

Energy Benchmarking Secondary Wastewater Treatment and Ultraviolet Disinfection Processes at Various Municipal Wastewater Treatment Facilities



Submitted to

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- A: Secondary Wastewater Treatment Plants – Additional Information
- B: UV Plants – Additional Information
- C: Investigation of Energy Use and Disinfection Performance at a Wastewater Treatment Plant
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Executive Summary

The California Energy Commission reported that wastewater treatment plants are often the single largest electricity users in local governments. The secondary wastewater treatment process is usually the most energy intensive unit process at municipal wastewater treatment plants. The ultraviolet (UV) disinfection process is being used at an increasing number of municipal wastewater treatment plants, due to the many advantages of that method of disinfection. However, UV disinfection is also an energy intensive process.

In an effort to facilitate sustainable energy efficiency improvements in the wastewater treatment sector, the Pacific Gas and Electric Company undertook this project to develop benchmark information quantifying the amount of energy used by various secondary wastewater treatment and UV disinfection processes based on actual operating data. Treatment plant enlargements and upgrades are being undertaken as a result of increasing population, increased regulatory requirements and increasing interest in water reuse. This energy benchmark report provides useful information about the energy requirements of various secondary treatment and disinfection processes and equipment options. With better knowledge of the energy requirements of various options, plant designers and plant managers will be able to make more informed decisions when selecting a secondary treatment or disinfection process. The benchmark information will also be valuable to plant managers who do not have near term enlargement projects. Plant managers will be able to compare the amount of energy used by the secondary treatment and disinfection processes at their existing plant to the benchmark information. Those plant managers will be in a more knowledgeable position to assess whether additional energy efficiency measures would be appropriate for their plant.

Because municipal wastewater treatment plants receive wastewater with varying characteristics and effluent permit limits vary for each plant, the performance requirements of the secondary treatment and disinfection processes vary from plant to plant. In addition, treatment plants utilize equipment of varying ages and types to provide the same unit process. For these reasons, it is important to include information regarding the influent quality, effluent permit requirements and other treatment plant characteristics when presenting benchmark information.

The three benchmark parameters calculated for the secondary wastewater treatment process were energy used per pound of BOD removed (kWh/lb BODr); energy used per million gallons of wastewater treated (kWh/MG) and oxygen transfer efficiency (OTE). The benchmark parameters observed during the project are summarized in Table A.

Table A. Summary of Energy Benchmark Parameters and Energy Use Information for the Secondary Wastewater Treatment Process and for Total Plant Operations

Parameters	Range of Values	
	Observed	Generic (3)
Energy (1) /lb BODr (kWh/lb BODr)	0.4 - 2.6	
Energy (1) /MG treated (kWh/MG)	508 - 2,428	279 - 928
OTE (%) (2)	2.6 - 83	
Electrical Use for Total Plant Operations (kWh/MG)	1,073 - 4,630	978 - 1,926
% of Total Plant Energy Used for Secondary Treatment Only (%)	27 - 60	29 - 48

- (1) Electrical energy for the secondary wastewater treatment process only
- (2) Oxygen Transfer Efficiency for air activated sludge and high purity oxygen activated sludge processes
- (3) See reference [2].

While conducting the site investigations, some plants were identified as using a significantly larger amount of energy than the other plants in the study. Thus, even during the benchmarking process, the information was useful in identifying plants for which further investigation of energy efficiency improvements appears warranted.

The energy used for UV disinfection ranged from 117 to 557 kWh per million gallons treated when meeting disinfection limits of 200 MPN of Fecal Coliform /100 ml of wastewater. When complying with an NPDES effluent permit requiring a very high level of disinfection, 2.2 MPN of Total Coliform/100 ml of wastewater, energy use of 1,001 kWh per million gallons treated was required, even though the plant had an effluent TSS concentration of 1 mg/l and uses an automated control system to adjust the energy used for disinfection based on flow and UV transmittance.

Based on information from the benchmarking study, UV disinfection performance is not a linear function of the applied energy. An increasing amount of energy needs to be applied in order to obtain successive reductions in microorganism concentration. This observation is supported by findings in the report “Recent Developments in Ultraviolet Disinfection” [7]. The above conclusion is also supported by the findings in the report “Investigation of Energy Use and Disinfection Performance at a Wastewater Treatment Plant” provided in Attachment C of this report.

The UV disinfection process required 14% and 23% of the total electrical energy used by the two plants for this benchmarking study. It is inappropriate or statistically insignificant to draw a definitive conclusion regarding the comparative energy efficiency of low vs. medium pressure UV systems from the limited treatment plant data obtained for this study. However, it appears that low pressure systems are more energy efficient than the medium pressure systems. This observation is consistent with information reported in the literature [6] that low pressure lamps are more efficient than medium pressure lamps.

A “Back-of-the-Envelope” calculation was prepared to provide a comparison of the energy required for a chlorine/hypochlorite and dechlorination process compared to the energy used by an ultraviolet disinfection process. The analysis is included in Attachment D of this report. On a global energy basis, it appears that UV disinfection can be competitive with chlorine/hypochlorite disinfection and dechlorination.

1. Project Description and Objectives

The California Energy Commission reported that wastewater treatment plants are often the single largest electricity users in local governments [1]. The secondary wastewater treatment process is usually the most energy intensive unit process at municipal wastewater treatment plants. The ultraviolet (UV) disinfection process is being used at an increasing number of municipal wastewater treatment plants, due to the many advantages of that method of disinfection. However, UV disinfection is, also, an energy intensive process.

In an effort to facilitate sustainable energy efficiency improvements in the wastewater treatment sector, the Pacific Gas and Electric Company undertook this project to develop benchmark information quantifying the amount of energy used by various secondary wastewater treatment and UV disinfection processes that are in operation. Treatment plant enlargements and upgrades are being undertaken as a result of increasing population, increased regulatory requirements and increasing interest in water reuse. This energy benchmark report provides useful information about the energy requirements of various secondary treatment and disinfection processes and equipment options. With better knowledge of the energy requirements of various options, plant designers and plant managers will be able to make more informed decisions when selecting a secondary treatment or disinfection process. The benchmark information will also be valuable to plant managers who do not have near term enlargement projects. Plant managers will be able to compare the amount of energy used by the secondary treatment and disinfection processes at their existing plant to the benchmark information. Those plant managers will be in a more knowledgeable position to assess whether additional energy efficiency measures would be appropriate for their existing plant.

Because municipal wastewater treatment plants receive wastewater with varying characteristics and effluent permit limits vary for each plant, the performance requirements of the secondary treatment and disinfection processes vary from plant to plant. In addition, treatment plants utilize equipment of varying ages and types to provide the same unit process. For these reasons, it is important to include information regarding the influent quality, effluent permit requirements and other treatment plant characteristics when presenting benchmark information.

2. Energy Benchmarking Secondary Treatment Processes

2.1 Energy Benchmarking Secondary Treatment Processes

A site investigation of the secondary wastewater treatment process at ten treatment plants was conducted. Extensive information was obtained about each plant, including flow and loading to the plant, unit processes employed, equipment used for secondary treatment, NPDES effluent permit requirements, plant performance data and energy use data. The treatment plants investigated ranged in size from about 1 to 72 MGD. Most of the plants receive wastewater from residential, commercial and industrial facilities. One plant (Plant G) receives approximately half of its Biochemical Oxygen Demand (BOD) load from a food processing facility. All the plants provide primary wastewater treatment prior to the secondary treatment process. Some of the plants provide tertiary treatment. Each of the ten treatment plants has a National Pollutant Discharge Elimination System (NPDES) permit written specifically for the plant. The NPDES permits for the treatment plants investigated require effluent BOD and Total Suspended Solids (TSS) concentrations that range from 10 to 45 mg/l BOD, as a monthly average. Some key characteristics about the plants are summarized in Table 1. Additional information about the plants is provided in Attachment A.

Table 1. Key Characteristics of Treatment Plants Investigated

WWTP	Annual Avg Plant Flow (MGD)	Primary Treatment Provided	Secondary Treatment Process (1)	Type of Equipment for Secondary Treatment	Additional Treatment Provided (2)	NPDES Permit Requirements
A	1.8	Yes	RBC	---	None	Mo. Ave. 10 mg/l BOD 10 mg/l TSS
B	9.8	Yes	Bio-tower/ AAS	Fine bubble aeration	None	Mo. Ave. 25 mg/l CBOD 30 mg/l TSS
C	2.8	Yes	AAS	Fine bubble aeration	None	Mo. Ave. 10 mg/l CBOD 15 mg/l TSS
D	12.7	Yes	AAS	Fine bubble aeration	None	Mo. Ave. 20 mg/l BOD 15 mg/l CBOD 20 mg/l TSS
E	1.8	Yes	AAS	Fine bubble aeration	None	Mo. Ave. 10 mg/l BOD 10 mg/l TSS
F	19.4	Yes	AAS with N/D	Fine bubble aeration	Nitrification/ Denitrification	Mo. Ave. 10 mg/l BOD 10 mg/l TSS
G	5.5	Yes	AAS with N/D	Fine bubble aeration	Nitrification/ Denitrification	Mo. Ave. 30 mg/l BOD 30 mg/l TSS
H	5.5	Yes	HPO-AS PSA	Surface mixers	None	Mo. Ave. 45 mg/l BOD 45 mg/l TSS
I	19.9	Yes	HPO-AS PSA	Surface mixers	None	Mo. Ave. 30 mg/l BOD 30 mg/l TSS
J	72	Yes	HPO-AS Cryo	Surface mixers	None	Mo. Ave. 30 mg/l BOD 30 mg/l TSS

- (1) RBC: rotating biological contactor. AAS: air activated sludge. AAS with N/D: air activated sludge with Nitrification and Denitrification. HPO-AS PSA: high purity oxygen activated sludge, oxygen produced by pressure swing adsorption. HPO-AS Cryo: high purity oxygen activated sludge, oxygen produced by cryogenic process.
- (2) Treatment provided integral with the secondary treatment process, not a downstream treatment process.

