Anaerobic Digestion of Primary Sewage Effluent

Prepared for the

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Hawai‘i Energy Sustainability Program

Subtask 3.4: Biomass

Submitted by

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SUMMARY

A hybrid system comprised an up-flow packed bed anaerobic reactor and a down-flow trickling-filter reactor connected in series was shown to effectively treat primary clarifier effluent. When a clarifier and sand filter were added to the system, the effluent water quality achieved values of BOD5 and TSS that were below the EPA's water discharge limits of 30 mg/l and equivalent to highly efficient activated sludge systems. Best results were achieved at a hydraulic retention time of seven hours and with internal recycle applied to both the anaerobic and aerobic reactors. A scale-up evaluation of the system to treat three million gallons per day indicated total land use of approximately 0.6 acre, which is on the same scale currently used at the host wastewater treatment facility to treat primary clarifier effluent using activated sludge technology. An energy balanced showed that the tested system would utilize 48% of the energy currently used to operate the activated sludge system.

Overview of Reactor System

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PROJECT CONTRIBUTIONS

This project was funded by the US Department of Energy (DOE). Additional assistance was provided by Lee Mansfield, General Manager and Bruce Zhang, Plant Manager (East Honolulu Wastewater Treatment Plant), Rudy Mina, Vice President and District Manager, Dennis Tulang, Special Projects Manager, and Lambert Yamashita, Engineer (AECOM Pacific), Dennis Furukawa, President (RealGreen Power), Roger Babcock, Krishna Lamichanne, Ryan Lopez, and Scott Higgins (University of Hawai‘i).

PROJECT DESCRIPTION

This project investigated the application of high-rate anaerobic digestion (HRAD) to treat low-strength primary clarifier effluent, investigating the energy savings that could be gained by lowering the BOD5 of primary clarifier effluent (PCE) wastewater prior to its treatment in the activated sludge basins. If the reduction in BOD5 through anaerobic pretreatment was significant, HRAD systems could become a viable method of secondary treatment.

PROJECT OBJECTIVES

The project objectives were 1) to install and operate a pilot-scale HRAD system at an existing municipal sewage treatment plant (the Hawai‘i Kai Wastewater Treatment Plant – HKWWTP – located in Honolulu, Hawai‘i) and treat clarified primary effluent (PCE); 2) evaluate the potential for producing methane gas by HRAD on PCE; and 3) perform an effective analysis of the energy usage and costs impacts upon downstream aeration treatment processes that produce effluent BOD_5 and TSS levels below the national discharge limits (30 mg/L BOD_5/30 mg/L TSS).

RESULTS

This section summarizes progress against each of the project tasks. Each task was outlined in a research agreement the Hawai‘i Natural Energy Institute (HNEI) subcontracted to RealGreen Power (RGP) to execute the research project as funded by the DOE. The HNEI PI (Michael Cooney, PhD) supervised the subcontract, reviewed the deliverables, organized the Industrial Advisory Board (IAB) meetings, directed the project modifications, and provided support laboratory services.

Task 1: *Execute a Memorandum of Agreement (MOA) with Hawai`i American Waters (HAW) that grants RGP the required access to the HKWWTP to execute this project as per the Statement of Work (SOW) and Technical Plan of Work (TPW). RealGreen Power (RGP) shall also complete a TPW that tracks and expands upon the Tasks listed in the Statement of Work and seek approval of the TPW from the Technical Advisory Board (TAB).*

RGP executed a MOA with HAW that granted RGP the required access to the HKWWTP to execute this project as per the SOW. RGP completed a TPW that expands upon the Tasks in the SOW and received approval from the Technical Advisory Board to proceed with the project.

Task 2: *Execute a signed multiparty Non-Disclosure Agreement (NDA) with AECOM, HNEI, HAW, and RGP that fully defines the rights and use of project status and results.*

RGP coordinated the execution of a multiparty NDA between AECOM, HAW, RGP and HNEI that fully defined the rights, use, and ownership of the project data and results. The NDA addresses issues including, but not limited to, intellectual property, confidentiality, licensing, and data ownership.

Task 3: *Develop designs and specifications for the anaerobic system, inclusive of civil, mechanical, plumbing, electrical, and vendor shop drawings.*

RealGreen Power (RGP) consulted with AECOM, HNEI and HAW in the development of plans and specifications for the anaerobic bioreactor system installed between the effluent of the primary clarifier and the inlet of the secondary aeration basins at HKWWTP, inclusive of pumps, pipes, pH control system, flow meters, valves, and the like to permit complete operation of the anaerobic bioreactors, for all project requirements (Figures 1 & 2). Provision for the biogas system and the Organic Rankine Cycle Turbine (ORCT) was also made. Vendor shop drawings were coordinated with engineering documents.

