Right-Sizing the Design of Ozone Generators for Multiple Plant Upgrades in Orlando

Greg Taylor, P.E.; Chuck DiGerlando; Tim Rynders;
Christopher R. Schulz, P.E.; Laurie Gilmore, P.E.

The Orlando Utilities Commission (OUC) operates ozone systems for hydrogen sulfide oxidation at seven groundwater treatment plants serving the City of Orlando and Orange County. The Commission is executing the *Ozonator Replacement Project*, which will upgrade or replace ozone system equipment components at seven OUC water treatment plants (WTPs). The overall objectives of the project are to: (1) define water production, water quality, and treatment performance goals for the ozone system, (2) identify ozone system production requirements and equipment improvements to meet these goals, (3) establish a systematic ozone generator replacement program for the seven OUC plants, and (4) standardize, to the extent possible, the manufacturer, size, and components of ozone equipment systems to be replaced under the program.

Optimizing the capacity and turndown requirements of ozone generation systems uses a "right-sizing" methodology. The approach for optimal generator sizing is applied to the Southwest Water Treatment Plant—OUC's largest plant with a rated capacity of 40 million gallons per day (mgd)—as indicative of the approach that was used for sizing ozone generators at all seven OUC plants.

Greg Taylor is with CDM in Orlando, Chuck DiGerlando is with Orlando Utilities Commission, Tim Rynders and Christopher R. Schulz are with CDM in Denver, and Laurie Gilmore is with CDM in Atlanta.

Ozone Generator Right-Sizing Analysis

Vendor Coordination

Four major ozone equipment vendors were contacted to provide preliminary design information on their proposed ozone generator designs for the following generator design constraints:

- Use of standard horizontal shell, medium-frequency ozone generators with nominal rated capacities of 800, 1,000, 1,200, 1,500, 1,800, and 2,000 ppd at an ozone-in-oxygen concentration of 10 percent by weight. These represent a sufficiently wide range of ozone generator sizes to meet varied ozone production requirements, based on CDM's assessment of the existing ozone generation systems for the seven OUC plants. The final selection of standard generator sizes were determined based on the generator right-sizing analysis.
- Use of a closed-loop/open-loop cooling water system for cooling the ozone generators and power supply units (PSUs) with a maximum open-loop cooling water inlet temperature of 70 degrees Fahrenheit.

The design information from the vendors, together with historical ozone production trends for the seven OUC plants, was used to complete the generator right-sizing analysis presented below.

Optimal Ozone-in-Oxygen Concentration Analysis

The first step in correctly sizing the ozone generation system is to determine the optimal ozone-in-oxygen concentration for sizing the generators. Selecting an optimal ozone-in-oxygen concentration based on the prevailing cost of liquid oxygen and power in the OUC service area will allow proper sizing and cost-effective operation of the ozone generators for the OUC plants.

Figure 1 presents the specific energy curves for the proposed ozone generator designs from four vendors. As shown, specific energy curves for Generators A, B, and D were provided for several operating points (as a percent of generator rated capacity), whereas only one point was provided for Generator C. The curves for all generators follow a similar trend with more separation at lower ozone-in-oxygen concentrations (6 to 8 percent weight). As expected, the specific energy rate increases with increasing ozone-in-oxygen concentration, i.e., by up to 60 percent over a concentration range of 6 to 14 percent. Note that the vendors for Generators B and D provided specific energy values at the 14 percent ozone concentration.