2.2 Operation and Performance of the Secondary Treatment Processes

Selected data characterizing the operation and performance of the secondary treatment processes during the period of data collection is provided in Table 2.

Table 2. Selected Operation and Performance Data about the Secondary Treatment Processes During the Period of Data Collection

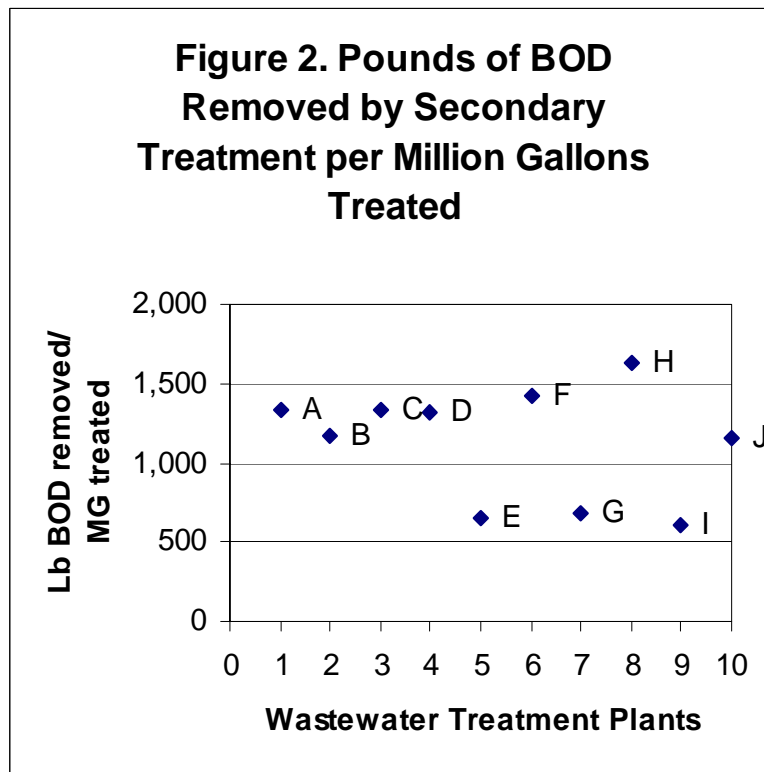
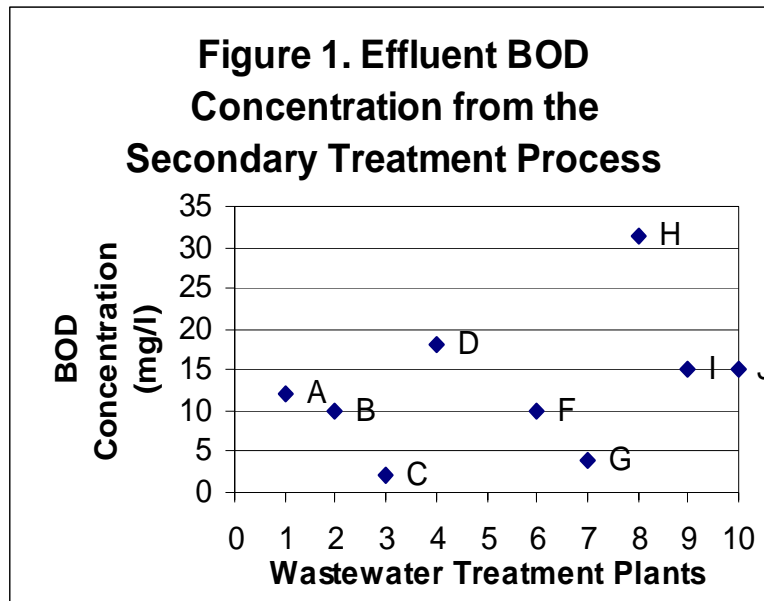
WWTP	Secondary Treatment Process	Plant Flow During Data Collection (MGD)	MCRT (days)	BOD Concentration		Lb of BOD Removed/ Day
				Influent to Secondary Treatment (mg/l)	Effluent from Secondary Treatment (mg/l)	
A	RBC	1.8	NA	172	12	2,402
B	Bio-tower/ AAS	10.1	5.4	151	10	11,877
C	AAS	2.4	19	165 (1)	2	3,199
D	AAS	11.5	0.33 (2)	175 (1)	18	15,101
E	AAS	1.7	NA	NA	NA	1,118
F	AAS with N/D	19.4	6.3	180	10	27,454
G	AAS with N/D	5.4	NA	85	4	3,694
H (3)	HPO-AS, PSA	5.5	3.5	228	31.5	9,000
I (4)	HPO-AS, PSA	19.8	NA	88	15	12,055
J (5)	HPO-AS, Cryo	63	NA	175	15	84,139

- (1) Estimated influent concentration
- (2) Appears low, but is the data reported
- (3) BOD based on conversion of COD data, using historical BOD:COD ratio 0.5
- (4) Typical plant values for dry weather flow
- (5) BOD based on conversion of COD data, using historical BOD:COD ratio .26

Some treatment plants do not conduct comprehensive sampling and laboratory analysis of the wastewater at intermediate locations within the plant. Thus, for some plants, it was necessary to estimate the BOD concentration of the influent to the secondary treatment process. Because some of the treatment plants have tertiary treatment, the BOD concentration of the secondary effluent is not necessarily the BOD concentration of the plant effluent.

All of the plants investigated were meeting BOD and TSS effluent permit requirements.

Figure 1 shows the annual average effluent BOD concentration from the secondary treatment process for each plant. Figure 2 shows the pounds of BOD removed by only the secondary wastewater treatment process per million gallons of wastewater treated.



2.3 Benchmark Parameters

Several parameters were calculated in order to compare the performance and energy used by the secondary treatment process at the various treatment plants. The benchmark parameters that were calculated were: energy used per pound of BOD removed (kWh/lb BODr); energy used per million gallons of wastewater treated (kWh/MG) and oxygen transfer efficiency (OTE). Table 3 summarizes the results from the ten plants investigated. In addition, information is provided for three generic treatment plants that represent theoretical estimates of energy used in wastewater treatment plants.

Table 3. Energy Benchmark Parameters for Secondary Wastewater Treatment

WWTP (1)	Secondary Treatment Process	Plant Flow During Data Collection (MGD)	Energy Used for Secondary Wastewater Treatment (kWh/d) (2)	Energy Used for RAS, WAS & ML (%) (3)	Energy Used per Pound of BOD Removed (kWh/lb BODr) (2)	Energy Used per MG Treated (kWh/MG) (2)	Oxygen Transfer Efficiency (%)	Electrical Use for Total Plant Operations (avg kWh/d)	Electrical Use for Total Plant Operations (avg kWh/MG)	% of Total Plant Energy Used for Secondary WWT (2)
A	RBC	1.8	1,166	10	0.5	648	NA	1,931	1,073	60
B	Bio-tower/ AAS	10.1	5,007	8	0.4	508	17.0	15,000	1,485	33
C	AAS	2.4	5,708	6	1.9	2,428	3.8	10,270	4,279	56
D	AAS	11.5	9,328	7	0.6	811	5.7	19,433	1,690	47
E	AAS	1.7	2,471	12	2.6	1,465	2.6	4,290	2,524	58
F	AAS with N/D	19.4	24,189	10	0.9	1,247	6.1	89,813	4,630	27 (4)
G	AAS with N/D	5.4	8,107	4	2.2	1,505	5.2	NA	NA	NA
H	HPO-AS, PSA	5.5	12,168	2	1.5	2,220	60.0	22,124	4,023	55
I	HPO-AS, PSA	19.8	14,375	8	1.2	726	60.0	45,716	2,286	31
J	HPO-AS, Cryo	63.0	46,557	22	0.7	755	83.0	101,650	1,410	49
A1	TF	5.0	1,397	NA		279		4,892	978	29
C1	AAS	5.0	2,873	7		575		6,779	1,356	42
F1	AAS with N/D	5.0	4,640	6		928		9,631	1,926	48