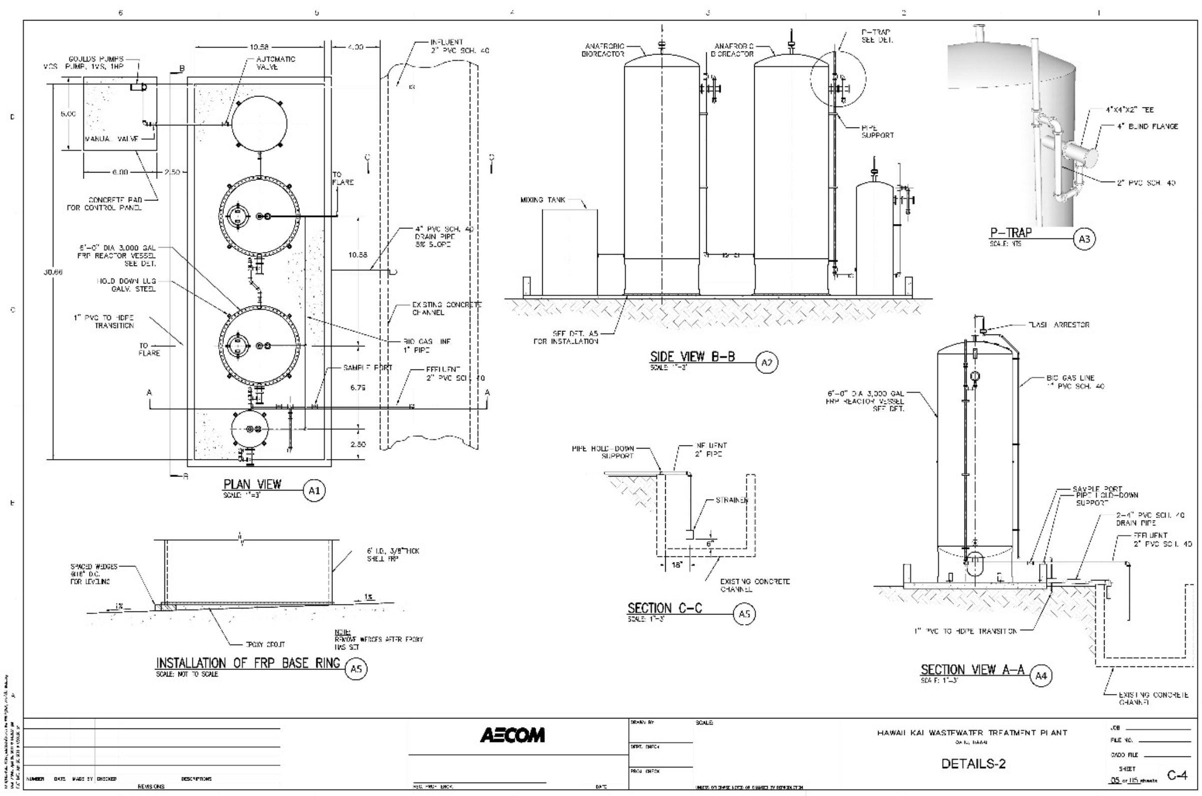


Figure 1: Anaerobic digester mark-up drawings

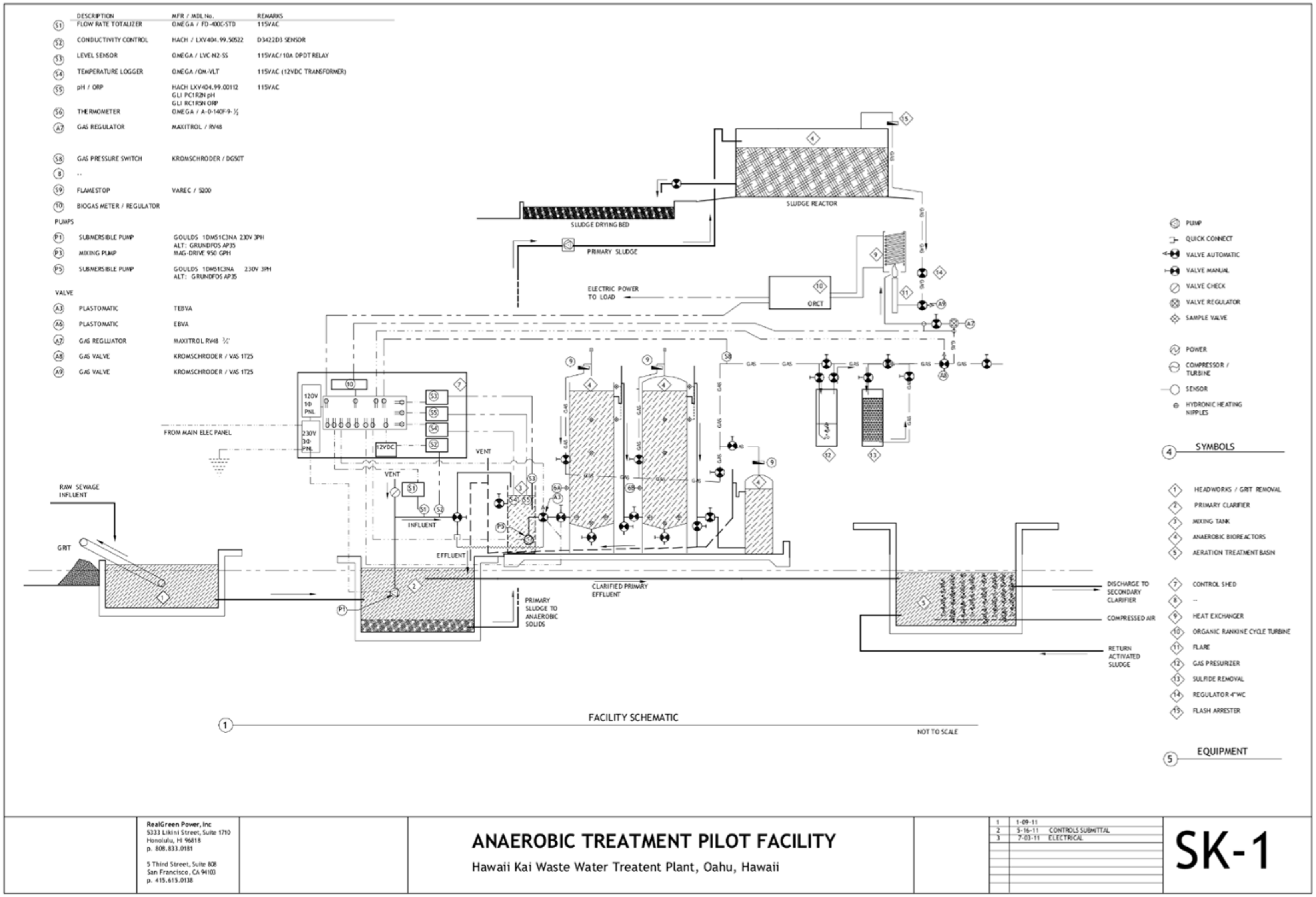


Figure 2: PI&D drawings of pilot scale installation

Plans were prepared by AECOM indicating the placement of a containment slab, the location of the control shed and reactor vessels, pumps and piping, including gas piping to the existing HKWWTP flare.

The HRAD system was installed as a bypass along a linear channel downstream from the Primary Clarifier, and ahead of the aeration treatment basins (Figure 3). Clarified primary effluent (PCE) was pumped from the channel and treated in the HRAD system; the anaerobically treated effluent was returned back to the channel approximately 15 feet downstream of the inlet. Construction documents for the containment slab and mechanical control shed, plus biogas piping to the existing flare on site, were provided by AECOM Pacific.

Task 4: *Design control system.*

RGP, in consultation with HAW, AECOM and HNEI, designed a control system capable of managing the anaerobic bioreactor on a full-time basis. Operational parameters were defined in a diagram and programmed into the control system, which executes the program automatically. Manual overrides were included. Remote monitoring capability was not included due to concerns that the existing SCADA system at the plant could not be reprogrammed to accept additional data streams. The system was therefore designed to operate in a failsafe mode if failure of any pump occurred, or if the power were interrupted. Control schematics are shown in Figure 4 and in Figure 5.

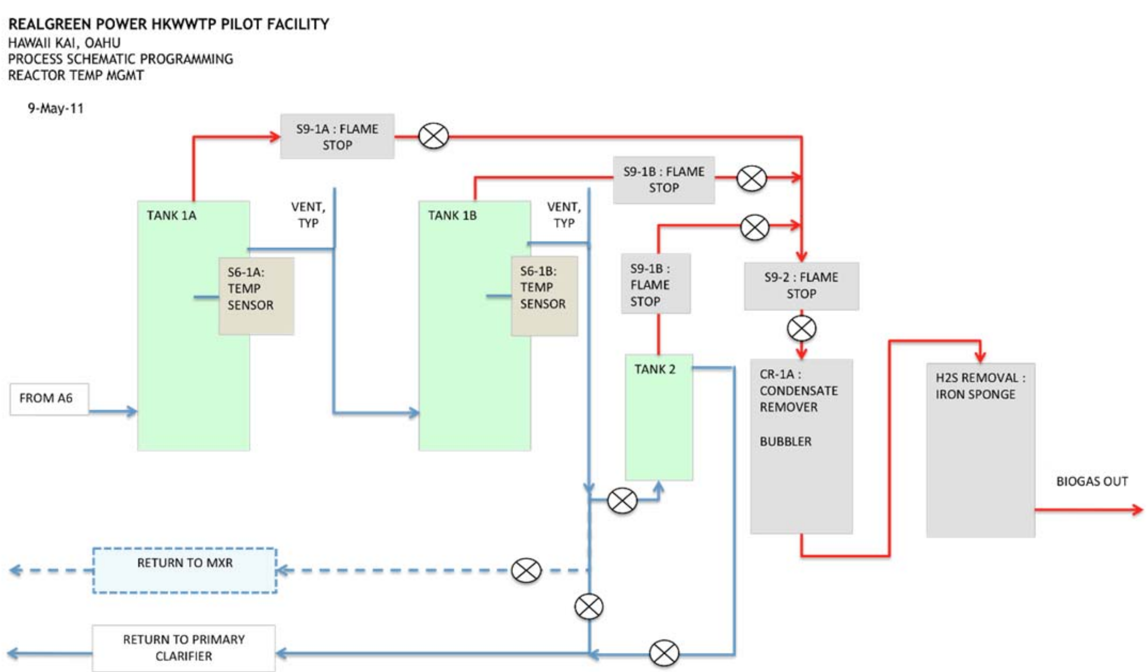


Figure 3: Control Schematics

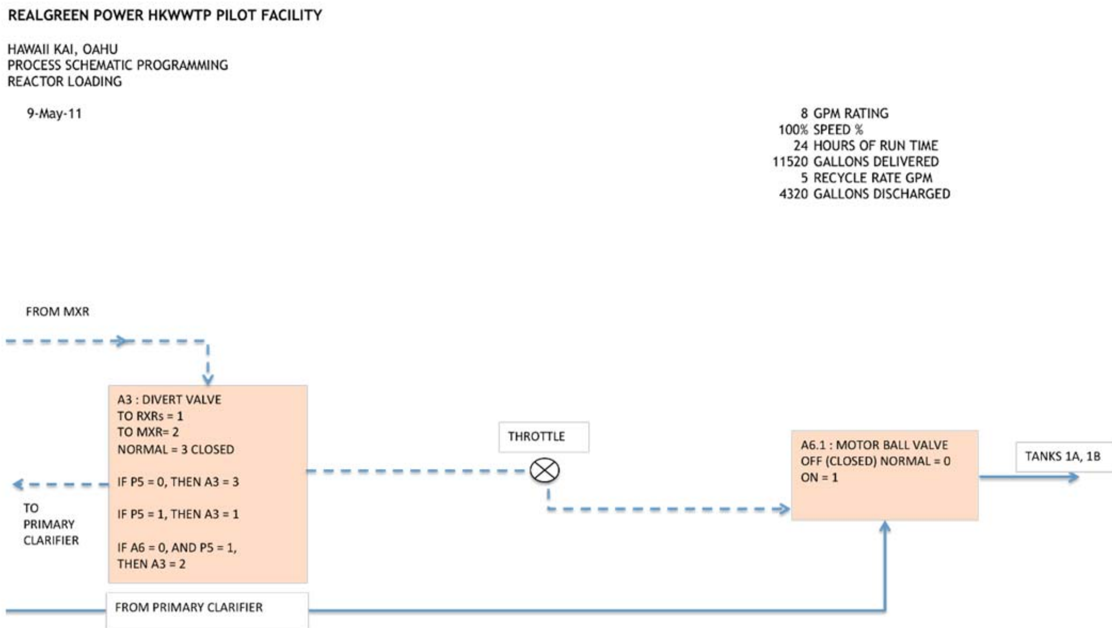


Figure 4: Control Schematics for Reactor Loading

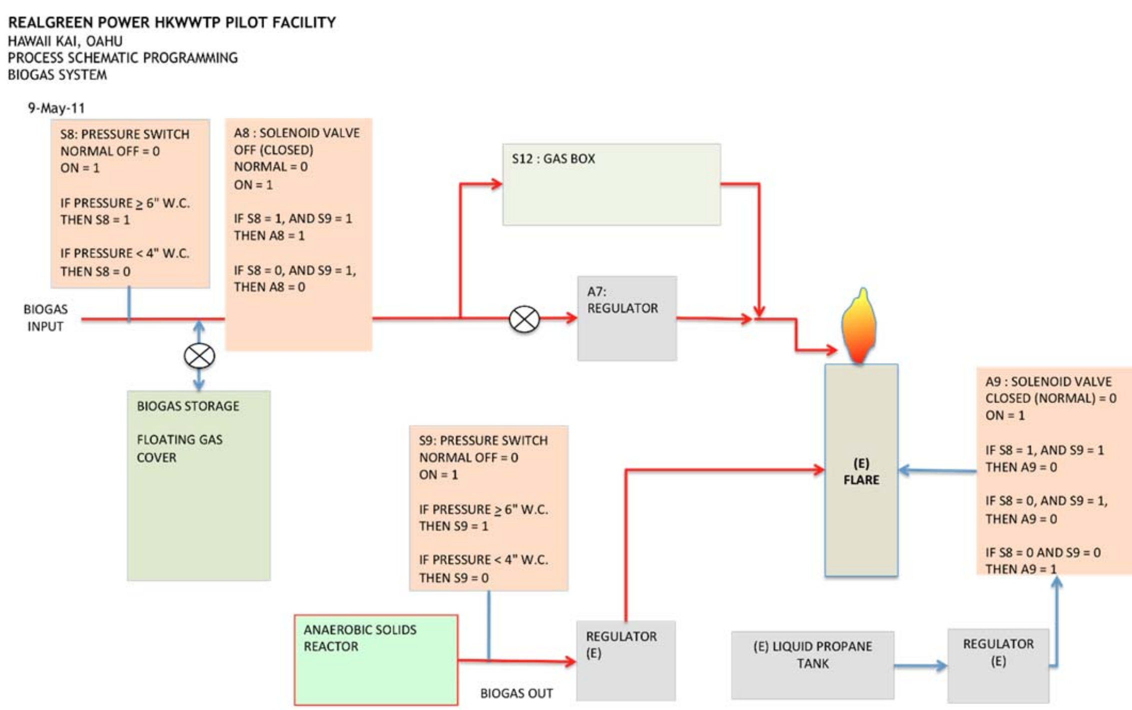


Figure 5: Control Schematics for the Biogas System

Task 5: *Obtain approval for system design from Technical Advisory Board.*

RGP presented the engineered plans and specifications for the RGP system to the Technical Advisory Board, which granted approval of the system design.