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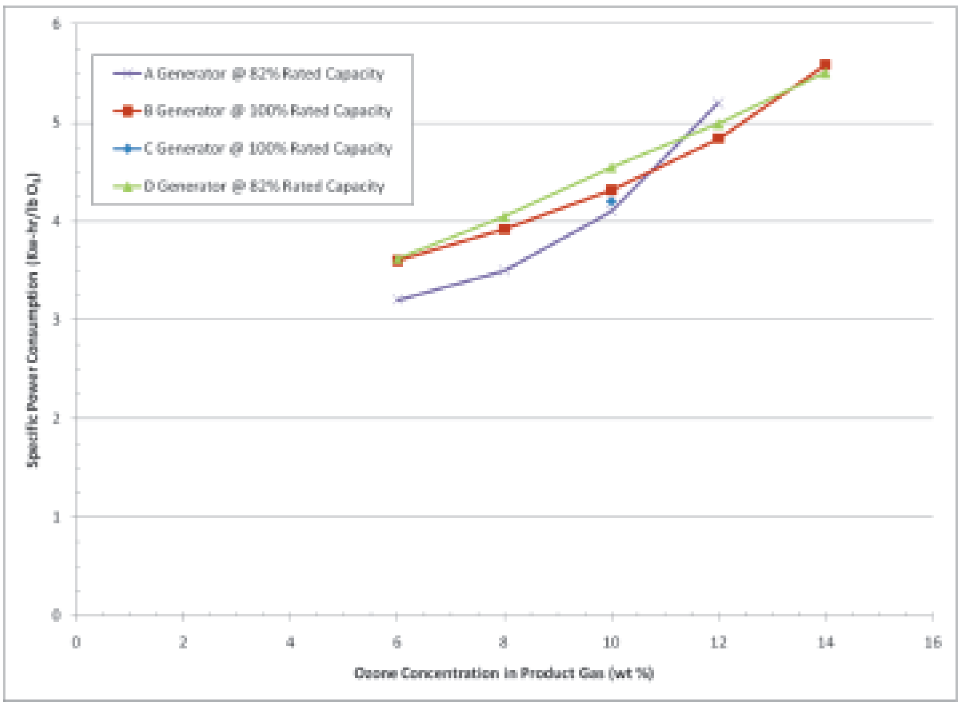

Figure 1 - Ozone Generator Specific Energy Curves (from four vendors)

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Figure 2 presents cost curves for specific energy and liquid oxygen consumption rates for Generators A, B, and D, as a function of the ozone-in-oxygen concentration. These curves were generated based on the trends presented in Figure 2 and prevailing unit costs for power ($0.10 per kW-hr) and liquid oxygen ($0.6007 per hundred cubic feet or $145.00 per ton). As expected, the total specific energy unit costs decrease with increasing ozone-in-oxygen concentration, while the liquid oxygen unit costs increase. The total minimum and maximum cost curves for producing a pound of ozone at different ozone-in-oxygen concentrations are also shown in the figure; these were produced by summing the specific energy and oxygen cost curves. The total cost curves flatten out over an ozone-in-oxygen concentration range between 10 and 14 percent by weight, with a net unit cost change of less than $0.10 per pound of ozone. The relatively high cost of liquid oxygen drives this analysis towards higher ozone-in-oxygen concentrations, which minimizes oxygen consumption rates.

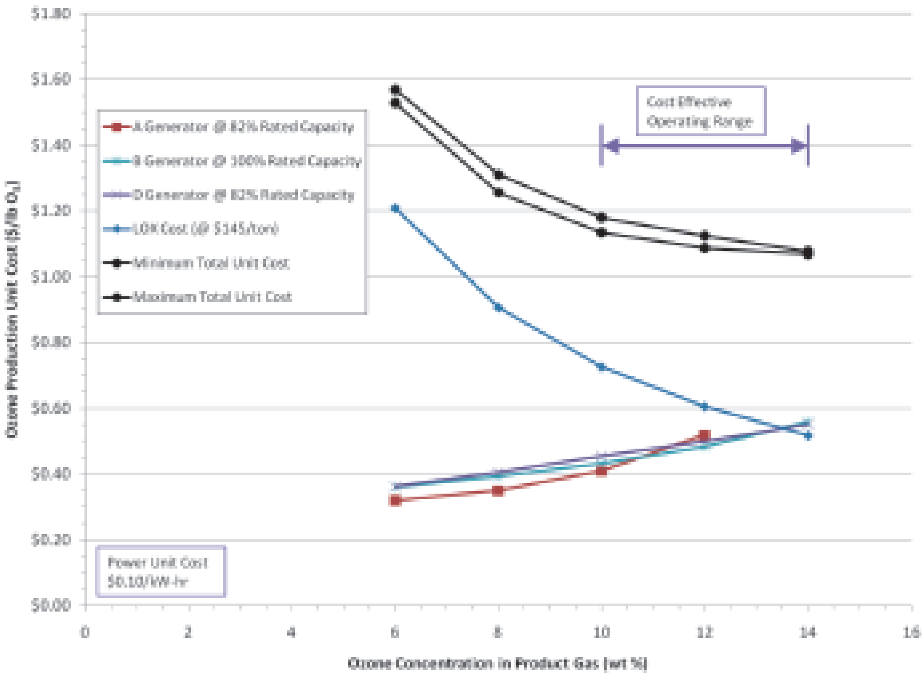

Figure 2 - Effect of Ozone Concentration on Ozone Production Unit Cost

Based on these results, the recommended optimal ozone-in-oxygen concentration for the OUC ozone systems is 12 percent by weight, with an allowable range for cost-effective operation of 10 to 14 percent by weight. These design values fall within an acceptable range for generator operation, based on information received from all the vendors. They were used in the generator right-sizing analysis for each OUC plant, as discussed later.