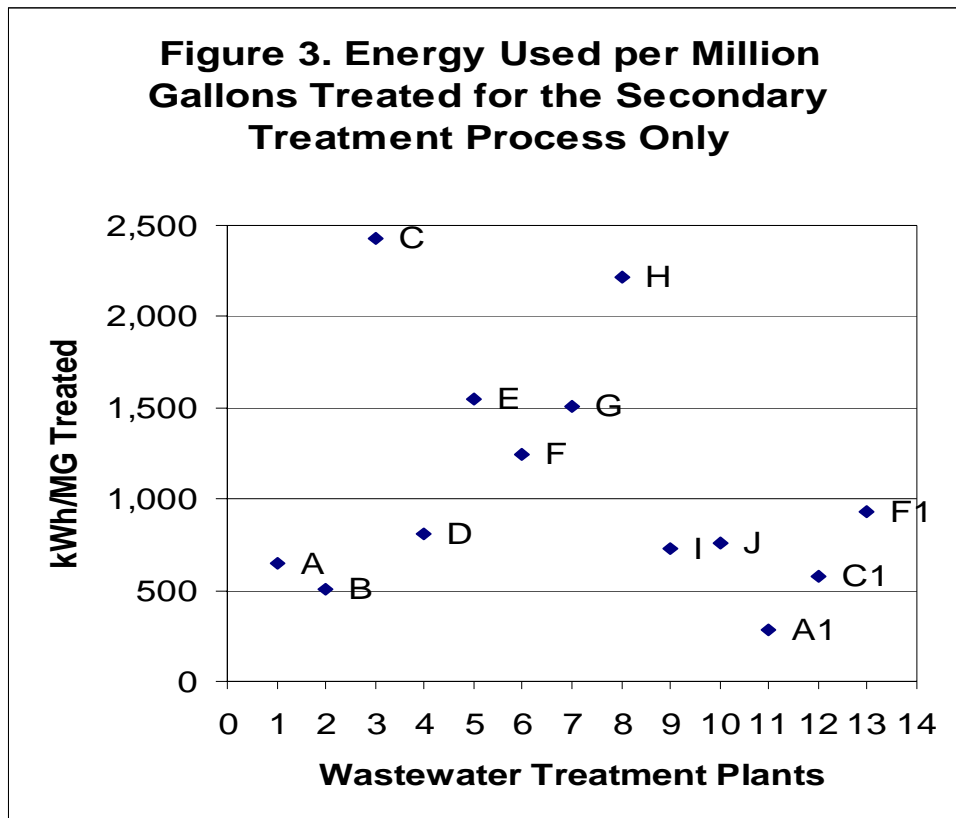
Note:

RBC - rotating biological contactor. AAS - air activated sludge. AAS with N/D - air activated sludge with Nitrification and Denitrification. HPO-AS PSA - high purity oxygen activated sludge, oxygen produced by pressure swing adsorption. HPO-AS Cryo - high purity oxygen activated sludge, oxygen produced by cryogenic process. TF - Trickling Filters.

- (1) Wastewater treatment plants A1, C1 and F1 are generic plants. Reference [2] was the source of the data. No background information regarding the basis for reported values was provided.
- (2) Energy used for secondary wastewater treatment unit process only, including return activated sludge pumping (RAS), waste activated sludge pumping (WAS) and mixed liquid pumping (ML).
- (3) Energy used for RAS, WAS & ML is provided as a percentage of the previous column, energy used for the secondary treatment unit process.
- (4) The % of total plant energy is low for this plant because the plant uses UV disinfection, which uses 21,020 kWh/day, approximately 23% of the electrical energy used by the plant.

Because some plants conduct limited BOD analyses, those parameters that utilize BOD results have a lower level of reliability for benchmark comparison. The parameters based on energy use and plant flow are expected to have the greatest reliability and comparability.

Excluding the three generic treatment plants, the energy used to process a million gallons of wastewater through a secondary treatment process ranged from a low of 508 to a high of 2,428 kWh/MG, as shown in Figure 3. For the generic treatment plants, the energy used to process a million gallons of wastewater through a secondary treatment process ranged from a low of 279 to a high of 928 kWh/MG. Fixed film processes had lower energy requirements while activated sludge processes had higher energy requirements. Plants C and H use a substantially larger amount of energy per million gallons treated than the other plants investigated.



As shown in Figure 4., the energy used per pound of BOD removed during secondary wastewater treatment ranged from a low of 0.4 to a high of 2.2 kWh/lb BOD removed. Again, the fixed film processes had the lower energy requirements and activated sludge processes had higher energy requirements. HPO-AS by PSA plants had a significantly higher energy requirement per pound of BOD removed than the HPO-AS by Cryo plant. Plants C, G and E use considerably more energy per pound of BOD removed than the other plants investigated.

Oxygen transfer efficiency (OTE) ranged from 4-20% for air activated sludge processes and 60- 83% for high purity oxygen activated sludge processes, as shown in Figure 5.

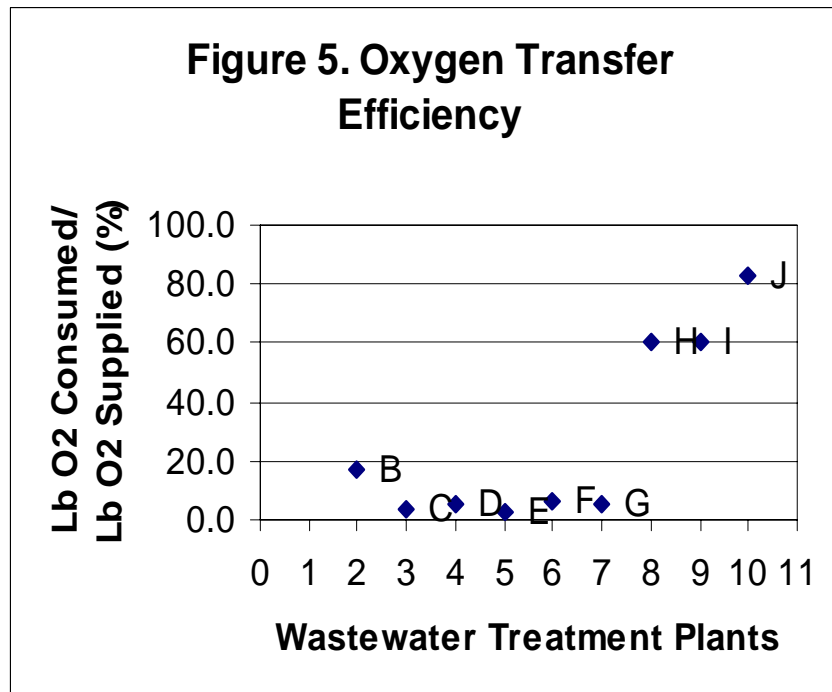
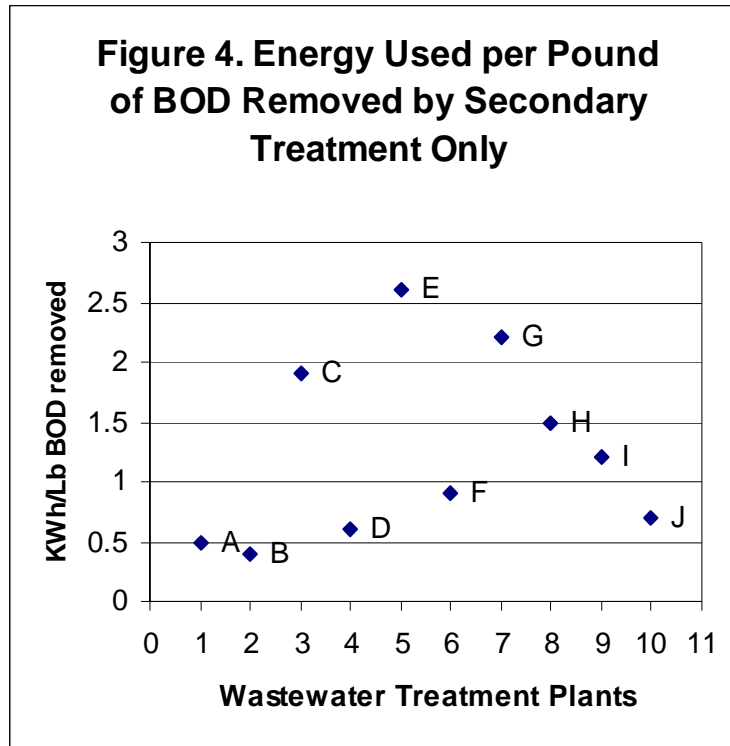
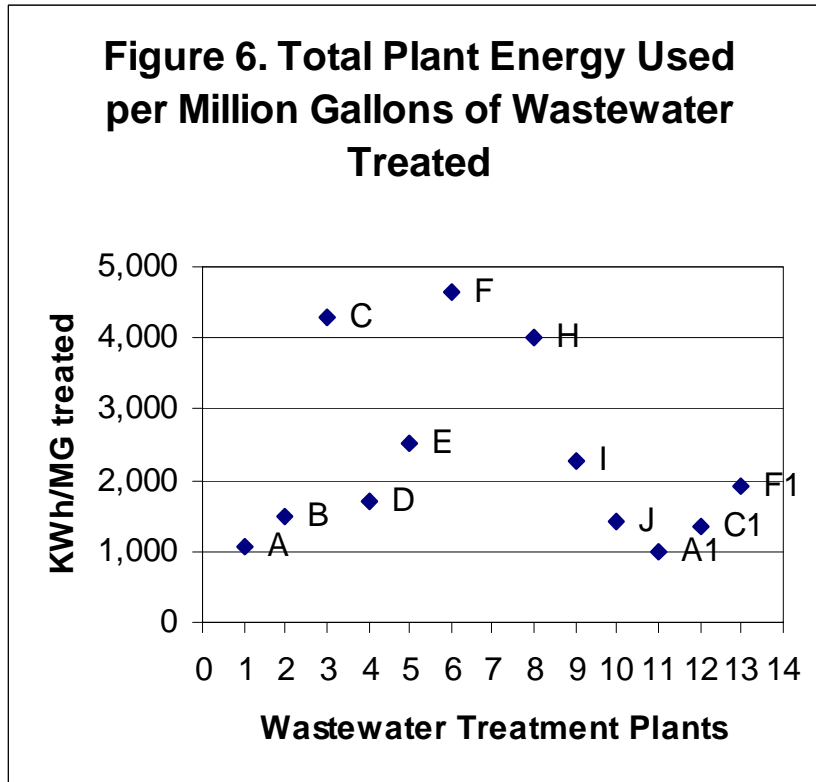
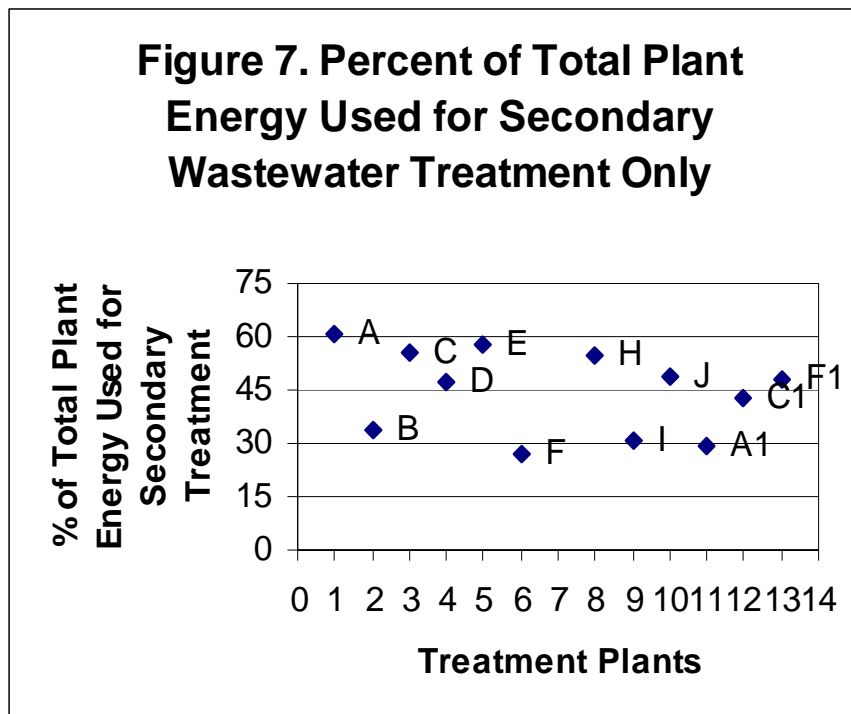