Task 6: *Obtain approval for control system from Technical Advisory Board.*

RGP submitted the programming logic and system specifications developed under Task 6 to the Technical Advisory Board for review and approval prior to initiating fabrication and assembly of the computerized control system. Approval to move forward with the fabrication and installation of the computerized control system as per the TPW was granted by the TAB.

Task 7: *Fabricate anaerobic bioreactors.*

RealGreen Power fabricated two Bionest bioreactors with a total liquid capacity of approximately 6,000 gallons, in accordance with the designs and specifications from Task 3. PlasTech, a specialist in fiberglass, fabricated the reactor vessels locally in Honolulu. Bionest material was packed into mesh disks and clipped to flanges inside the vessels such that the flanges acted as seals at the disk perimeter.

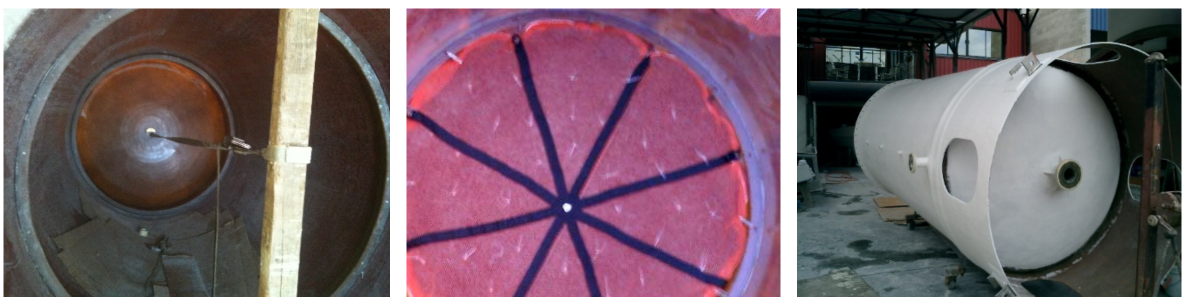


Figure 6 Bioreactor fabrication images
L: reactor interior view, M: Bionest media disk, R: dished bottom of reactor

Task 8: *Install concrete pad and underground piping.*

RGP subcontracted the placement of a concrete pad in accordance with the approved designs and specifications defined in Task 3. Accordingly, trenching and placing of underground piping was not needed for liquid piping. Piping of biogas according to plans developed in Task 3 was delayed pending the production of biogas in sufficient quantities as to warrant flaring of the biogas.

Electrical systems were installed using union subcontractors. Subsequent to the design of the system it was determined that available electrical power was less than originally thought by HKWWTP, specifically that neither 208 V nor three-phase power was available, only 120 V. Revision of the mechanical specifications resulted in the use of less efficient components and less operational flexibility.

Task 9: *Install anaerobic bioreactors as per the approved system designed in Task 3.*

RealGreen Power delivered and installed two anaerobic bioreactors, as approved by the Technical Advisory Board (Task 4), to HKWWTP. Reactor vessels were fabricated locally from tank drawings and specifications provided by RGP.

Two anaerobic reactors were set on the containment slab that drained directly back to the Primary Clarifier (Figure 7). A submersible pump located in the clarifier channel delivered water into a receiving/mixing tank. Another submersible pump, inside the mixing tank, pumped water into the bottom/side of the first of two anaerobic reactors. A smaller submersible pump provided constant mixing of the mixing tank contents.

A small, prefabricated shed housing the control system and instrumentation was installed just adjacent to the bioreactors. RGP integrated the anaerobic reactor within a framework of pumps, tubing, valves, sensors, effluent gas capture and the like to permit completion of all specific tasks outlined in this statement of work, except:

1. RGP did not install biogas piping to the flare, delaying that step until the need for such was proven by sustained biogas production.

2. Due to a lack of available channels, connection to HKWWTPs SCADA system was not allowed. Control of the system was successfully applied through daily visits to the facility to verify the condition and status of the components and through direct measurements of flow rates and composition of liquid samples.

Figure 7 Bioreactor installation

Task 10: *Beta test reactors with water.*

Upon completion of Task 9 the bioreactors were filled with treated sewage effluent to test the integrity of the bioreactor vessels, plumbing, pumps, and instruments prior to the treatment of septic wastewater. The reactors were pressurized to 5 psi, well above design operational pressures (<1 psi) to ensure that no leaks existed. Leaks were detected at the gasketed joint between the upper and lower sections of both reactor vessels; in addition, several ball valves were observed to leak. Replacement of deficient components or systems was performed, and the gasketed joints were sealed. Testing of entire system under pressure was repeated, resulting in no leaks in the system.

Task 11: *Install and calibrate and beta test control systems.*

Upon completion of Task 10, and prior to the filling of the bioreactors with untreated sewage, the control system was beta tested for operational control. The various sensors in the system were subjected to test solutions and various conditions were simulated to test the controller responses.

Task 12: *Initial inoculation into anaerobic digesters with anaerobic sludge from HKWWTP anaerobic sludge digesters.*

Upon completion of Task 11, the bioreactors were emptied of the water used in beta testing. The water was discharged to the HKWWTP secondary clarifier.

Inoculation.
350 gallons of viable anaerobic sludge, obtained from the sewage plant's anaerobic solids reactor, were added directly into the mixing tank, and the system was then filled to capacity with PCE (approximately 5,950 gallons) and the pumping system was set to recycle mode. Following this initial inoculation a second effort was initiated that included nutrient addition and long (10-day) HRTs. An additional 300 gallons of anaerobic sludge obtained from the sewage plant's anaerobic solids reactor was added directly into the mixing tank. This second effort included addition of nutrients including wastes from biodiesel refining, aqueous-phase effluents from grease traps, sugar, whey, and soy proteins. Addition of these nutrients to incoming primary clarifier effluent was maintained at 10-day HRTs. Biogas production was monitored through the use of a gas totalizer. Biogas production rapidly developed during inoculation, evidence of the presence of a diverse anaerobic culture comprised of hydrolytic, acidogenic, acetogenic, and methanogenic bacteria. A rapid increase in biogas production was observed within 30 minutes following the addition of nutrients, indicative of a healthy anaerobic culture.

Task 13: *Stabilization of anaerobic inoculum on clarified primary effluent.*

Following inoculation, culturing of a microbial biofilm on the internal bioreactor packing was encouraged by maintaining the addition of nutrient media into the RGP system on a daily basis. The nutrient media consisted of 15 gallons of the aqueous fraction grease-trap waste (i.e., the wastewater from grease-trap waste after stratification and removal of the fats, oils and grease content). The 15 gallons of aqueous effluent plus 5 cups of whey protein were added to the MXR on a daily basis for two months, while maintaining the 10 day HRT. On occasion, 3 to 5 gallons of liquid wastes from the esterfication process of biodiesel refining (predominantly glycerin), along with 5 to 10 cups of soy protein power, were substituted for grease-trap effluent. Development of active biology was evident within 3 days, with the production of combustible biogas, higher pH readings at sample ports in RXR2 as opposed to RXR1, and the observed decrease in COD in the discharge from the bioreactors. Observations of pH in the system during stabilization of the inoculum revealed an increasing level of acid uptake in response to the addition of fermentable substrates (Figure 8):

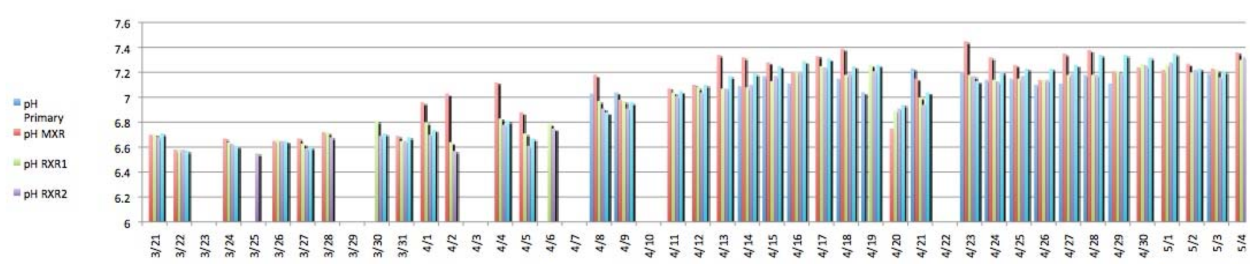


Figure 8: pH Stabilization Phase

Temperatures at the facility remained in a narrow band during the period (

Figure 9). Temperature variations showed no significant effect on pH.

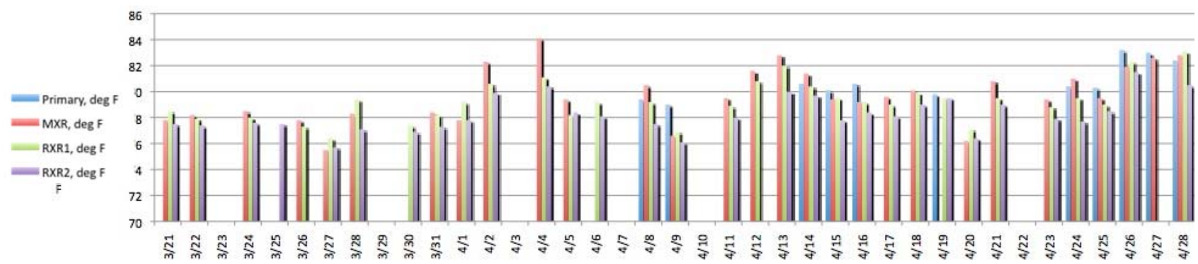


Figure 9: Reactor Temperatures, Stabilization Phase

Recycle of solids from the bottoms of each bioreactor was performed on a daily basis initially, then reduced in frequency as the amount of solids collecting in the bottom cones of the reactors diminished to less than 5 gallons per week in RXR1, and less that one gallon of sludge in RXR2.

