically used for polish-

Table 2. Summary Nitrogen and Phosphorus Data for OESIS-750 during 6-Month Standard Performance Period

Parameter	Number of samples	Average value	Standard deviation
Nitrogen			
Influent total nitrogen (mg N/L)	26	23.1	4.4
Effluent total nitrogen (mg N/L)	26	18.6	2.9
Total nitrogen removal (%)		19	
Phosphorus			
Influent total phosphorus (mg P/L)	26	4.6	1.5
Effluent total phosphorus (mg P/L)	26	3.8	1.5
Total phosphorus removal (%)		17	

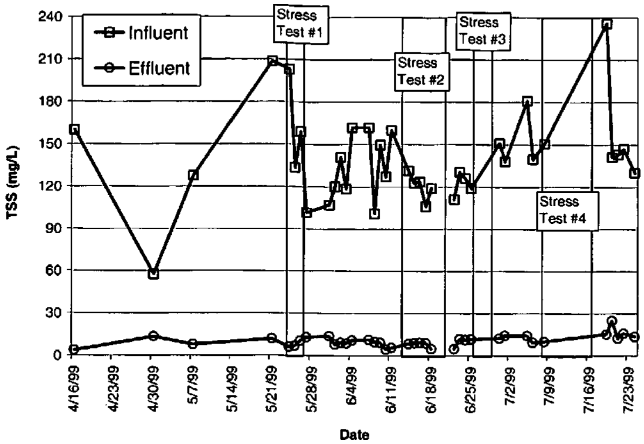

Fig. 6. Total suspended solids (TSS) during a series of four stress tests

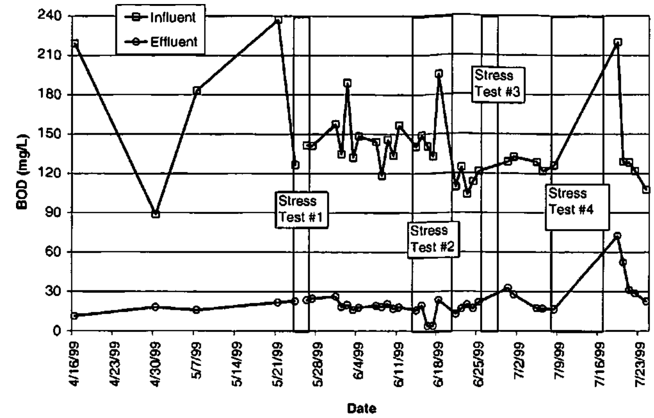

Fig. 7. Biochemical oxygen demand (BOD_5) during series of four stress tests

ing. The aerobic chamber only reduced BOD_5 from 20 to 13 mg/L (35% removal), but higher removal efficiencies would be expected for higher, typical loading rates. Voigtlander and Kulle (1994) found 60% removal from the anaerobic suspended-growth chamber in a multichambered on-site treatment system.

The nitrogen species data (Table 2) indicate that the OESIS-750 unit did not achieve significant nitrogen removal via nitrification/denitrification. In addition, the effluent nitrogen speciation indicates the nitrification was not complete (effluent nitrogen was 70% ammonia). The observed average nitrogen removal rate of 19% was about as expected from stoichiometric metabolic uptake by bacteria. It was suspected that nitrogen removal (via nitrification followed by denitrification) could be achieved in the OESIS-750 unit. The aeration requirements for oxidation of BOD_5 and for nitrification were calculated for the OESIS-750 unit using average loadings during the standard performance period. It was found that the oxygen requirement was approximately 170 g/day, however, the standard air pump could only deliver approximately 120 g/day (undersized by 40%). This is suspected to be the main cause for the lack of significant nitrification as well as subsequent denitrification. The removal rate of phosphorus (17%) was also about as expected from metabolic considerations. The average value for settleable solids was 0.1 ml/L. The effluent turbidity varied significantly from about 2 to 10 NTU and the overall average was approximately 5 NTU. Influent and effluent oil and grease were measured on three occasions. The average influent concentration was 7.0 mg/L (standard deviation 1.7 mg/L) and the average effluent concentration was 1.3 mg/L (standard deviation 0.7 mg/L). These data indicate an average removal of 82%.