Figure 6 shows the total plant energy used per million gallons of wastewater treated. Plants C, F and H had substantially higher energy use than the other plants.



The secondary treatment process accounted for a low of 27% (for Plant F) to a high of 60% of total plant energy used, as shown in Figure 7. As noted previously, Plant F has nitrification and denitrification and uses UV for disinfection. These processes would account for the low percentage of total plant energy used by Plant F for secondary wastewater treatment.



2.4 Summary of Benchmark Parameter Results and Discussion

The three benchmark parameters calculated were energy used per pound of BOD removed (kWh/lb BODr), energy used per million gallons of wastewater treated (kWh/MG) and oxygen transfer efficiency (OTE).

Table 4. Benchmark Parameters and Energy Use Factors for Total Plant Operations

Parameters	Range of Values	
	Observed	Generic
Energy (1) /lb BODr (kWh/lb BODr)	0.4 - 2.6	
Energy (1) /MG treated (kWh/MG)	508 - 2,428	279 - 928
OTE (%)	2.6 - 83	
Electrical Use for Total Plant Operations (kWh/MG)	1,073 - 4,630	978 - 1,926
% of Total Plant Energy Used for Secondary Treatment Only (%)	27 - 60	29 - 48

(1) Energy usage for only the secondary wastewater treatment process

Plants C had high energy usage per million gallons of wastewater treated for the secondary treatment process, high energy usage for the total plant per million gallons of wastewater treated and relatively high energy used per pound of BOD removed by secondary treatment. Although the effluent BOD concentration is very low, a more detailed evaluation of the equipment, process control and operations of Plant C appears warranted.

Plant H had high energy usage per million gallons of wastewater treated for the secondary treatment process. In addition, the Plant has a high BOD effluent concentration from the secondary treatment process. For these reasons, a more detailed evaluation of the equipment, process control and operations of Plant H appears warranted.

Plants E and G had high energy usage per pound of BOD removed by secondary treatment. Although Plant E has restrictive NPDES permit limits for BOD and TSS effluent concentration, a more detailed evaluation of the equipment, process control and operations at those plants appears warranted.

Plant F had high total plant energy usage per million gallons of wastewater treated. However, Plant F has restrictive NPDES permit limits for BOD and TSS effluent concentrations and a very restrictive limit for disinfection requirements. An ultraviolet treatment system is used to achieve the very high level of disinfection required by the NPDES permit. Based on the very high levels of wastewater treatment required at Plant F, the level of energy use appears reasonable.

In general, fixed film processes (RBCs and bio-towers) were more energy efficient than activated sludge processes. This observation is supported by the values reported in literature and by the information about the generic plants. Subsequent efforts to refine energy benchmarking the secondary wastewater treatment process could obtain information on a larger sample of treatment plants and thus produce a better understanding of the energy usage by the various secondary treatment options.

3. Energy Benchmarking UV Disinfection Processes

3.1 Energy Benchmarking UV Disinfection Processes

A site investigation of the UV disinfection process at two wastewater treatment plants was conducted. Extensive information was obtained about each treatment plant, including flow and loading to the plant,

unit processes employed, equipment used for UV disinfection, plant performance data, NPDES effluent permit requirements and energy use data. Information about five additional treatment plants that utilize UV disinfection is included in this discussion, also. The information about those plants was drawn from the report, “Assessment of Operation and Maintenance Costs for Ultraviolet Disinfection Systems”, presented at the Water Environment Federation Exposition and Conference in year 2000 [3]. The five plants in that study are located in the state of Washington.

Light in the wavelength range of 240 to 280 nm, particularly light having a wavelength around 254 nm, penetrates the cell wall of microorganisms and is absorbed by cellular material, including the DNA and RNA. The absorbed light changes molecular bonds within the DNA and RNA. Because the DNA and RNA carry genetic information for reproduction, if the microorganism is subjected to a sufficient dose of UV light, those portions of the DNA and RNA which regulate reproduction will be damaged and the microorganism will not be able to reproduce. A microorganism that is incapable of reproduction is generally considered to be ineffective and no longer poses a health concern to humans. A larger dose of UV light can cause the organism to die. A more detailed description of the mechanism by which UV light causes disinfection can be found in reference [4].

The principal types of UV systems can be classified as 1) monochromatic low-pressure low intensity, 2) monochromatic low-pressure high intensity, and 3) polychromatic medium-pressure high intensity. In addition to the types of UV systems available, there are several other variables that impact the performance of UV systems, including:

- output spectra of the lamp: lamps of the same principal type but produced by differing manufacturers produce different spectra
- lamp age: as a lamp ages, the output of the lamp declines
- extent of algae growth and mineral deposits on the sleeve surrounding the lamp: usually, the UV lamp is enclosed in a transparent quartz sleeve, and it is the sleeve which is in contact with the wastewater
- water quality parameters, such as amount and size of suspended particles, turbidity and heavy metals concentration, in particular, iron concentration: particles can shade microorganisms from UV light, hence, reducing the effectiveness of the UV dose in achieving disinfection
- mechanism for controlling the UV dose: methods of control range from manual startup & shut-down of lamps at the bank level to automated control systems with adjustable power levels based on continuously monitored parameters
- the indicator microorganism used in assessing the degree of disinfection: Fecal Coliform, Total Coliform and Enterococci are the principal microorganisms used by regulatory agencies as the indicator for assessing disinfection performance. However, the same dose of UV light produces differing levels of disinfection on those microorganisms.