On 4/4/2012 the HRT was reduced to 7 days. The nutrient was switched to the addition of approximately ten pounds of sugar dissolved in water, plus two cups of soy protein, added to the MXR on a daily basis. The amount of nutrient was lowered (3/28/2012) to five lbs of sugar and one cup of soy protein, and within ten days nutrient addition was ended (4/8/2012). On 4/12/2012 the HRT was reduced to 5 days and nutrient addition was ended, except for one day on 4/19/2012 when sugar and protein were added. The flow rate was decreased to approximately 4,000 gallons per day, while maintaining a 5-day HRT. On 4/22/2012 HRT was reduced to 3 days, maintaining the flow rate of 4,000 gpd. No nutrients were added to the incoming clarified primary effluent, and an increase of system pH was noted. The flow rate was increased to 6,000 gpd on 5/2/2012, while maintaining the 3-day HRT.

Task 13 ended with the cessation of adding nutrient media and the establishment of a Steady-State period wherein a consistent hydraulic loading rate and hydraulic retention time were applied.

Task 14: *Data acquisition of relevant liquid and gas phase parameters as defined in the TPW.*

Flow rates for throughput and discharge were maintained at a steady-state for six weeks, resulting in a consistent HRT of 3 days. Measurement and logging on a daily basis was performed on pH (Figure 10) and temperature (see Figure 11) from several points in the system (i.e., influent and effluent ports on each reactor). Other sensors and indicators allowed monitoring of hydraulic flow rates, oxidation-reduction potential (ORP), liquid fill levels, biogas pressure, and valve positions. The use of chemical buffers to control pH in the system was not necessary, as the system was able to respond to organic loading sufficiently such that the pH never fell below 6 or climbed above 8.

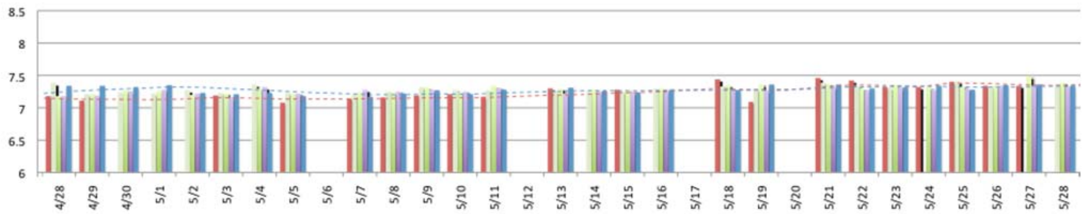


Figure 10: pH Steady State

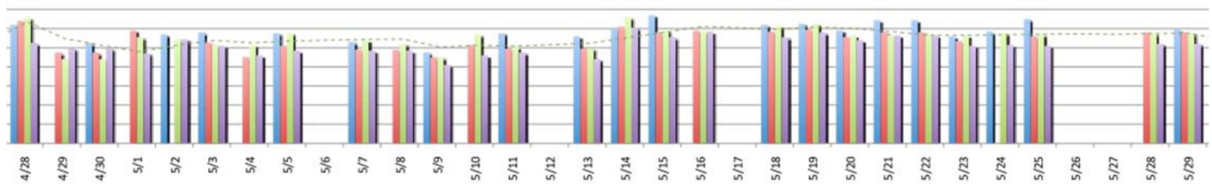


Figure 11: Temperatures Steady State

Filterable suspended solids (TSS) were reduced by an average of 85% during the steady-state period (see Figure 12). Suspended solids in the treated effluent were maintained below 20 mg/L throughout the steady-state period. A spike in loading rate on 6/9/2012 resulted in only a minor rise in final TSS.

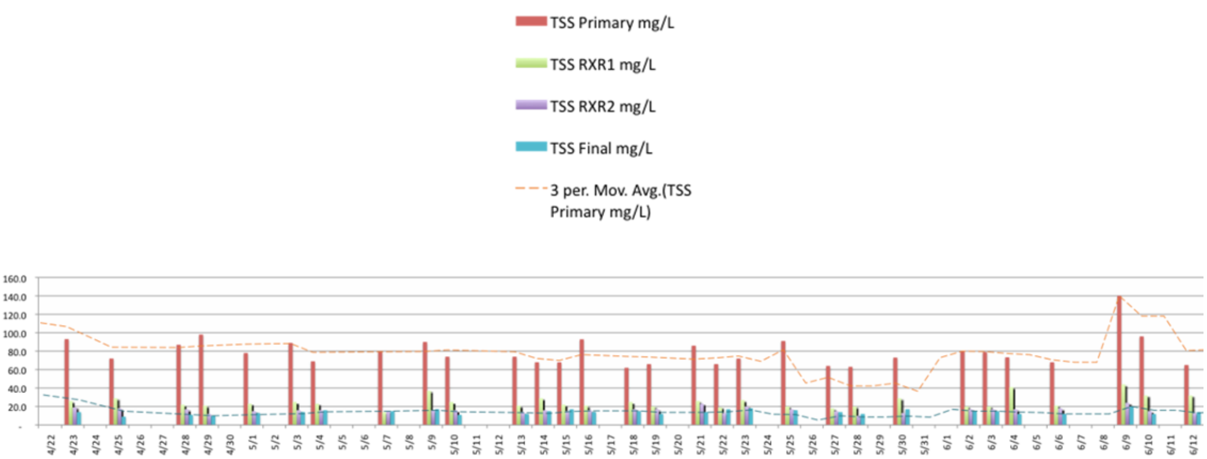


Figure 12: Steady State TSS

Available organic acids were quickly metabolized; nutrient levels (N and P) were unaffected while BOD5 levels were lowered by approximately 50%, along with TSS reductions of over 80%. COD was lowered by an average of 23%. The significant reductions in BOD and solids entering aeration treatment basins are predicted to result in reduced energy costs and sludge accumulations. Results are summarized in Table 1.

Table 1: Summary Results

Characteristics of the RGP anaerobic system at the HKWWTP
System HRT 3 days 5/23/12 thru 6/6/12

	PC			R1	R2	Final			average	notes	method
	value	deviation +/-		value	value	value	deviation +/-				
TDS mg/L	4,920			5,250	5,050	4,900				1	
TSS mg/L	78.6	14.4	(10.6)	23.4	17.0	14.2	2.8	(2.2)	*	2	
TSS reduction %	85.62%								*		
TCOD mg/L	300	52.8	(39.3)	230	233	230	30.3	(15.8)	*		Hach 8000
SCOD mg/L	198	4.7	(14.3)	200	218	203	13.0	(23.0)	*	3	Hach 8000
TCOD removal	23.48%								*		
TCOD loading rate kg/m3 RXR/day	0.098								*		
TCOD removal rate kg/m3 RXR//day	0.023								*		
TBOD5 mg/L	94.8	23.2	(14.6)			48.0	16.3	(9.7)	*	4	
SBOD5 mg/L		62.0	62.0			44.3	14.7	(8.8)	*	4	
TBOD5 removal	49.33%								*		
TN mg/L	25.3	10.7	(10.3)	31.0	27.0	24.0	2.0	(10.0)	*		Hach 10072
STN mg/L	24.0			23.0	27.0	24.0				5	Hach 10072
NH3-N mg/L	19.3	22.0	(5.3)	32.0	28.0	20.5	10.5	(6.5)	*		Hach 8155
SNH3-N mg/L	26.0			32.0	31.0	29.0				5	Hach 8155
TP mg/L	15.0	5.2	(2.6)	11.7	13.4	15.8	6.0	(5.3)	*		Hach 8190
STP mg/L	9.6			17.9	14.2	13.6				5	Hach 8190
TVOA mg/L	24.5	9.5	(24.5)	20.8	10.2	0.0	0.0	0.0	*		Hach 9196

Notes:
1 6/6/12 10 mL dried samples (24 hrs 105C)
2 average 5 periods; 49 mm 1.5 micron filter
3 1.5 micron filtered
4 analysis performed by HAW
5 6/6/12 data

The lack of biogas production during the steady-state period is attributed to a deficit of carbon. This is evidenced by the ratio of COD to N and P concentrations (100:8.7:5.0) in the PCE (see Table 1 on page 13), where COD is less than needed (100:4:0.5)[i] to support optimized growth of anaerobic biomass. Ratios of COD:N:P for optimized methane production are reported to be 100:2.5:0.5, far higher in COD than PCE provides for. In PCE, the COD may also be significantly comprised of compounds (e.g., detergents, lignin, plastics) that cannot be sufficiently degraded anaerobically, such that if the non-degradable fraction of COD were subtracted from the overall COD, the ratios of COD:N:P might be significantly lower. If VOAs in the PCE are used as the indicator of carbon availability, the ratios fall to 100:102:61. However, if in the anaerobically-treated effluent, the masses of VOA, TN, and TP that were removed are compared, the ratio (100:5:3.8) is close to the optimized ratio for anaerobic methane production (100:2.5:0.5).

The rate of solids removal through anaerobic pretreatment was over 80%, and organic acids were reduced to non-detectable levels. By reducing the pollutant concentrations through anaerobic pretreatment, the amount of food available to microbes in the aeration treatment basins was correspondingly reduced.

Lower food (organic pollutant) levels will lead to a lower aerobic respiration requirement in the aeration basins which theoretically requires less oxygen supplied and less sludge produced. Removing and dewatering sludge accumulations from aeration treatment basins occupies a significant part of the sewage plant operator's time, and where landfills are scarce, the cost of sludge disposal is high. When applied to five million gallons per day (the average daily throughput at the HKWWTP), the projected reductions of solids entering the aeration basins (by over 1,200 kg per day) should result in significant reductions in costs associated with aeration, sludge handling and disposal.