Ozone Generator Production Rates

Figure 3 presents the ozone production rates for proposed generator designs as a function of ozone-in-oxygen concentration. The ozone production values were normalized on a percentage basis relative to the ozone production rate at the optimal ozone-in-oxygen concentration of 12 percent by weight. The results indicate that Generators A and C follow a similar trend, with higher ozone production capability than Generator B at ozone-in-oxygen concentrations less than 12 percent, and lower production capability at 14 percent.

The average values for the Generator A and C curves were used in the generator right-sizing analysis presented for each OUC plant to estimate ozone generator production rates at different ozone-in-oxygen concentrations.

Generator Right-Sizing Design Approach

Based on over 10 years of operating experience with ozone generation equipment from three vendors, OUC has determined that ozone generation equipment at a few OUC plants may be over-sized or under-sized with respect to meeting current ozone production and capacity turndown requirements. To avoid some of the operational problems associated with non-optimally sized generators in the past, the historical flow, ozone dose, and ozone production trends from this period of operation, together with recent CUP limits imposed on the OUC plants, can be used to support the right-sizing of ozone generation equipment.

The approach by CDM to right-sizing the

ozone generation equipment at the seven OUC plants consists of the following steps:

1. Determine optimal ozone-in-oxygen concentration for sizing ozone generation equipment based on prevailing power and liquid oxygen unit prices.
2. Review ozone generator production data for different ozone-in-oxygen concentrations provided by the vendors.
3. Establish "optimal" and "non-optimal" ozone generation system design constraints that are tied to plant well field pumping operations and their frequency of occurrence.
4. Analyze "historical" and "design" plant flow trends based on average daily flow measurements.
5. Determine plant-specific ozone production requirements using the "ozone dose ratio" and "ozone utilization" methods, as described below.
6. Select ozone generator quantities and sizes to meet ozone production and plant operational constraints for each plant.

Steps 1 and 2 were discussed previously; the recommended ozone-in-oxygen concentration of 12 percent by weight and vendor-supplied ozone generator production data were considered in the generator right-sizing analyses presented below for the Southwest WTP. Steps 3 through 6 are also described below.

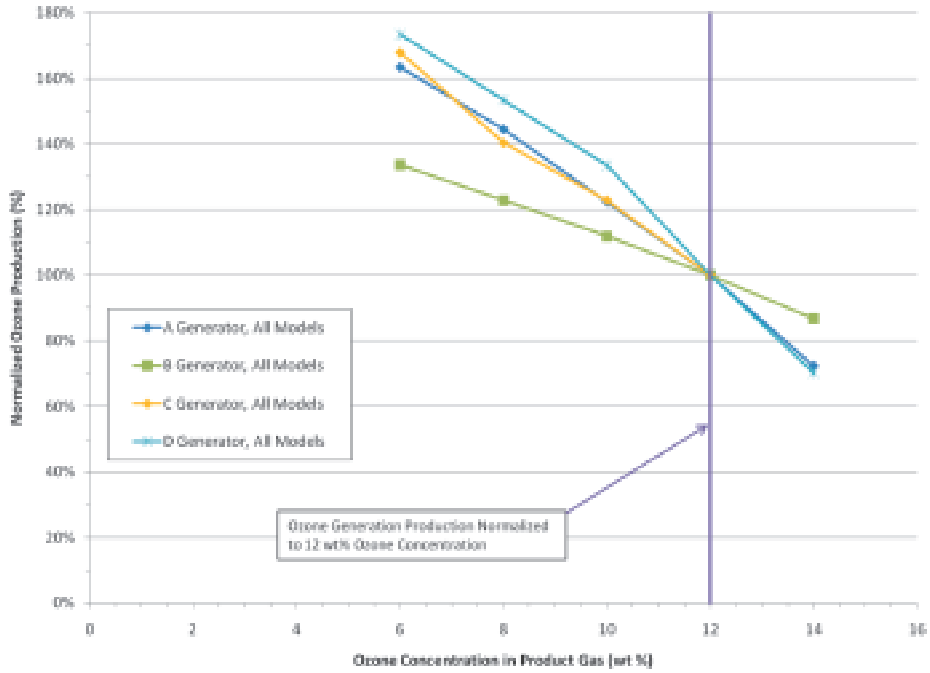

Figure 3 - Effect of Ozone Concentration on Ozone Generator Production Rates

Design Constraints

Table I presents three sets of design constraints for the ozone generation system corresponding to different levels of operational efficiency. The Level 1 constraints provide the highest level of operational efficiency and equipment redundancy and apply to well pumping operational scenarios (i.e., different groups of pumps operating together) that occur