Additional information about the factors affecting the UV disinfection process can be found in references [5] and [6].

Information is provided in Table 5 about the two plants located in California (Plants AA and BB) and the five plants located in Washington (Plants CC to GG). Additional information about Plants AA and BB is also provided in Attachment B. All seven plants are publicly-owned treatment plants serving primarily residential populations with some commercial and industrial loads. Plant BB has a very restrictive NPDES effluent permit requirement of 2.2 MPN/100 ml of Total Coliform as a 7-day median value. All the other plants have a much less stringent effluent permit requirement. All the plants were operating at less than their design capacity at the time of data collection.

Table 5. Key Characteristics of the Treatment Plants Evaluated for the UV Disinfection Benchmark Study

WWTP	Avg Annual Plant Flow (MGD)	Secondary Treatment Process	Treatment Subsequent to Secondary Treatment	Type of Equipment for UV Disinfection	Layout of UV Equipment	NPDES Permit Requirements (1) (MPN/100 ml)	UV System Control
AA	43	AAS	none	Low pressure, low intensity, horizontal	2 basins: 3 channels/basin: 3 banks/channel	Max. 30 day log mean value: 200 FC	Manual, "On" or "Off", no turn down
BB	19.4	AAS with N/D	Anthracite filter	Medium pressure, high intensity	3 channels: 2 reactors/channel: 2 banks/reactor	7-day median value: 2.2 TC Daily max. 23 TC	Programmable controller with turn-down
CC	3	AAS	none	Low pressure, horizontal	2 channels: 2 banks/channel	Monthly geometric mean: 200 FC	1 bank used normally, 2nd bank for peak flow
DD	1.8	RBC	none	Low pressure, vertical	2 channels: 4 modules/channel	Monthly geometric mean: 200 FC	Constant power used
EE	3.6	AAS	none	Medium pressure, high intensity, open channel	2 channels: 2 banks/channel	Monthly geometric mean: 200 FC	Flow paced
FF	5.3	AAS	none	Medium pressure, high intensity, open channel	1 channel: 2 banks always in operation	Monthly geometric mean: 200 FC	Flow paced at higher flow
GG	0.4	Oxidation Ditch	none	Medium pressure, high intensity, in-vessel	2 vessels, 4 lamps/vessel	Monthly geometric mean: 200 FC	Flow paced at higher flow

(1) FC is used as the abbreviation for Fecal Coliform. TC is used as the abbreviation for Total Coliform.

3.2 Operation and Performance of the UV Disinfection Processes

Operation and performance information regarding the disinfection process at each plant is provided in Table 6.

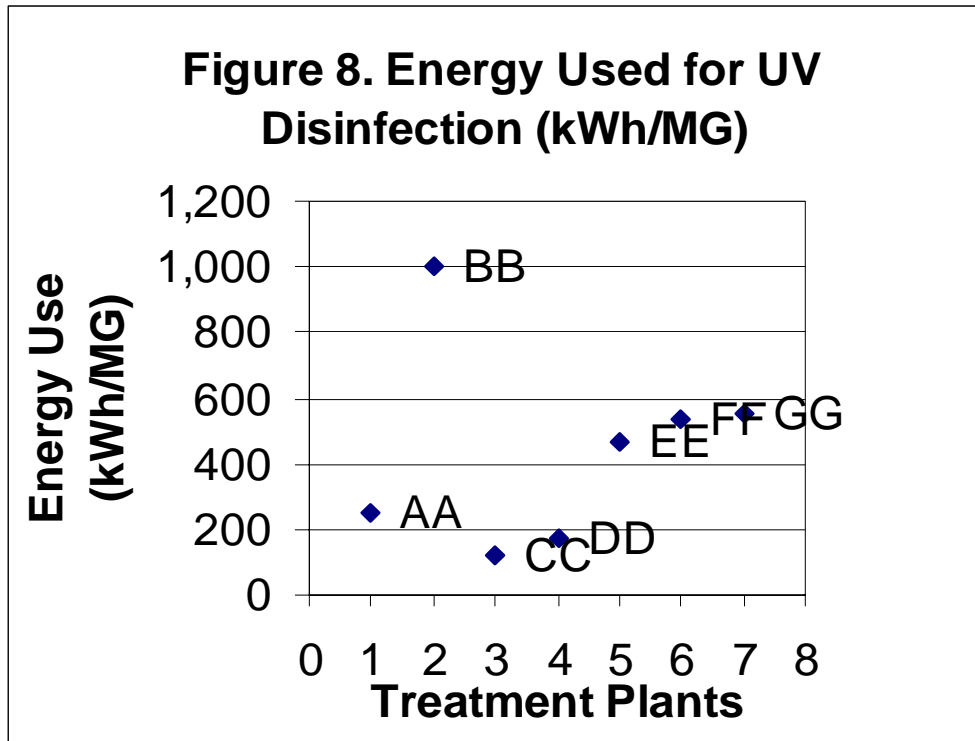
Table 6. Plant Operations and Performance Data

WWTP	Flow to UV System (MGD)	Coliform Concentration after disinfection (MPN/100 ml)	Effluent TSS (mg/l)	Lamps Changed after ___ Hours of Operation	Energy Used for UV Disinfection (kWh/d)	Energy Used per MG Disinfected (kWh/MG)	Energy Used for Total Plant Operations (1) (avg kWh/d)
AA	43	60 FC	8	12,000	10,743	250	76,992
BB	21	<2 TC	1	5,000	21,020	1,001	89,813
CC	2.8	4 FC	5	13,000	328	117	
DD	1.4	100 FC	7	9,000	239	171	
EE	3.4	15 FC	9	5,000	1,579	464	
FF	3.8	1.4 FC	3	5,000	2,038	536	
GG	0.3	NA	NA	11,000	167	557	

(1) Note: Plant AA uses steam drive for blowers supplying air for secondary treatment, thus lowering its total plant electric energy usage.

3.3 Benchmark Parameters

The energy used for UV disinfection ranged from a low of 117 kWh per million gallons disinfected to a high of 1,001 kWh per million gallons disinfected. UV disinfection accounted for 14% and 23% of the total electrical usage at the two California plants investigated. Figure 8 shows the energy used for disinfection per million gallons treated at each of the plants.



3.4 Discussion of Performance Parameters

Table 7 provides a summary of key information and parameters relevant to UV disinfection at the seven treatment plants.

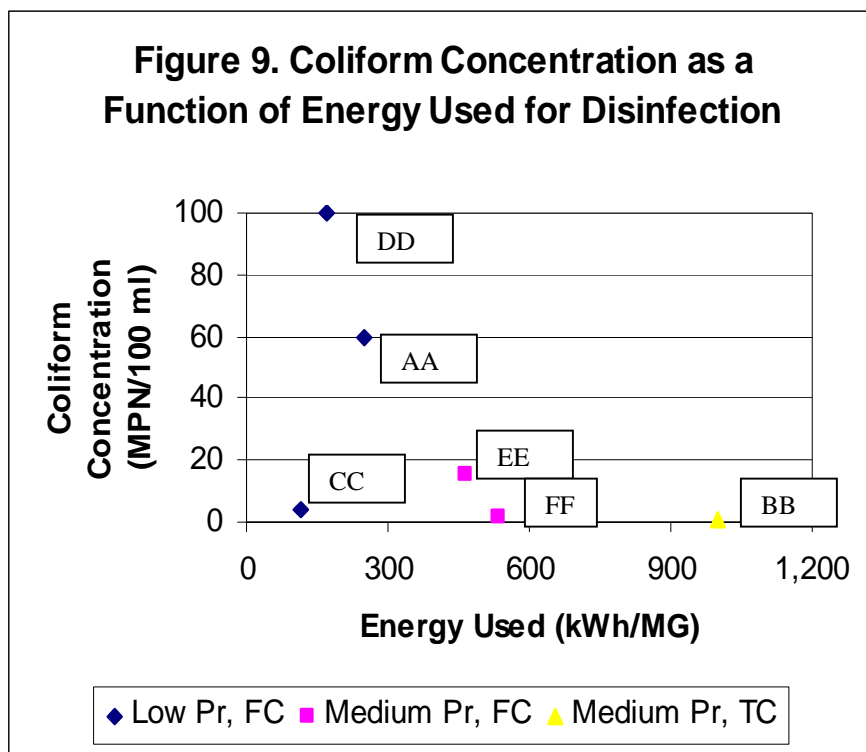
Table 7. Summary of Key Information and Parameters

WWTP	Avg Annual Plant Flow (MGD)	Secondary and other Treatment Processes	Plant Effluent TSS (mg/l)	Type of Equipment for UV Disinfection (Pressure)	Max. Lamp Hours	UV Dose Control System	Effluent Coliform Concentration (MPN/100 ml)	Energy Used/ MG Disinfected (kWh/MG)
AA	43	AAS	8	Low	12,000	On/off	60 FC	250
BB	19.4	AAS & ND with Anthracite Filtration	1	Medium	5,000	Program-able Controller	<2 TC	1,001
CC	3	AAS	5	Low	13,000	On/off	4 FC	117
DD	1.8	RBC	7	Low	9,000	Constant	100 FC	171
EE	3.6	AAS	9	Medium	5,000	Flow Paced	15 FC	464
FF	5.3	AAS	3	Medium	5,000	Flow Paced at High Flow	1.4 FC	536
GG	0.4	Oxidation Ditch	NA	Medium	11,000	Flow Paced at High Flow	NA	557

The energy used for disinfection ranged from 117 to 557 kWh per million gallons treated when meeting disinfection limits of 200 MPN/100 ml of Fecal Coliform. When complying with an NPDES effluent permit requiring a very high level of disinfection of Total Coliform, energy use of 1,001 kWh per million

gallons treated was required, even though the plant had an effluent TSS concentration of 1 mg/l and uses an automated control system to adjust the energy used for disinfection based on flow and transmittance.