Task 15: *Perform detailed energy analysis of the performance of the (Bionest) up-flow fixed-film anaerobic reactors in the context of the impacts upon downstream aeration costs that still result in effluent BOD5 and TSS levels below the national discharge limits (30 mg/L BOD5/30 mg/L TSS).*

The energy required to oxidize the residual pollutants remaining in the treated PCE being fed to the aeration basins can be calculated by quantifying the oxygen required to reduce the remaining BOD5 concentrations to below 30 mg/l and the TSS to below 30 mg/l, and then factoring in the efficiency of aeration technologies used to supply the oxygen. Specifically, the levels of BOD5 (inclusive of NH_3 and NO_2^-) remaining in the anaerobically-treated effluent was used to estimate the mass of oxygen required for their degradation, and by extension, the energy consumed to pump the required amounts of oxygen into solution. Energy usage was calculated to achieve compliance with NPEDS (National Pollution Elimination Discharge System) BOD5 levels of below 30 mg/L. Aeration energy requirements are principally driven by the head pressure of the bubble diffusers and the required volume of flow, while anaerobic energy requirements at HKWWTP were limited to pumping water into the reactors. The energy consumed was calculated as the net anaerobic-aerobic system energy balance. The anaerobic-aerobic digestion system energy balance was then comparable against the existing energy usage at the HKWWTP for aeration treatment to determine whether significant energy savings can be expected using the AD system ahead of the existing aeration treatment.

Oxygen Demand: Steady-State Oxygen Requirement

If the BOD5 loading rate into aeration basins is constant, a steady-state oxygen demand will be established. As oxygen is mixed into the water through mechanical or other means, it is depleted at a constant rate as soluble and suspended pollutants are digested by biological metabolism and chemical oxidation/reduction reactions occurring in the aeration reactor. The steady-state oxygen requirement is dependent upon the BOD5, TKN, the aerated volume, and sludge retention time (RO2 = ***Q(CSØ – SSe) + 4.57Q(CTKNØ – STKNe) – 2.86RN2 – 1.98(VXv / Θ_x)*** Eq.):[ii]

$$R_{O2} = Q(C_{SØ} - S_{Se}) + 4.57Q(C_{TKNØ} - S_{TKNe}) - 2.86R_{N2} - 1.98(VXv / \Theta_x) \qquad \textbf{Eq. 1}$$

Where:

$C_{SØ}$ = the influent soluble plus particulate substrate concentration (kg TBOD/m^3)
$C_{TKNØ}$ = the influent soluble plus particulate total Kjeldahl nitrogen (TKN) concentration (kg N/m^3)
Q = the settled or raw sewage flow rate (m^3/day)
R_{N2} = the nitrogen gas production rate (kg N_2/day)
R_{O2} = the oxygen utilization rate (kg O_2/day)
S_{Se} = the final effluent soluble organic matter concentration (kg BOD/m^3)
S_{TKNe} = the final effluent soluble TKN concentration (kg N/m^3)
V = the aeration tank volume (m^3)
Xv = the volatile suspended solids concentration in the aeration tank (kg VSS/m^3)
Θ_X = the solids retention time (days)

and:

$4.57g\ O_2$ = the oxygen demand exerted for the conversion of TKN to HNO_3 (kg O_2/kg TKN)
2.86 = the net oxygen yield for the conversion of HNO_3 to nitrogen gas (kg O_2/kg N_2)
1.98 = the net oxygen yield of the VSS, assuming complete oxidation to CO_2, H_2O, and HNO_3 (kg O_2/kg VSS)

[Note that in the BOD5 testing applied at HKWWTP, samples are diluted in the test cultures such that the amount of dissolved oxygen will not be depleted, as an oxygen-limited BOD5 test would give erroneous results[iii], and therefore nitrification can proceed unless inhibited. ***This means that oxidation of ammonium and nitrite can add to the BOD5 readings.*** In denitrification, the reduction of NO_3^- to N_2 occurs under anoxic conditions, and therefore denitrification should not typically occur in the BOD5 test.]

In determining changes in TKN, our data indicates small differences in total nitrogen (TN) and NH_3-N, evidence that the levels of nitrite and nitrate are small in both the PCE and HRAD effluent. Therefore a small change in TKN results in no appreciable contribution to O_2 savings.

$\boldsymbol{4.57Q\ (C_{TKN\emptyset} - S_{TKNe}) = +/-0}$

Similarly, denitrification does not proceed during aeration, resulting in the rate of N_2 production from NO_3 being zero:

$\boldsymbol{2.86R_{N2} = 0}$

In our comparison we will ignore the contribution of activated sludge to net rate of O_2 consumption in order to isolate the effect of changes in BOD_5 levels.

$\boldsymbol{1.98(VXv / \Theta_x) = 0}$

Therefore the change in oxygen utilization rate (kg O_2/day), $\boldsymbol{R_{O2\ savings}}$, resulting from lowering $C_{S\emptyset}$ is given as:

$$\boldsymbol{R_{O2\ savings} = Q\ (C_{S\emptyset 1} - C_{S\emptyset 2})} \qquad \textbf{Eq. 2}$$

Q = 5Mgd (19,000 m^3/day)
$C_{S\emptyset 1} = BOD_{initial}$ = 95 mg/L
$C_{S\emptyset 2} = BOD_{final}$ = 48 mg/L

Therefore:

$\boldsymbol{R_{O2\ savings}}$ = 19,000 m^3/day x (95mg/L – 48mg/L = 47 mg/L) **= 893 kg O_2 /day**

The maximum BOD_5 concentration allowed under EPA NPDES rules for ***discharges ($BOD_{discharge}$)*** into streams, lakes, and bays is 30 mg/L, so the ***residual O_2 demand ($BOD_{residual}$)*** is taken as the amount of BOD that needs to be removed subsequent to anaerobic treatment, and prior to its discharge. Hence the residual BOD_5 in the HRAD effluent is given as (BODfinal - ***BODdischarge = (48 mg/L – 30 mg/L) = 18 mg/L = BODresidual*** Eq.):

$$BOD_{final} - BOD_{discharge} = (48\ mg/L - 30\ mg/L) = 18\ mg/L = BOD_{residual} \qquad \textbf{Eq. 3}$$

Using $\boldsymbol{R_{O2} = Q(C_{S\emptyset} - S_{Se})}$, the current activated sludge ***Steady-State O_2 demand*** required for discharge is therefore:

$\boldsymbol{R_{O2}} = Q(BOD_{initial} - BOD_{discharge})$ => (95 mg/L - 30 mg/L) x 19,000m^3/day **= 1235 kg O_2/day**

After anaerobic pretreatment, the new ***Steady-State O_2 demand ($R_{O2(b)}$)*** imposed upon the aeration treatment basins is given by RO2(b)**= *RO2 - RO2* *savings*** Eq. :

$\boldsymbol{R_{O2(b)} = R_{O2} - R_{O2\ savings}}$ Eq. 4

$R_{O2(b}$ = 1235 kg O_2/day – 893 kg O_2/day = 342 kg O_2/day

The total % reduction in O_2 demand is therefore given by:

$\boldsymbol{1-(R_{O2(b)} \div R_{O2})}$ Eq. 5

= 1-(342 kg/day ÷ 1235 kg/day) = 72%

Accordingly in order to meet the NPDES BOD_5 discharge limits, the steady-state oxygen requirement is reduced by an estimated 72%.

Regardless of the steady-state oxygen demand, a minimum concentration of oxygen must be present in the mixed liquor in order to support microbial populations. The rate of carbonaceous BOD_5 removal is reduced at dissolved oxygen (DO) concentrations below about 0.5 mg/L; however, consensus over higher aeration tank DO levels center on 2 mg/L. For non-nitrifying systems, the Joint Task Force (1988)iv recommends a DO of 2 mg/L under average conditions and 0.5 mg/L during peak loads. Other agencies recommend or require a minimum DO of 2 mg/L at all times.

Oxygen Transfer

The primary function of the aeration system is to transfer oxygen to the wastewater at such a rate that the amount of DO in the reactor never becomes a limiting factor. If steady-state conditions are to be maintained, the rate of oxygen transfer must be equal to the rate of consumption by the aerobic microorganisms. Oxygen solubility in water is greatly affected by temperature and pressure (see Figure 13). For an aeration reactor 15’ deep (at sea level), the ambient pressure of the reacted solution is 1.5 bar, and at reaction temperatures of 25 to 30 ºC, oxygen saturation is achieved at very low concentrations.

Studies have shown that oxygen transfer efficiency ranges from 3% to 6%, depending principally on the bubble size and time of bubble submersion, and temperature.[v] The type of bubble diffusers varies greatly between sewage treatment facilities, and the properties and maintenance of each aeration system affect the energy efficiency, oxygen transfer, and mixing. Various manufacturers offer proprietary diffuser designs and materials, and the precise efficiency of oxygen transfer differs greatly between them. Clogging of diffuser or membrane pores significantly affects the performance of each type.

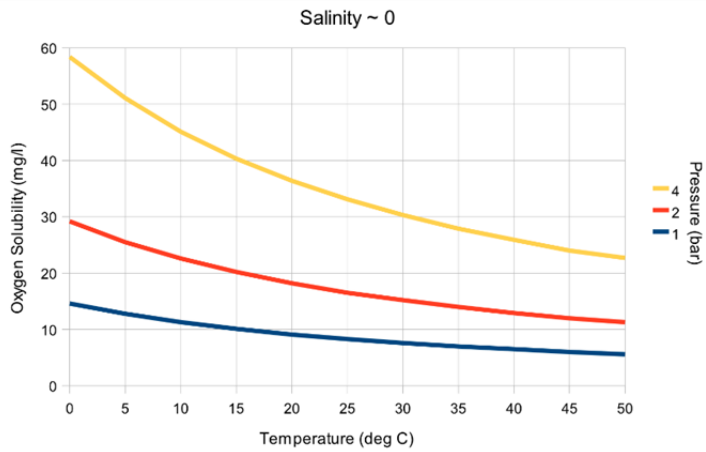


Figure 13: Oxygen Solubility

The selection of bubble size is complicated due to the use of bubbles for mixing of the sewage. Larger bubbles are more efficient at mixing the liquor, as their greater size and buoyancy impart more mixing energy to the liquor as opposed to small bubbles, which are prone to lateral or downward movement due to eddies and particulate concentrations.[vi] Finding the balance between the need for more or less mixing is a practical decision that will affect the energy usage at the treatment plant, however mechanical mixing is an option. The clear trend in aeration treatment is in the use of fine bubble diffusers that are capable of generating tiny bubbles with decreased fouling.