Data collected during the series of four stress tests is shown in Figs. 6 and 7. Inspection of Fig. 6 indicates that effluent TSS concentrations were unaffected by the first three stress tests. Stress test 4 may have caused the effluent TSS to increase very slightly for 1 day, however, the values remained well below 30 mg/L. Inspection of Fig. 7 indicates that effluent BOD_5 was affected by each of the four stress tests to different degrees. The first stress test (wash day) had a fairly substantial effect on effluent BOD_5, which increased by 5–10 mg/L followed by a recovery after approximately 7 days. During the first stress test, the effluent BOD_5 did not increase to greater than 30 mg/L. The second stress test (working mother) did not seem to have any impact on effluent BOD_5. The third stress test (power failure) caused the effluent BOD_5 to increase slightly above 30 mg/L for 1 day, however, the criteria for Class I effluent were always achieved. Stress test 4 (return from vacation) had the greatest impact on effluent BOD_5. The effluent BOD_5 increased to 72.5 mg/L for day one and then decreased to 52.5 mg/L the next day, and then to 31.3 mg/L the third day. By the fourth day after the test, the effluent BOD_5 was below 30 mg/L. It is apparent that the 30-day average BOD_5 would not have increased to greater than 30 mg/L. It is also apparent that the 7-day average BOD_5 would not have increased to greater than 45 mg/L. Overall, the OESIS-750 unit performed well during the series of four stress tests. As expected, some of the stress tests had a significant effect on the treatment performance (particularly effluent BOD_5). However, these observed effects were short-lived and the system recovered quickly to typical long-term performance within 3 to 4 days following the return of normal flows.

Cost estimates (including equipment, piping, earthwork, engineered backfill, labor, etc.) were prepared to compare a septic tank plus leach field versus an OESIS-750 unit plus a seepage pit for a typical two-bedroom installation in Hawaii. It was found that while the OESIS-750 unit was nearly twice as costly as a septic tank, the cost of the leach field was much greater than the seepage pit and the total installed cost of each system was essentially the same ($10,000). Estimated annual operation and maintenance costs for the two alternative systems of $325 and $420 for the septic tank system and the OESIS-750 system, respectively, indicate that the OESIS-750 system would be more costly to operate. The operations costs for the septic tank plus leach field system included sludge pumping and electricity for a leach field dosing pump while the OESIS-750 system costs included sludge pumping, aeration electricity, chlorine tablets, and an inspection/maintenance contract.

Water reclamation experiments focused on filtration and disinfection individually and combined. DOH requirements for numbers of indicator organisms (fecal coliform) in finished reclaimed water are less than 23 CFU/100 mL for R-2 water and less than 2 CFU/100 mL for R-1 water (DOH 2002). DOH requirements for filtration of R-1 water allow direct filtration of effluents with turbidity less than 5 NTU and specify chemical coagulation prior to filtration for higher turbidity. The turbidity after filtration (before UV disinfection) must be less than 2 NTU and UVT_{254} transmittance must be greater than 55%. The OESIS-750 unit produced effluent with turbidity less than 5 NTU approximately 50% of the time during the standard performance period. Also, the UVT_{254} dropped below 55% approximately 27% of the time. This was due

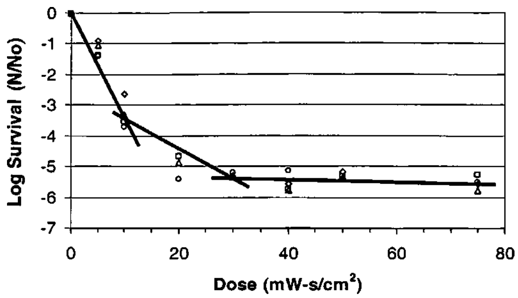

Fig. 8. Fecal coliform dose-response curve

to the highly turbid and septic nature of the SIWWTP influent used in this study (range of 20–80 NTU). When the effluent turbidity was greater than 5 NTU, filtered water turbidity always exceeded 2 NTU, however, final treated water microbial quality requirement (less than 2 CFU/100 mL) was achievable even when turbidity requirements were not met. Our simply constructed sand filter averaged approximately 44% turbidity removal which is relatively low compared with 70% which is possible by well-engineered sand filters (Asano et al. 1998). In order to demonstrate feasibility, coagulation with alum was tested in laboratory jar tests and on one occasion in the field with the OESIS-750 unit. Laboratory alum doses from 15 to 300 mg/L were examined and a dose of 50 mg/L of alum was found to be required to reduce effluent turbidity below 5 NTU. However, the use of chemical coagulation at a residential unit is not considered practical due to the need for a chemical supply and attention to chemical feed equipment.