Plants AA, CC and DD are low pressure UV systems with no automated turndown control. Plants EE and FF are both medium pressure UV systems with some automated turndown control. If all other factors were equal, the plants with automated turn-down should be more energy efficient, however, Plants AA, CC and DD use considerably less energy for each million gallons of wastewater treated than Plants EE and FF. Plants AA, DD and EE had similar effluent TSS concentrations. Plant EE had considerably lower effluent Fecal Coliform concentration, however considerably more energy was used. Plants CC and FF had similar effluent TSS concentration. Although Plant FF had a slightly lower effluent Fecal Coliform concentration, Plant FF used considerably more energy. Figure 9 shows the above information in graphical form. (Plant GG is not included in the graph since effluent Coliform concentration and effluent TSS were not available.)



It is inappropriate to draw a definitive conclusion regarding the comparative energy efficiency of low vs. medium pressure UV systems from the limited data in this report. However, comparing similar facilities, Plant CC with Plant FF indicates the low pressure system is more energy efficient than the medium pressure system. In the literature, it is reported that low pressure lamps are more efficient than medium pressure lamps [6].

The graph of coliform concentration as a function of energy used for disinfection, shown in Figure 9 suggests that UV disinfection performance is not a linear function of the applied energy. An increasing amount of energy appears to be needed in order to obtain successive reductions in microorganism concentration. This observation is supported by findings in the report “Recent Developments in Ultraviolet Disinfection” [7]. The above conclusion is also supported by the findings in the report “Investigation of Energy Use and Disinfection Performance at a Wastewater Treatment Plant” provided in Attachment C.

The energy used for UV disinfection ranged from 117 to 557 kWh per million gallons treated when meeting disinfection limits of 200 MPN/100 ml of Fecal Coliform. When complying with an NPDES effluent permit requiring a very high level of disinfection, 2.2 MPN/100 ml of Total Coliform, energy use of 1,001 kWh per million gallons treated was required, even though the plant had an effluent TSS concentration of 1 mg/l and uses an automated control system to adjust the energy used for disinfection based on flow and transmittance.

A “Back-of-the-Envelope” calculation was prepared to provide a comparison of the energy required for a chlorine/hypochlorite and dechlorination process compared to the energy used by an ultraviolet disinfection process. The analysis is included in Attachment D of this report. On a global energy basis, it appears that UV disinfection can be competitive with chlorine/hypochlorite disinfection and dechlorination.

4. References:

[1] California Energy Commission (1990) *The Second Report to the Legislature on Programs Funded Through Senate Bill 880*. PL 400-89-006.

[2] Kennedy, T., et.al., *Energy Conservation in Wastewater Treatment Facilities*, Water Environment Federation Manual of Practice No. MFD-2, 1997. pg 6-9.

[3] Swift, J., Wilson, J. K. et.al. *Assessment of Operation and Maintenance Costs for Ultraviolet Disinfection Systems*, Presentation at the Water Environment Federation Exposition and Conference (WEFTEC), 2000.

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[5] *Disinfection 2000: Disinfection of Wastes in the New Millennium*, Proceedings from the Water Environment Federation Conference March 15-18, 2000, New Orleans, LA.

[6] Water Environment Federation, Manual of Practice FD10, 1996.

[7] Tchobanoglous, G., Emerick, R., et.al., *Recent Developments in Ultraviolet Disinfection*, Presentation at the USEPA 6th National Drinking Water and Wastewater Workshop, August 2-4, 1999, Kansas City, MO., August 2-4, 1999.

Attachment A

Attachment B

Attachment C: INVESTIGATION OF ENERGY USE AND UV DISINFECTION PERFORMANCE AT A WASTEWATER TREATMENT PLANT

A special investigation was conducted by the staff at Plant BB to provide information about the performance of the UV disinfection system and to assess whether any energy savings could be achieved. The disinfection system consists of three channels, each containing 2 reactors in series. During the investigation, only two of the channels were used. Wastewater samples were collected at five locations, once each day, for 16 days. The five locations were:

- The influent to the UV system
- Effluent from the first reactor (in each of the two channels)
- Effluent from the second reactor (in each of the two channels)

The samples were analyzed to determine the Most Probable Number of Total Coliform organisms (MPN TC) in each sample. Plant data, including reactor output and total UV dose was recorded for each of the days of the investigation. However, as a result of unusual activities at the plant, data for June 7, 8 and 13 were deleted from the analysis. In addition, one MPN TC data point was not available for the June 21st results.

Plant parameters were within usual ranges during the testing period. Plant flow ranged from a low of 10 MGD to a high of 29 MGD, % of UV transmittance ranged from 67% to 71% and turbidity ranged from .4 to .8 NTU. The UV dose was managed by a controller that is operator adjustable. The UV dose is automatically adjusted based on flow and transmittance information. During the test period, the controller was set for a minimum dose of 150 mW-sec/cm².

Key data from the investigation is provided in Tables C1 and C2. Based on review of the effluent MPN TC concentration data in Tables C1 and C2, data was provided for 13 days for each channel. On 12 of the 13 days, the effluent concentration was less than 2.2 MPN TC concentration. On only 1 day for each channel was the effluent concentration greater than the 2.2 MPN TC concentration.

The dose provided by each reactor was calculated based on multiplying the total dose applied to the wastewater times the ratio of the percent of output of each reactor divided by the sum of the percent of output provided by both reactors. The following is an example of the calculation for Channel 1 on June 12th. The total dose applied to the wastewater on that date was 151 mW-sec/cm sq. Reactors 1 and 2 had percent outputs of 34 and 74, respectively. Therefore, reactor 1 provided $34/(34+74)$ or 31% of the dose. Reactor 2 provided $74/(34+74)$ or 69% of the dose. Based on the total dose of 151 mW-sec/cm sq and reactor 1 providing 31% of that dose, reactor 1 provided a dose of 48 mW-sec/cm sq. Reactor 2 provided a dose of 103 mW-sec/cm sq. On June 11th, a dose of 152 mW-sec/cm sq was used. Reactor 1 had '0' % output and reactor 2 had 74% output. Since reactor 2 was the only reactor in-service, it provided the total dose of 152 mW-sec/cm sq. The calculation procedure above was used to calculate the UV dose provided by each reactor for each day of the test.

Figure C1 is a plot of the first UV dose and the corresponding MPN TC achieved. Data from both channel 1 and channel 2 were used to produce this figure. Figure C2 has 12 lines. Each line is based on two data points. The two data points are a plot of the first UV dose and the resulting MPN TC in channel 1 and channel 2, on the same day. Ideally, this demonstrates the effect of two different UV dose rates on “the same wastewater”. Note that in Figures C1 through C4, when the laboratory analysis of a sample resulted in an MPN TC value that was less than the detectable limit, that data point was graphed at 1.5 MPN TC/100 ml.

Figure C3 is a plot of the UV dose and the corresponding MPN TC achieved when two reactors in series (in the same channel) were used to treat the wastewater. Hence, each line corresponds to two data points. The data point at the higher MPN TC is the UV dose from and the resulting MPN TC after treatment through the first reactor. The data point at the lower MPN TC value is the UV dose from and resulting MPN TC after treatment through the second reactor. Figure C4. is a second plot of the data used in Figure C3. In Figure C4, there are 14 lines. Each line is comprised of two data points. The data point at the higher MPN TC is the UV dose from and resulting MPN TC after treatment through the first reactor. The second data point for each line is located at the point of the sum of the UV dose from reactor 1 plus reactor 2 and the corresponding MPN TC from the total UV dose.

From review of Figure C1, the following observations can be made:

- For 8 of 22 days, the minimum dose of 150 mW-sec/sq cm was significantly greater than was needed to meet a 2.2 MPN TC/100 ml.
- For 6 of 22 days, a dose of 150 mW-sec/sq cm or more was used, however it is not conclusive that the 150 mW-sec/sq cm or more dose rate was necessary to meet 2.2 MPN TC/100 ml.
- For 7 of 22 days, a dose of 110 mW-sec/sq cm or less was not sufficient to meet 2.2 MPN TC/100 ml.
- On only 1 of 11 days was a dose of 150 mW-sec/sq cm insufficient to meet 2.2 MPN TC/100 ml.
- The MPN TC concentration is inversely related to the UV dose rate.