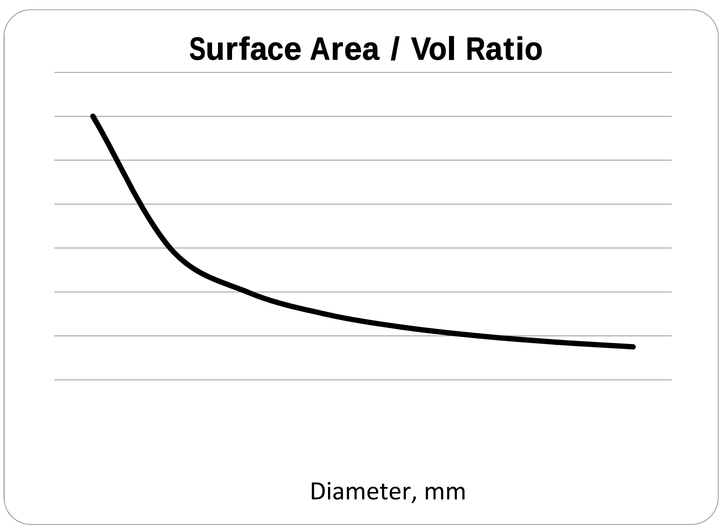


Figure 14: Surface Area / Volume Ratio

Aeration efficiency
Considering the effects of temperature on oxygen solubility, we if choose 3% efficiency as the rate of oxygen transfer, the ***total reduction in pumped oxygen per day*** is:

$$V_{O2\ savings} = R_{O2\ savings} \div \text{efficiency of transfer}$$

$V_{O2\ savings}$ = 893 kg O_2/day ÷ 3% eff of O_2 transfer = 29,700 kg O_2/day

As oxygen comprises 23% of air by weight, the ***reduction in the mass of air pumped per day*** equals:

$V_{air\ savings} = V_{O2\ savings} \div \%O_2$ ***in air***

$V_{air\ savings}$ = 29,700 kg O_2/day ÷ 23% = 129,000 kg/day

Energy Requirements

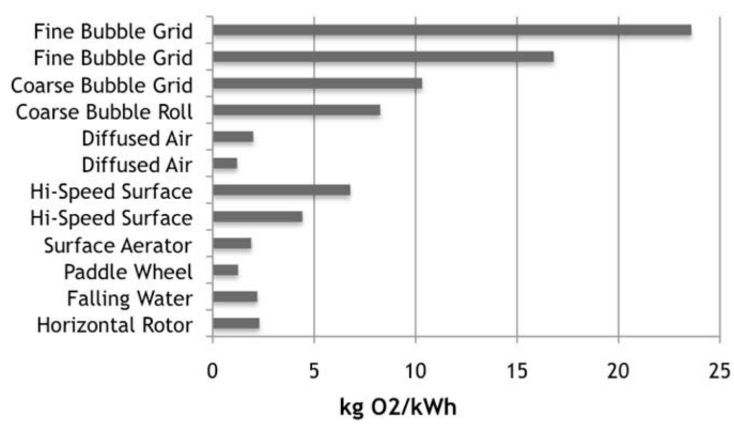
The energy used to deliver the O_2 into the effluent solution is affected by many variables:

1. Configuration and depth of air diffusers in the Aeration Reactor,
2. Shape and size of tanks/distribution of diffusers,
3. Pore size of diffusers,
4. Clogging of pores,
5. Static pressure of air system,
6. Type and voltage of air pump, and
7. Rate of air pumping.

Some of these variables are fixed by the design of the particular aeration system, while others vary with the condition of the components of the system[vii]. The variations in system designs result in energy efficiency values that differ widely. The only practical way to determine the efficiency of systems has been through physical modeling and on-site audits.[viii]

For our purposes, we can use approximations of aeration efficiency that have been developed by ASCE (American Society of Civil Engineers)[ix] and others (see Table 2).

Table 2: Efficiency of Typical Aerators[x,xi]



Energy Balance

The aeration system at the HKWWTP is powered by electric pumps rated at 150 hp each and operate at 460 V, 175 A. Generally only one pump out of three operates at one time. For this analysis we will calculate the energy used by one pump at the nameplate rating.

The energy currently used per day in aeration is:

150 hp x 24 hrs/day = 112 kW x 24 hrs/day = 2,690 kWh/day (see Table 3)

Table 3: Energy Balance, Activated Sludge

		5,000,000	gal/day
		18,927	m3
Energy Balance			
Δ BOD mg/L (95-30)	65 mg/L		
aerator eff. (kg O2/kWh)	15 kg/kWh		
eff. of O2 transfer	3%	2,689	kWh/day
Energy Usage		2,689	kWh/day

Table 4: Energy Balance, Anaerobic Pretreatment plus Aeration

		5,000,000	gal/day	
		18,927	m3	
Energy Balance				Δ kWh
Secondary Treatment				
Anaerobic	19.2 kW/h	460	kWh/day	460 kWh
Tertiary Treatment				
Aeration				
Δ BOD mg/L (48-30)	18 mg/L			
aerator eff. (kg O2/kWh)	15 kg/kWh			
eff. of O2 transfer	3%	745	kWh/day	(1,944) kWh
Energy Usage		1,205	kWh/day	(1,485) kWh

Comparing the energy requirements for activated sludge treatment (Table 3) and activated sludge with anaerobic pretreatment (Table 4), energy savings due to the reductions in BOD_5 and sludge entering the aeration treatment zone is estimated to be 1,485 kWh.

Task 16: *Based upon analysis of Task 15 above, estimate the real-world energy demands and compare them against current energy demands*

The impacts on oxygen demand and energy demand are compared for the existing activated sludge (AS) and anaerobic pretreatment plus activated sludge (HRAD + AS) processes (Table 5)

Table 5: Energy Demand Comparison

	Existing AS	HRAD + AS	% change
Steady-State Oxygen Demand	1235 kg/d	342 kg/d	72%
Energy Demand	2690 kWh/d	1200 kWh/d	55%

Energy costs at the HKWWTP constitute approximately 60% of the total costs to operate the plant (OPEX), including the cost of labor. A savings of 55% in expenditures for energy would reduce the overall OPEX by 30%. Energy costs would fall to 43% of overall OPEX.

In order to implement the system as currently configured, based upon a HRT of 3 days, the system would require a capacity of 15 million gallons. Assuming the use of larger tanks (24,000 gal each), the system would require 625 tanks and consume 2.5 acres of land. The cost of installing such a system would be approximately $1.1 per gallon, or $16.5 million.

Task 17: *Perform a design and cost analysis of the installation of additional packing media that complements Bionest in the context of operating up-flow fixed-film packed-bed hybrid anaerobic digesters.*

Additional Packing Material

The preceding sections theorized the reductions in energy usage by aeration treatment processes due to application of HRAD reactors where a modest amount of Bionest packing material was used. ***Feedback from our IAB indicated that although the potential energy savings are significant, the overall size and capital cost of the system as tested is too high to bear***. To make our approach more attractive, it was decided to retrofit the first of the two HRAD reactors to incorporate additional packing materials to complement the existing Bionest. The purpose was to both increase performance in terms of BOD_5 reduction (hopefully to below the NPDES limits) and decrease the HRT, leading to savings in capital costs and land area.

The second suggestion of the IAB was to retrofit the second HRAD reactor to a reverse-flow aerated trickling filter.

The estimates shown below are for the costs for the addition of these and other packing materials per cubic meter, including particles of biocarbon (biochar), coconut coir, or similar materials. The total cost to modify the reactor packing media is shown in Table 6.

Installing aeration would require the opening of the reactor vessels, and therefore would involve most of the costs associated with installing additional media, except for the media holders and additional media. Air diffusers suspended below media would be inexpensive, costing less than $200 per vessel, including hoses and holders. Air can be supplied from the existing aeration pumps, resulting in very low overall costs for installing the entire system.

Table 6: Media Alternatives

Media Costs			Installed cost
Mixed Woods Biochar	$ 488 /m3	$ 3,454	$ 24,696
Coco-char	$ 1,305 /m3	$ 9,239	$ 30,481
Coir	$ 30 /m3	$ 212	$ 21,454
Bio-Balls ™	$ 2,642 /m3	$ 18,705	$ 39,947
Bionest			
PVC	$ 450 /m3	$ 3,186	$ 24,428
Salvaged ABS	$ 370 /m3	$ 2,620	$ 23,862
Stainless Steel	$ 1,810 /m3	$ 12,811	$ 34,053
Recycled HDPE	$ 100 /m3	$ 708	$ 21,950
Recycled mixed plastic	$ 25 /m3	$ 177	$ 21,419

Task 18: *Define the potential of the hybrid system (defined in Task 17 above) to fully eliminate the need for aeration.*

The use of coarse biochar as a reactor packing has been evaluated as a way of reducing effluent residual pollutant levels in treated wastewater, as well as its ability to immobilize thick layers of microbes; its pitted surfaces provide excellent anchorage for the formation of biofilms. Related work (M. Cooney University of Hawaii, data not presented) has shown the packed beds of corn cob and wood derived biochar to be extremely effective at treating high strength wastewater (>20 kg COD/m^3) to COD reductions above 90% at HRT's as low as 1 day. The relatively high surface roughness of the biochar make it a highly attractive biofilm support media. Moreover, its dissimilar shape between pieces upon processing facilitate its reasonably dense packing whilst maintaining a relatively high degree of interstitial spaces between particles. Biochar is also highly buoyant in water which reduces packing compression. Biochar also supports the absorbance of organic municipal and industrial pollutants and toxics, holding them in the system for a time equal to or greater than the solids residence time. The presence of the Bionest material below the biochar offers advantages in terms of filtering large solids and fats, oils and greases that may be carried over into the primary clarifier effluent.

As the remaining amount of BOD_5 needing removal in the HRAD treated effluent ($\boldsymbol{BOD}_{\textit{residual}}$) is 18 mg/L, this amount of BOD_5 may be easily trapped by improved biofilm thicknesses and by the adsorbant properties of the biochar, and therefore the potential for achieving compliance with the EPA discharge requirement of 30/30 (mg/l BOD5 and TSS) with the hybrid system appearing very promising.