Four sets of collimated beam UV dose experiments were conducted in the laboratory in order to establish a dose response curve for fecal coliforms for doses between 5 and 75 mW s/cm^2 (see Fig. 8). Such a curve allows determination of the actual UV dose received by the organism under any set of conditions (by measuring the values of No and N under process conditions and then using the curve to determine the corresponding received dose). This is necessary because DOH regulations specify a measured minimum received dose of 100 mW s/cm^2. Given a known received dose, the required number of passes through the UV disinfection unit can be calculated. On several occasions, filtered effluent was passed through the UV unit and the average once-through received dose was determined using Fig. 8 to be 6.4 mW s/cm^2 (corresponding to 99% or 2 logs of removal). During these tests, fecal coliform counts prior to filtration were highly variable (100,000–8,000,000 CFU/100 mL) and routine maintenance included only cleaning of the inner quartz sleeve with acetic acid and/or scale remover (monthly). The average received dose data dictates that filtered water must be passed through the UV unit 16 times to meet DOH requirements. In actual multiple-pass experiments in which fecal coliform was measured after each pass, 10 passes (total received dose = 64 mW s/cm^2) were always sufficient to achieve the less than 2 CFU/100 mL requirement. The results from the multiple-pass test can be related to those of other researchers. A study by Braunstein et al. (1996) found that fecal coliform counts of less than 2.2 MPN/100 mL were consistently met with an effective dose of 112 mW s/cm^2. Another study by Darby et al. (1993) showed that the criteria of less that 2.2 MPN/100 mL was met with a minimum UV dose of 97 mW s/cm^2 using total coliform as the tested organism.

The OESIS-750 unit has a 22 L chlorine contact section from which the effluent overflows: 3 in. (7.6 cm) diameter chlorine tablets were placed into the tablet holder that allows clarified effluent to pass over the tablets and dissolve them within the OESIS-750 unit. This chlorination system was operated for a period of 4 weeks and on several occasions chlorine species and fecal coliform were measured. Measurements were unable to detect a free chlorine residual and the average total chlorine residual was 0.15 mg/L. Measurements did not find any significant reduction in fecal coliform due to the chlorination system. This was likely because the chlorine tablets did not dissolve well since the wastewater only passed over them very briefly, and the contact time within the contact section was very short when wastewater was flowing through (7.5 min.). These tests indicated that the chlorination system would need to be redesigned with a greater capacity in order to provide disinfection to less than 23 CFU/100 mL as required for R-2 water.

Investigation of the DOH guidelines for R-1 water treatment and reuse indicated several potential roadblocks. The R-1 guidelines were written in consideration of facilities, equipment, and personnel available at large-scale POTWs and include requirements for continuous turbidity measurement, daily fecal coliform measurement, visual and audible alarms, separate piping and signage, certified operations personnel, monthly reporting, etc. Many of these R-1 requirements would not be feasible for an on-site residential treatment and reuse system. Based upon the reclamation study results, it may be most feasible to create a filtered R-2 water. This would involve a separate above-ground system containing a sand filter and a UV unit with a recycle pump to pass filtered effluent through the UV unit at least 5 times before going to a final holding tank. This system could produce water which could meet R-2 requirements and would be suitable for subsurface drip irrigation of lawns and gardens. Because the reclaimed water would be filtered, the system should reliably produce a water which would not clog drip irrigation lines. The operating and maintenance costs of such a system (monthly inspection, annual lamp replacement, biannual coliform tests, and electricity) were estimated at $775/year which could be prohibitive except in areas where other water sources are scarce. The initial installation cost of the postsecondary R-2 treatment system could be in the range of $1,500–$2,500.

The cost effectiveness of this approach must be investigated further. It is possible that it would be less costly in some communities to partially or fully subsidize the installation of such systems at residences than to install collection systems, pump stations, additional treatment capacity at the POTW, and centralized recycling treatment and distribution systems. There are both advantages and disadvantages to decentralized wastewater treatment. Presumably, the main advantage is the cost savings afforded by the lack of a collection system and centralized treatment plant both of which are expensive to construct and operate. In areas with low population densities the costs for collection systems can account for 75–91% of capital costs for centralized treatment systems (“On-site” 1980). The main potential disadvantages are environmental damage and public health degradation due to inadequate treatment and disposal of sewage primarily due to lack of centralized control over operation and maintenance. These disadvantages can be avoided by on-site treatment systems that perform well with few if any moving parts (like the OESIS-750 studied here) and are inspected and serviced by qualified operations personnel on a regular basis.

The results obtained here for the OESIS-750 system can be compared to previous studies. A year-long study comparing four different types of individual treatment units at 22 different sites was conducted by the Boyd County Sanitation District No. 3 (northeastern Kentucky) by Nicholas and Foree (1981). Mixed liquor and effluent samples were collected monthly from two Bi-A-Robi, three Cromaglass, four Eastern Environmental Controls Incorporated (EEC), and three Multi-Flo units during the study. Unlike the OESIS-750 tested herein, none of the systems achieved NSF Standard 40 Class I effluent.