Data was available to compare differing UV dose rates on ‘the same wastewater’ for 12 days. The results of that ‘test’ are provided in Figure C2. The following observations can be drawn from review of that graph:

- For 6 of the 12 days, a lower UV dose resulted in a higher MPN TC concentration and a higher UV dose produced a lower MPN TC concentration.
- For 3 of the 12 days, the lower UV dose was sufficient to produce an MPN TC concentration that was less than the detectable level and the higher UV dose also produced an MPN TC concentration that was less than the detectable level.
- For 2 of the 12 days, the lower UV dose was sufficient to produce an MPN TC concentration that was less than the detectable level, and the higher UV dose produced an MPN TC concentration that was equal to the detectable level.
- On 1 of the 12 days, the lower UV dose produced a lower MPN TC concentration than the higher UV dose.
- On 2 days, a dose of 175 mW-sec/sq cm or larger was used. Based on the change in MPN TC concentration for a unit change in UV dose that occurred for other pairs of data,

it appears the 2 doses above 175 mW-sec/sq cm were substantially greater than the amount needed in order to meet a 2.2 MPN TC/100 ml concentration.

From review of Figure C3, the following observations can be made:

- There were 14 times in which the wastewater was disinfected by 2 reactors in the same channel.
- On 7 of the 14 times, the initial UV dose was sufficient to reduce the MPN TC concentration to 2.2 MPN TC/ml or lower.
- On 6 of those 7 times, the second UV dose was sufficient to reduce the MPN TC concentration to 2.2 MPN TC/100 ml or lower.
- On 1 of the 14 times, the initial and second UV dose was insufficient to meet 2.2 MPN TC/100 ml.

From review of Figure C4, the following observations can be made:

- On 12 of 14 days, a combined UV dose rate of 150-155 mW-sec/sq cm was sufficient to meet 2.2 MPN TC/100 ml.
- On 1 of the 14 days, a combined UV dose rate of more than 200 mW-sec/sq cm was used and the 2.2 MPN TC/100 ml concentration was achieved. It is not clear however, that such a large UV dose was needed in order to achieve the MPN TC concentration.
- On 1 of the 14 days, a combined UV dose rate of more than 175 mW-sec/sq cm was insufficient to meet a 2.2 MPN TC/100 ml concentration.

Based on review of the data from this investigation, it appears likely that a lower UV dose, such as 140 mW-sec/sq cm would be sufficient to meet effluent permit requirements. It is suggested the plant staff conduct additional testing of the UV system to investigate whether a minimum dose rate of 140 mW-sec/sq cm would provide a level of disinfection that would comply with the Plant's effluent permit requirements. An investigation into whether the lower dose would meet effluent permit requirements could be conducted by using the first reactor in a channel to dose at 140 mW-sec/sq cm and using the second reactor to provide a minimum additional dose. Sampling and analysis should be conducted after the initial dose to determine whether that dose is adequate for meeting the MPN TC effluent permit requirements. Testing could be conducted in this configuration without concern of failing to meet effluent permit requirements, while investigating the performance of the lower dose rate.

It was also observed that an increasing amount of energy needs to be applied in order to obtain successive reductions in microorganism concentrations. This finding is consistent with the information obtained from the overall benchmarking study in which UV disinfection performance is found to be not a linear function of the applied energy.

Table C1. Special Investigation of the UV Disinfection System: Data and Results for Channel 1

Date	Plant Flow (MGD)	Dose (mWsec/cm sq)	% UV Transmittance	Reactor 1 % of Output	Reactor 2 % of Output	Reactor 1 % of Dose	Reactor 2 % of Dose	UV System Influent (1)	Reactor 1 Effluent (1) (2)	Reactor 2 Effluent (1) (2)
9-Jun-01	14.7	155	69	0	53	0	100	8,000		1.5
10-Jun-01	15.4	151	69	0	53	0	100	8,000		2
11-Jun-01	20.8	152	68	0	74	0	100	11,000		1.5
12-Jun-01	29	151	67	34	74	31	69	30,000	2	2
14-Jun-01	11.1	152	68	53	0	100	0	50,000	1.5	
15-Jun-01	24.6	152	68	89	0	100	0	90,000	1.5	
16-Jun-01	25.5	150	68	93	27	78	22	50,000	2	1.5
17-Jun-01	10.4	214	68	53	0	100	0	90,000	1.5	
18-Jun-01	12.2	181	68	53	0	100	0	160,000	2	2
19-Jun-01	25.5	151	71	86	0	100	0	160,000	1.5	
20-Jun-01	26.7	151	71	0	91	0	100	160,000		1.5
21-Jun-01	25.3	152	71	0	86	0	100	500,000		4
22-Jun-01	16.1	153	70	27	58	31	69	1,600,000	8	1.5

(1) MPN TC/100 ml

(2) MPN value of 1.5 was used to represent the data when the result of the sample analysis was 'less than the detectable level, 2.0'

Table C2. Special Investigation of the UV Disinfection System: Data and Results for Channel 2

Date	Plant Flow (MGD)	Dose (mWsec/cm sq)	% UV Transmittance	Reactor 1 % of Output	Reactor 2 % of Output	Reactor 1 % of Dose	Reactor 2 % of Dose	UV System Influent (1)	Reactor 1 Effluent (1) (2)	Reactor 2 Effluent (1) (2)
9-Jun-01	14.7	155	69	27	27	50	50	8,000	1.5	1.5
10-Jun-01	15.4	151	69	29	27	52	48	8,000	1.5	2
11-Jun-01	20.8	152	68	50	27	65	35	11,000	1.5	1.5
12-Jun-01	29	151	67	43	67	39	61	30,000	4	1.5
14-Jun-01	11.1	152	68	29	43	40	60	50,000	1.5	1.5
15-Jun-01	24.6	152	68	50	41	55	45	90,000	4	1.5
16-Jun-01	25.5	150	68	77	46	63	37	50,000	1.5	
17-Jun-01	10.4	214	68	27	27	50	50	90,000	4	1.5
18-Jun-01	12.2	181	68	27	27	50	50	160,000	8	4
19-Jun-01	25.5	151	71	50	39	56	44	160,000	8	1.5
20-Jun-01	26.7	151	71	43	50	46	54	160,000	17	1.5
21-Jun-01	25.3	152	71	36	50	42	58	500,000	NA	1.5
22-Jun-01	16.1	153	70	53	36	60	40	1,600,000	2	1.5

(1) MPN TC/100 ml

(2) MPN value of 1.5 was used to represent the data when the result of the sample analysis was 'less than the detectable level, 2.0'

Figure C3. MPN TC as a Function of UV Dose after Reactor 1 and Reactor 2

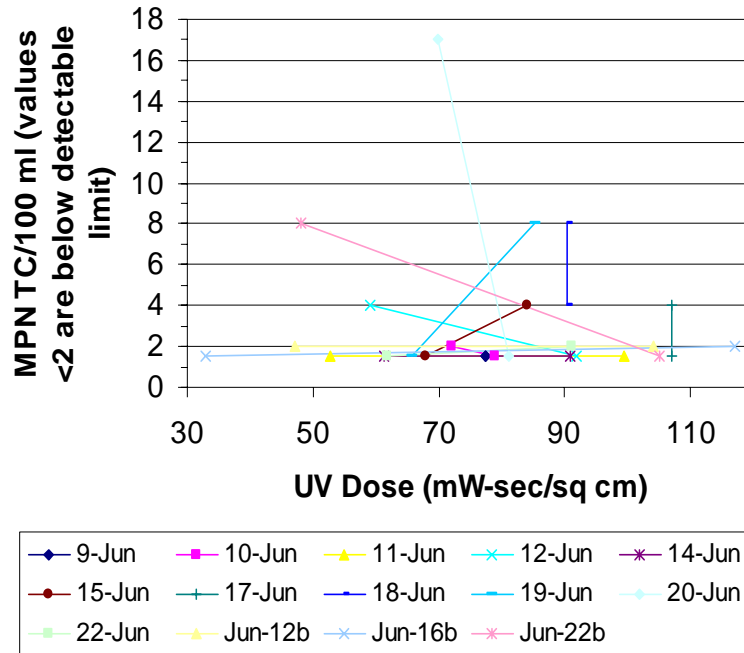
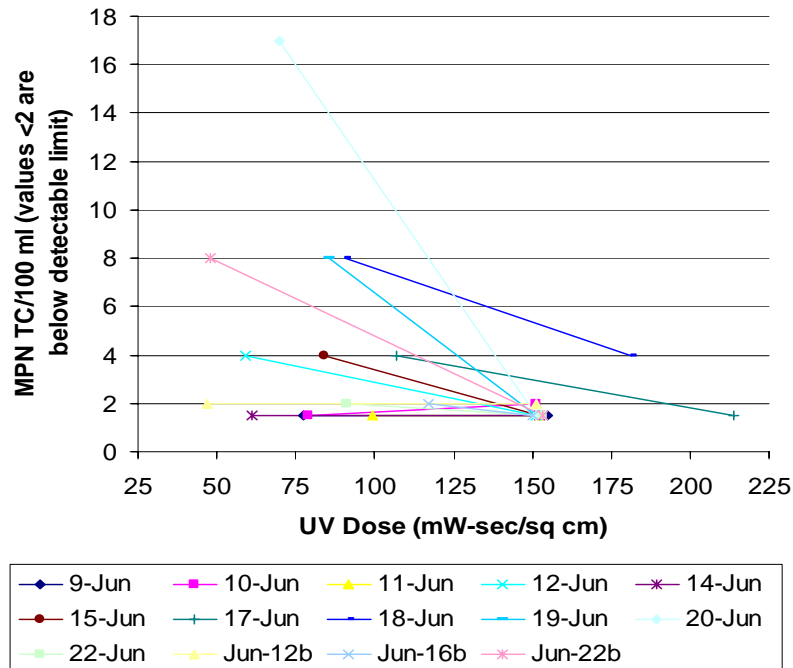