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greater than 10 percent of the time, or 36 days per year. The Level 2 constraints apply to pumping scenarios that occur greater than 1 percent of the time, or 4 days per year. These constraints are the same as Level 1, except that the duty generators do not need to operate at 30 to 90 percent of generator rated capacity (i.e., at the lowest specific energy consumption rates for the generator). The Level 3 constraints apply to pumping scenarios that occur less than 1 percent of the time, or 4 days per year. They allow some flexibility in meeting ozone production capacity turndown requirements by operating the generators at non-optimal ozone-in-oxygen concentrations, or operating the system without a standby generator.

Plant Flow Trends

Flow frequency histograms were used to analyze average daily flow data for the years 2004 through 2009 for the seven OUC plants. Separate histograms were generated for "historical" flows and "design" flows; the latter were calculated by multiplying historical flow values by a design flow adjustment factor. The adjustment factor for each plant was defined as the maximum day flow CUP limit divided by the maximum day historical flow value.

Flow intervals for the histogram were defined by pumping rates associated with different well field pumping configurations, ranging from one pump operating by itself to all pumps in service with no standby capacity. While it is recognized that certain well pump configurations may not reflect actual plant operations, it does provide a reasonable, consistent design approach for estimating the frequency of well pump operations for the OUC plants. Each flow interval was populated with average daily flow values (approximately 2,000 data points per plant) to generate the flow frequency histogram. The frequency of occurrence was stated both as a cumulative numerical value and as a percentage.

Ozone Production Trends – OSD Ratio Method

The ozone-to-sulfide dose (OSD) ratio method for estimating ozone production trends relies on calculating the applied ozone design dose based on ozone demand, decay, and mass transfer efficiency characteristics of the water being treated. The calculated applied ozone dose is then

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TABLE I - DESIGN CONSTRAINTS FOR OZONE GENERATOR RIGHT-SIZING ANALYSIS

Percent of Time Well Pump Groupings in Service	Operational Efficiency Level	Design Constraints
>10% (or 36 days/ yr)	1	• Meet maximum ozone production with N+1 equipment redundancy • Meet maximum ozone production at optimal ozone concentration (10% by weight) • Meet minimum ozone production at optimal ozone concentration • Meet minimum generator gas flow rate at optimal ozone concentration • Number of ozone generators must fit within existing generator building footprint • Operate duty generators at 30 to 90% of generator rated capacity
>1% (or >4 days/ yr)	2	• As above, except: • Duty generators can operate at 10 to 100% of generator rated capacity
< 1% (or <4 days/ yr)	3	• Meet maximum ozone production at non-optimal ozone concentration (6 to 9% by weight), **or** • Meet maximum ozone production with N+0 equipment redundancy • Meet minimum ozone production at optimal ozone concentration (10% by weight) • Meet minimum generator gas flow rate at non- optimal ozone concentration (6 to 9% by weight) • Number of ozone generators must fit within existing generator building footprint. • Duty generators can operate at 10 to 100% of generator rated capacity

TABLE II - AVERAGE APPLIED OZONE DOSE TO H_2S RATIO

	Average Well H_2S (mg/L)	Base Applied Ozone Dose (mg/L)	Applied Ozone Dose to H_2S Ratio (unitless)
Conway	2.53	10.0	3.95
Navy	2.02	8.0	3.96
Pine Hills	0.64	2.0	3.125

TABLE III - OZONE UTILIZATION RATIOS FOR OUC WATER TREATMENT PLANTS

Parameter	Units	OUC Water Treatment Plants						
		Southwest	Conway	Kirkman	Lake Highland	Navy	Pine Hills	Sky Lake
Daily Flow Rate:								
Minimum	mgd	12.2	6.4	1.3	6.1	2.2	5.6	5.9
1st Percentile	mgd	15.3	8.3	4.6	9.9	3.5	8.6	8.3
50th Percentile	mgd	20.0	13.7	6.4	14.2	5.4	11.3	12.5
99th Percentile	mgd	25.3	19.3	10.9	21.6	7.4	14.4	15.5
Maximum	mgd	27.2	22.1	12.3	23.2	8.8	16.3	17.4
Daily Ozone Production Rate (2005-2009):								
Minimum	lb/day	964	595	112	581	147	65	775
1st Percentile	lb/day	1051	721	361	765	231	138	932
50th Percentile	lb/day	1414	1180	553	1253	355	215	1387
99th Percentile	lb/day	1876	1631	885	1948	495	402	1745
Maximum	lb/day	2072	1833	983	2043	558	451	1933
Ozone Utilization Ratio								
Minimum	lb/MG	58	58	23	54	30	5	87
1st Percentile	lb/MG	62	70	66	62	50	12	97
50th Percentile	lb/MG	70	86	85	87	66	19	110
99th Percentile	lb/MG	82	101	109	110	85	34	128
Maximum	lb/MG	140	110	341	131	120	39	164