Task 19: *Retrofit the reactors as per the design specifications approved by the IAB.*

The retrofitted reactor system is shown in Figure 15. The first reactor was retrofitted with the new packing material that included biochar and a second filamentous fiber media (Springflo) fabricated from a rubberized plastic material covered with a calcium-carbonate-based coating with an impressed weave to provide crevices for biofilms to adhere and grow. The second of the two anaerobic column towers was packed with highly porous polystyrene media (Jaeger Bio Pac SF#30) and converted to a down-ward flow aerated tricking filter. The system has been operational since August of 2013.

Figure 15: retrofitted reactors.

Task 20: *Prepare an experimental plan for evaluation and optimization of the reconfigured reactor system*

An experimental plan was developed that ranged over a series of hydraulic retention times and recycle rates applied to the trickling filter. The final results are presented in Table 7. On its own the system was able to achieve a final effluent BOD_5 of just at 30 mg/l and a TSS between 30 and 50 mg/l and a hydraulic retention time of only seven hours. With the addition of a clarifier and short bed sand filter the effluent BOD_5 was reduced to around 14 mg/l and the TSS to 12 mg/l or even lower. Fecal coliform counts after the sand filter were around $17x10^4$. Key observations indicated that the improved packing density did permit enhanced degradation of the wastewater pollutants but that some form of aeration was still required to bring the BOD_5 down to values in line with EPA discharge requirements. Finally, meeting the EPA discharge requirements required the addition of two additional unit operations, namely a clarifier and sand filter. The trickling filter actually produced TSS (owing to slight sloughly of biofilms) while the anaerobic digester produced BOD_5 (owing to the solubilization of biosolids).

Table 7: Final results of trials applied to retrofitted reactor system.

Flow in (R1 HRT)	Flow rate (gpd)	Start date	Recirculation		BOD_5 (total, mg/l) and Organic loading rate (OLR, kg/d)							
			HRAD (R1)	TF (R2)	PCE (mg/l)	OLR (kg/d)	R1 (mg/l)	OLR (kg/d)	R2 (mg/l)	OLR (kg/d)	SF (mg/l)	OLR (kg/d)
Q1 (14 hrs)	4767	3/28/2014	Q1	2*Q1	88.0	1.6	90.0	1.6	70.0	1.3		
Q1 (14 hrs)	4855	4/2/2014	Q1	2*Q1	92.0	1.7	80.0	1.5	34.0	0.6		
Q1 (14 hrs)	4780	4/11/2014	2*Q1	2*Q1	109.0	2.0	93.0	1.7	35.0	0.6		
Q1 (14 hrs)	4695	4/18/2014	2*Q1	3*Q1	98.0	1.7	76.0	1.4	36.0	0.6		
Q2 (10 hrs)	5939	4/25/2014	2*Q2	2*Q2	95.0	2.1	77.0	1.7	34.0	0.8		
Q2 (10 hrs)	6219	5/2/2014	2*Q2	3*Q2	80.0	1.9	84.0	2.0	36.0	0.8		
Q2 (10 hrs)	6219	5/9/2104	2*Q2	4*Q2	90.0	2.1	74.0	1.7	31.0	0.7	14.0	0.3
Q3 (7 hrs)	8144	5/16/2014	2*Q3	2*Q3	100.0	3.1	73.0	2.3	36.0	1.1	30.0	0.9
Q3 (7 hrs)	7794	5/30/2014	2*Q3	3*Q3	84.0	2.5	75.0	2.2	26.0	0.8	19.0	0.6
Q3 (7 hrs)	7822	6/7/2014	2*Q3	4*Q3	87.0	2.6	71.0	2.1	32.0	0.9	18.0	0.5
Q3 (7 hrs)	7822	7/4/2014	2*Q3	4*Q3							11.8	
Q3 (7 hrs)	7822	7/14/2014	2*Q3	4*Q3							16.9	

Flow in (R1 HRT)	Parameters: BOD_5 (soluble, mg/l)				Nitrogen BOD_5 (total, mg/l)				TSS (mg/l)				NH_4^+				NO_2^-				NO_3^-			
	PCE	R1	R2	SF	PCE	R1	R2	SF	PCE	R1	R2	SF	PCE	R1	R2	SF	PCE	R1	R2	SF	PCE	R1	R2	SF
Q1 (14 hrs)	43.0	65.0	10.0						90.0	20.0	56.0		31.6	23.5	19.6		ND	ND	1.59		ND	ND	ND	
Q1 (14 hrs)	14.0	20.0	17.0						71.0	18.0	28.0		31.1	22.0	18.8		ND	ND	1.15		ND	ND	ND	
Q1 (14 hrs)	49.0	48.0	10.0		7.0	10.0	10.0		81.0	35.0	49.0		20.4	21.1	21.4		ND	ND	1.61		ND	ND	ND	
Q1 (14 hrs)	51.0	48.0	8.0			9.0	12.0		67.0	53.0	63.0		22.2	21.8	20.1		ND	ND	1.14		ND	ND	ND	
Q2 (10 hrs)	46.0	41.0	10.0		24.0	11.0	8.0		60.0	35.0	45.0		22.5	21.4	21.6		ND	ND	1.14		ND	ND	0.39	
Q2 (10 hrs)	45.0	41.0	9.0		6.0	11.0	9.0		54.0	61.0	71.0		18.2	22.0	18.6		ND	ND	0.78		ND	ND	0.33	
Q2 (10 hrs)	48.0	41.0	9.0		10.0	9.0	7.0		73.0	41.0	45.0	19.0	21.1	27.4	19.5	22.7	ND	ND	ND	ND	ND	ND	0.27	ND
Q3 (7 hrs)	40.0	35.0	10.0		22.0	NA	NA	NA	59.0	46.0	50.0	11.0	22.1	22.5	21.0	25.8	ND	ND	ND	ND	ND	ND	0.29	ND
Q3 (7 hrs)	13.0	36.0	11.0	14.0	6.0	3.0	0.0		79.0	74.0	18.0	17.0	17.7	17.5	19.1	24.6	ND	ND	ND	ND	3.23	0.23	0.37	ND
Q3 (7 hrs)	43.0	38.0	9.0	13.0	9.0	5.0	12.0	2.0	72.0	32.0	62.0	9.5	15.4	18.8	13.3	17.6	ND	ND	ND	ND	ND	ND	0.26	ND
Q3 (7 hrs)												14.7												
Q3 (7 hrs)											36.2	5.7												

Task 21: *Estimate the total energy required to treat the current flow of primary clarifer effluent passing through the Hawaii Kai wastewater treatment plant and compare against their current activated sludge process.*

The system was scaled up to treat the same amount of wastewater currently treated at Hawaii Kai and the energy load calculated. These results were then compared against the existing energy load of activated sludge process currently employed. Initially the energy load for a single unit of employing a 25,000 gallon anaerobic digester (and trickling filter and clarifier appropriately scaled) was calculated (Figure 16). Two pumps are used to apply recycle to the anaerobic reactor at two times the total system flow rate of wastewater. Four pumps were selected to apply the recycle to the aerobic reactor at four times the total system flow rate. As summary of these flow rates are presented in Table 8 and the energy calculations in Table 9. It should be noted that these energy calculations do not consider the cost of pumping the wastewater through the system as this will be incorporated in the next section when multiple units are considered.

Next a row of twelve units were sequenced together. This is presented in Figure 17. The total flow rate for the row is just over one million gallons per day. The total energy load for the row also includes the energy load of a single pump to deliver wastewater to all twelve units. It should be noted that a blower for the trickling filters were not included in the calculations as they will added in the next section. The flow rate and energy calculations are given in Tables 10 and 11.

Finally, three rows were sequenced together (Figure 18). The final effluent is dumped to a single sand filter and a single blower has been added. The total flow through the system is just over three million gallons per day. The total number of units, 36, represent the total number required to treat just over three million gallons per day at a hydraulic retention time of seven hours. The flow rates and energy calculations are given in Tables 12 and 13.

Figure 19 depicts the two systems compared side by side with a reasonable correlation to scale (i.e. the total land configuration of the combined anaerobic – aerobic system was estimated to be just at 0.6 acres assuming 100x200 ft^2 or each unit. Our estimate of the Hawaii Kai load accounted for a single blower to the aerated sludge as well as the pump to recycle the activated sludge from the deep-well settling tank. The energy comparisons between the two systems (combined anaerobic – aerobic versus the current plants activated sludge system) is presented in Table 14. **In comparison, a comparison of the two energy loads showed that the high rate anaerobic – aerobic system consumed 48% of the current load (or estimated current load) consumed by the activated sludge system at Hawaii Kai.**

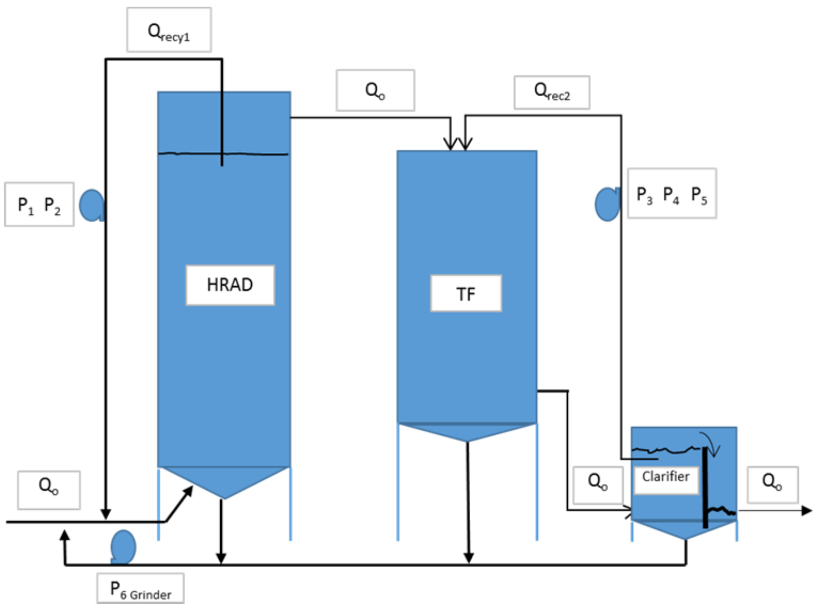


Figure 16: Energy Load Calculation Elements

Table 8: Summary of Flow Rates

V_{HRAD}	25000.0	gallons
HRT_{HRAD}	7.0	hours
Q_o	3571.4	gph
Q_o	85714.3	gpd
Q_o	324.4	m^3pd
Q_o	13.5	m^3ph
Q_{rec1}	7142.9	gph
Q_{rec1}	171428.6	gpd
Q_{rec1}	648.9	m^3pd
Q_{rec1}	27.0	m^3ph
Q_{rec2}	14285.7	gph
Q_{rec2}	342857.1	gpd
Q_{rec2}	1297.7	m^3pd
Q_{rec2}	54.1	m^3ph
$HRT_{Clarifier}$	2.0	hours
$V_{Clarifier}$	7142.9	gallons