Figure C4. MPN TC as a Function of UV Dose after Reactor 1 and Reactors 1+2



Attachment D: ENERGY CONSUMPTION OF CHLORINE AND SODIUM HYPOCHLORITE DISINFECTION

Although Ultraviolet, (UV) disinfection of wastewater is becoming more common, the majority of wastewater plants still use chlorine gas or chlorine compounds for disinfection. One of the objectives of the PG&E benchmarking project is to measure and compare the energy consumption of UV disinfection, at different plants. Since chlorine compounds are still the dominant wastewater disinfection processes, it is interesting to also compare their energy intensity with UV. Based on the fact that wastewater plants usually purchase the chlorine or chlorine compounds used for disinfection from outside vendors, the energy consumption for production of these disinfectants is not part of the plant energy balance.

When chlorine gas or hypochlorite salts are added to water, hydrolysis and ionization take place to form hypochlorous acid (HOCl) and hypochlorite ions (OCl). Free available chlorine is defined as the concentration of chlorine existing in the form of hypochlorous acid and hypochlorite ions. After disinfection, chlorine residuals persist in the effluent. Most states will not allow the use of chlorination alone for pristine receiving waters because of its effects on aquatic species. To minimize these effects, chlorinated wastewater must often be dechlorinated.

Dechlorination is the process of removing the free and combined chlorine residuals to reduce residual toxicity after chlorination and before discharge. Sulfur dioxide, sodium bisulfite, and sodium metabisulfite are the most commonly used dechlorinating chemicals.

At one time chlorine gas was the dominant method for wastewater disinfection with sulfur dioxide used for de-chlorination when required by the discharge permit. Both chlorine and sulfur dioxide are toxic gasses, and recent regulations have imposed significant safety requirements on plants using these gasses. These regulations and the cost of compliance have resulted in many plants switching to hypochlorite for disinfection, and sodium bisulfite for dechlorination.

Chlorine Disinfection

Chlorine is manufactured by an energy intensive electrochemical process. The energy required to produce chlorine is approximately 1.5 kWhr/lb of chlorine¹. The chlorine dosage for disinfection will vary based on chlorine demand, wastewater characteristics, and discharge requirements. The chlorine dosage usually ranges from 5 to 20 mg/l and the chlorine required to disinfect 1MG of wastewater using various chlorine dosages can be calculated using the following equation:

$$\text{lbs Cl}_2/\text{MG} = \text{mg/l Cl}_2 \times 10^{-3} \text{ gms/mg} \times 3.785 \text{ l/G} \times 10^6 \text{ G/MG} \times 1/454 \text{ gms/lb}$$

The energy consumption to produce the required chlorine gas is:

$$\text{KWhr/MG} = \text{lbs Cl}_2/\text{MG} \times 1.5 \text{ kWhr/lbCl}_2$$

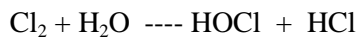
Table A shows the pounds of chlorine and the energy required to generate the chlorine to disinfect one million gallons of wastewater at various chlorine dosages.

Table A
Chlorine Production Energy at Various Cl₂ Dosages

Cl ₂ Dose	Lb Cl ₂ /MG	kWhr/MG
20 mg/l	166.8	250.2
10mg/l	83.4	125.1
5mg/l	41.7	62.6

Sodium Hypochlorite Disinfection

Similar to chlorine, sodium hypochlorite is produced by an energy intensive electrochemical process. The energy to produce sodium hypochlorite is approximately 2.5 kWhr/lb of sodium hypochlorite². This energy consumption figure is based on production of sodium hypochlorite at a concentration of 10g/l from a brine feed of 30g/l of sodium chloride. It is based on a bi-polar electrolysis cell suitable for on-site generation. The relationship between lbs of chlorine gas and lbs of sodium hypochlorite is often confused. Although there are two atoms of chlorine per molecule of chlorine gas and only one atom of chlorine per molecule of sodium hypochlorite, chlorine gas reacts with water according to the following equation:



Thus, one atom of chlorine becomes HCl and is inactive for disinfection. Consequently, one molecule of chlorine is equivalent to one molecule of HOCl, which is equivalent to one molecule of sodium hypochlorite (NaOCl). Mathematically, 71 grams of Chlorine gas (2 x 35.5), is equivalent to 52.5 grams of HOCl, which is equivalent to 74.5 grams of NaOCl. Therefore, the factor for converting pounds of Cl₂ to pounds of NaOCl is 74.5/71 or 1.05. The equation for calculating the pounds of hypochlorite to disinfect 1 MG at various chlorine dosages is as follows:

$$\text{lbs NaOCl/MG} = \text{mg/l Cl}_2 \times 10^{-3} \text{gms/mg} \times 3.785 \text{ l/G} \times 10^6 \text{G/MG} \times 1/454 \text{ gms/lb} \times 1.05$$

And the equation for calculating the energy consumption to produce the sodium hypochlorite is:

$$\text{kWhr/MG} = \text{lbs NaOCl/MG} \times 2.5 \text{ kWhr/lb NaOCl}$$

Table B shows the pounds of chlorine, the pounds of equivalent sodium hypochlorite and the energy required to generate the hypochlorite to disinfect one million gallons of wastewater at various chlorine dosages.

Table B
NaOCl Production Energy at Various Cl₂ Dosages

Cl₂ Dose	Lb Cl₂/MG	Lb NaOCL	kWhr/MG
20 mg/l	166.8	174.3	437.8
10 mg/l	83.4	87.57	218.9
5 mg/l	41.7	43.8	109.5

Secondary Energy Consumption

There is obviously secondary energy consumption in the production, handling and shipping of chlorine and sodium hypochlorite. Chlorine for example is compressed, liquified, and shipped by rail, truck, or barge. Sodium Hypochlorite is usually transported by tanker truck in relatively dilute form. Sodium hypochlorite also decomposes during storage and transport. The quantification of these secondary energy debits is complex, subject to local conditions, and beyond the scope of this analysis. However, the calculated energy consumption for both chlorine and sodium hypochlorite should be considered as minimum values.

Dechlorination

The energy content of dechlorination chemicals is very difficult to quantify. Sulfur Dioxide (SO₂) is produced by oxidation of elemental sulfur, which is an exothermic reaction (produces heat), or as a by-product from petroleum refining. Sodium bisulfite is produced by the absorption of sulfur dioxide into soda ash, a commodity chemical, produced from mineral deposits. Both obviously require energy to purify, store, ship and apply.

Comparison with UV

The energy consumption for chlorine and sodium hypochlorite disinfection at a dose of 20mg/l (250.2 kWhr/MG for Cl₂, and 437.8 kWhr/MG for hypochlorite) is well within the range of UV disinfection with low pressure mercury lamps at Plant AA (259kWhr/MG). Even at a chlorine dose of 10mg/l, there is published data for low pressure UV systems that are comparable with the energy consumption of chlorine and sodium hypochlorite. UV disinfection with medium pressure mercury lamps at Plant BB (1000kWhr/MG) is considerably above even hypochlorite disinfection at a dose of 20mg/l. However, published data for medium pressure UV systems is in the range of hypochlorite disinfection at high chlorine dosages.

Conclusions

On a global energy basis, low pressure Hg UV is competitive with chlorine/hypochlorite disinfection and dechlorination. Medium pressure Hg UV, however, is more energy intensive than chlorine disinfection, but competitive with hypochlorite at high dosages.

References:

1. EPRI ElectroTechnology Reference Guide, TR-101021-Revision 2, August 1992.
2. "General Electrochemistry", by Dr. R. C. Rhees, Vice President Research, Pepcon Systems Inc., P.O. Box 629, Cedar City, Utah 84720.