An 8-month study comparing 10 different types of individual treatment units treating primary effluent at a municipal wastewater treatment plant was conducted by Tokyo University (Hamada and Nakanishi 1994). Their results indicate that all of the systems tested achieved very good BOD removal (average effluent results were between 15 and 28 mg/L for each of the different units) and many of the systems may have achieved NSF Standard 40 Class I effluent (uncertain because of only monthly sampling and no TSS monitoring).

A recent study indicated that 92% of 419 on-site aerobic treatment units in operation in West Virginia did not perform as well as expected due to infrequent and inadequate maintenance (Sextone et al. 2000). A different study indicated that when properly sized and adequately maintained, more than 95% of 250 units sampled (out of approximately 2,500 such units) in Harris County Texas performed well enough to meet treatment regulations (''Quality'' 2000). The most common problem was inadequate disinfectant. In a survey conducted on 54 aerobic packaged systems, it was found that proper, routine maintenance of household treatment systems is essential for the proper operation of these units (Brewer et al. 1978). A similar study of five operating on-site treatment units in Virginia over a 1-year period found overall poor field performance including 82 and 62% of effluent samples with BOD_5 and TSS exceeding 30 mg/L, respectively (Kellam et al. 1993). They cited unreliable maintenance by homeowners, ineffective chlorinators, inadequate biological treatment, and mechanical malfunctions as the causes of problems and recommended preventative maintenance and regular inspections (about every 3 months) to ensure proper operation and a high-quality effluent. These reports indicate that for on-site water reclamation to be feasible and reliable, adequate maintenance must be provided to ensure treatment objectives are met and reclaimed water can safely be utilized.

Conclusions

An OESIS-750 aerobic wastewater treatment unit performed well at its design capacity with minimal maintenance when evaluated under the controlled conditions of the NSF Standard 40 protocol including the 6-month standard performance period and the four stress tests. The aerobic treatment unit reduced BOD_5, TSS, turbidity, nitrogen, and phosphorus species to acceptable levels without producing offensive odors, oily film, or foam under steady-state conditions (1,520 L/day). The OESIS-750 unit was able to easily meet all requirements for a NSF Standard 40 Class I effluent equivalent to ''secondary'' effluent (undisinfected, R-3). Since total nitrogen and phosphorus species were only reduced by less than 20% each, a soil absorption system would be required after the unit if complete removal of nutrients is desired or required. Alternatively, nitrogen removal might be significantly enhanced by increasing the capacity of the OESIS-750 air pump. Regular inspections (monthly for aeration tank DO and water clarity) and maintenance (biannually for cleaning of diffusers and removal of accumulated sludge if operated at design capacity) are necessary to ensure peak performance. The OESIS-750 unit may be a cost effective alternative to septic tanks that could provide enhanced environmental protection.

The technical and economic feasibility of producing recycled water from the OESIS-750 unit was investigated. The built-in chlorine tablet disinfection system was found to not work well apparently due to inadequate retention time or poor dissolution of chlorine tablets. With additional equipment including a sand filter and a tubular UV disinfection unit, it was found to be possible to produce high quality recycled water (either R-1 or R-2 designations). Approximately 50% of the time, the OESIS-750 unit was unable to produce an effluent with turbidity of less than 5 NTU (which would allow direct filtration for production of R-1 recycled water) presumably due to the septic and highly turbid nature of the raw wastewater used in this study. With a fresh wastewater stream, it is likely that the unit could reliably meet the direct filtration requirement and the add-on recycled water system would not need to include chemical coagulation equipment which is not considered practical for a residential unit. The tubular UV unit performed well with little maintenance, and was able to reduce fecal coliforms by 99% or 2 logs with each pass through the unit. Five and 10 passes were always sufficient to reduce fecal coliform counts to below 23 and 2 CFU/100 mL, respectively. It was found to be possible to produce the highest quality of reclaimed water recognized by Hawaii regulations (oxidized, filtered, disinfected, R-1), but it may not be practical unless prefilter turbidity is less than 5 NTU. It is possible and may be economically feasible under certain circumstances to produce a lower quality reclaimed water (oxidized, disinfected, R-2) suitable for residential subsurface irrigation. The results of several previous studies have highlighted the importance of adequate inspections and routine maintenance for aerobic treatment units and this would also be critical for the proper operation of any add-on equipment to produce an effluent suitable and safe for on-site, residential water recycling.

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