Table 9: Energy Calculation

					ENERGY			
			Q	Head	Voltage	Current	Power	Power
			gph	ft	V	Amps	Watt	kW
	P_1 (Q_{recy1})		3571.4	5	115	2	230	0.23
	P_2 (Q_{recy1})		3571.4	5	115	2	230	0.23
	P_3 (Q_{recy2})		4761.9	20	115	2	230	0.23
	P_4 (Q_{recy2})		4761.9	20	115	2	230	0.23
	P_5 (Q_{recy2})		4761.9	20	115	2	230	0.23
	$P_{6\ Grinder}$ (Solids recycle)				230	9.8	31.1	0.0
	P_{unit}						1181.1	1.18

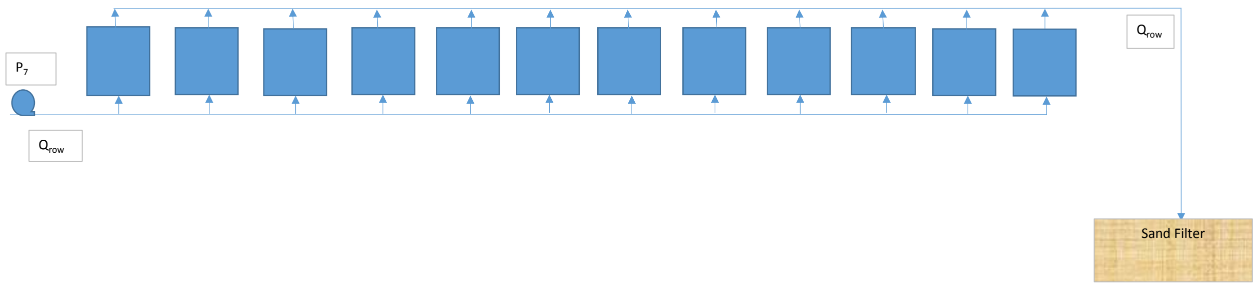


Figure 17: Twelve Units Sequenced Together

Table 10: Flow Rate Calculations for Twelve Units

Q_{row}	42857.14	gph
Q_{row}	1028571.43	gpd
Q_{row}	3888.00	m^3pd
Q_{row}	162.00	m^3ph
#units	12.00	

Table 11: Energy Calculations for Twelve Units

				ENERGY			
	Q	Head	Voltage	Current	Power/Unit	# of units	Power
	gph	ft	V	Amps	kW		kW
P_{units}					1.18	12.00	14.17
P_{air}					3.59	0	-
P_7	14267	30	400	11.5	4.60	1	4.60
Total							18.77

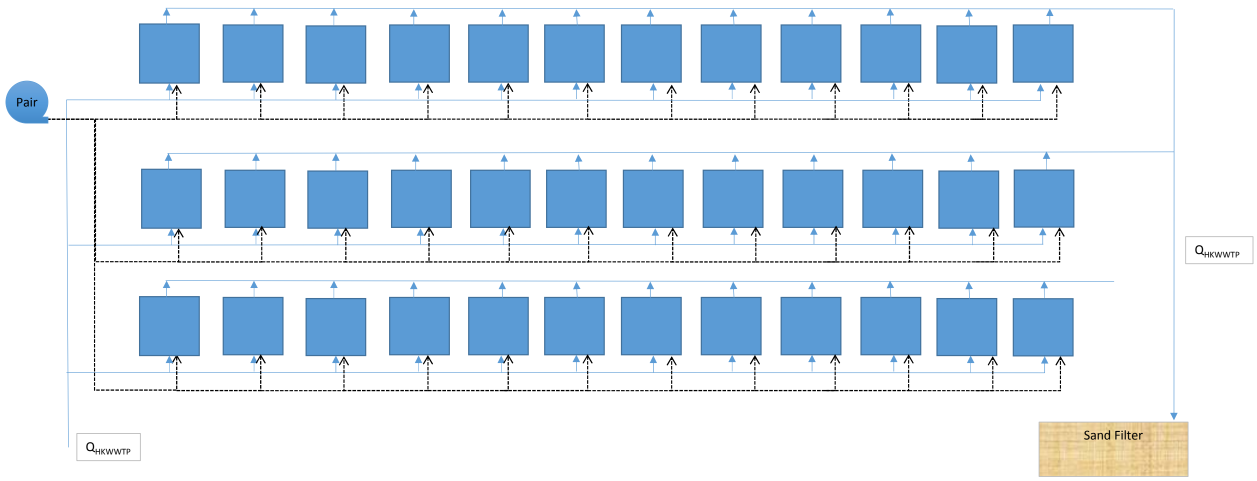


Figure 18: Three Rows of Twelve Units

Table 12: Flow Rate Calculations for Three Rows of Twelve Units

Q_{HKWWTP}	128,571.4	gph
Q_{HKWWTP}	3,085,714.3	gpd
Q_{HKWWTP}	11,941.7	m^3pd

Table 13: Energy Calculations for Twelve Units

					ENERGY				
		Q	Head	Voltage	Current	Power/row	# of rows	Load	
		gph	ft	V	Amps	kW	ea	kW	kWh/day
Row of 12		42857.1	30.0			18.8	3.0	56.3	1351.7
Air Blowe	VBN			400.0	9.0	3.6	1.0	3.6	86.2
								59.9	1437.8

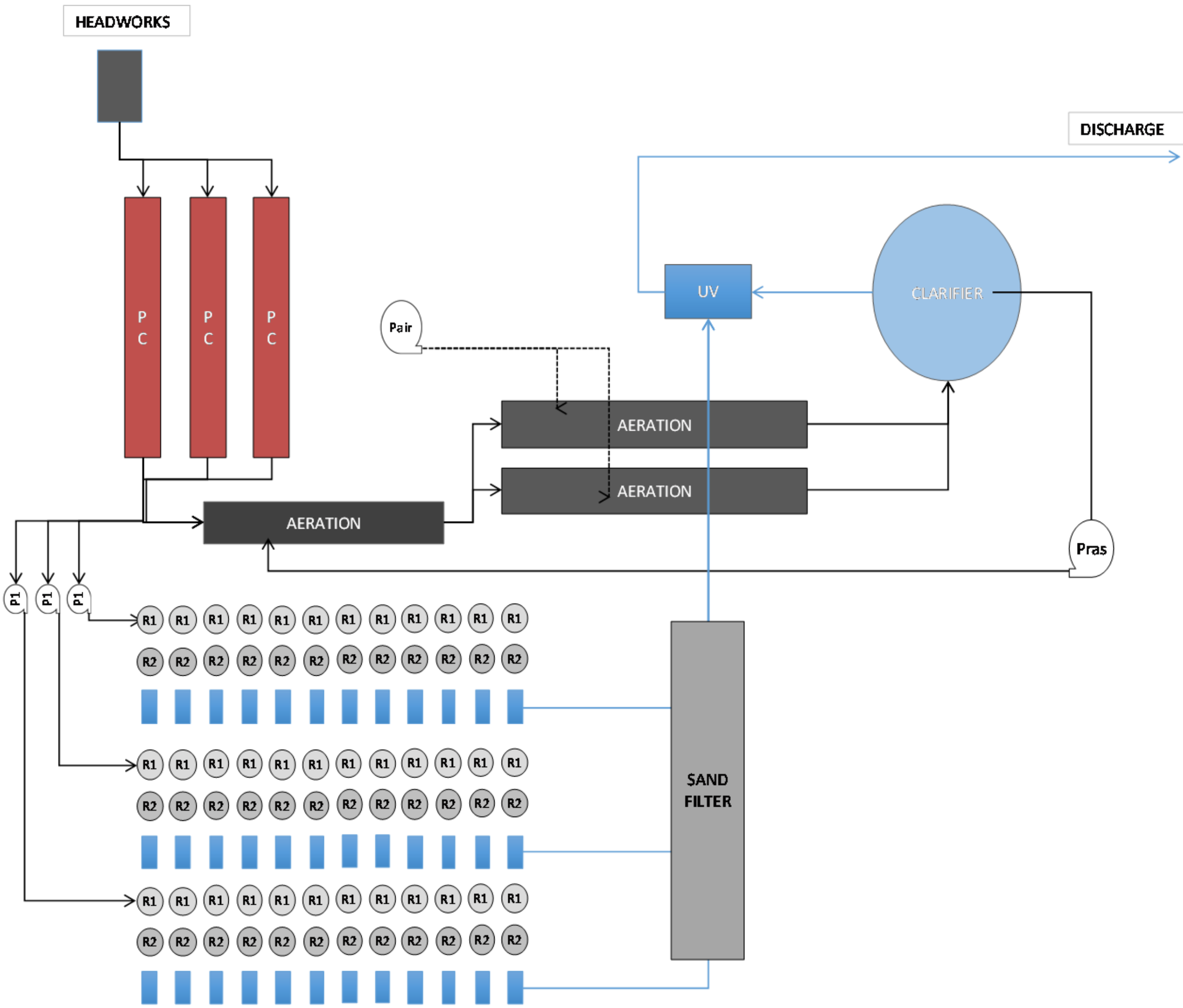


Figure 19: Side by Side Comparison of the Two Systems

Table 14: Energy Comparison for the Two Systems

	Q gpd	kWh/day
Exist HKWWTP	3,085,714	
Loading (gravity)		-
Blower (air)		2,640
RAS	925,714	115
Exist HK total		2,755
RGP HNEI	3,085,714	1,438
Energy Savings		48%

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