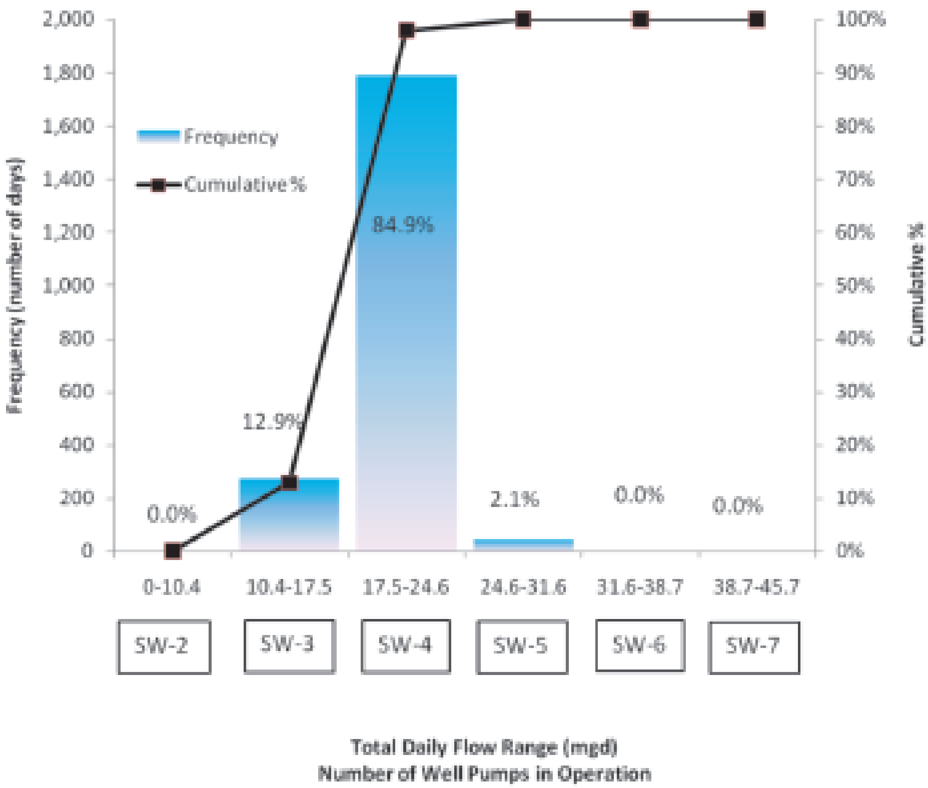

Figure 4 - Southwest WTP – Historical Flow Frequency Histogram

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multiplied by plant flow design values to obtain ozone production trends. For the OUC plants, the applied ozone dose for each plant can be calculated using the following factors:

- OSD ratio of 4:1, which was the design basis for the original design of the OUC ozone systems, and recently confirmed through ozone demand testing at the Conway, Pine Hills, and Navy WTPs (see Table II).
- Hydrogen sulfide concentration measurements in the well field supplies for each plant, which ranged from a minimum value of 0.4 mg/L at Pine Hills to a maximum value of 3.7 mg/L at Conway.
- Mass transfer efficiency (MTE) of 96 percent, based on guaranteed values for a sidestream injection ozone dissolution system.

For each plant, the ozone production rate "operating envelope" was calculated by multiplying historical plant flows for the five-year operating period by the minimum hydrogen sulfide concentration and 4:1 OSD ratio, and the design plant flows by the maximum hydrogen sulfide concentration and 4:1 OSD ratio. These data were then plotted on an ozone production frequency diagram, as discussed below. These conservative design values were selected to provide a wide operating envelope to define the ozone generator turndown requirements for each plant.

A limitation of the OSD ratio method is that it relies on hydrogen sulfide concentration measurements in the well field supplies, for which limited data are available (typically one sample per well per year), with uncertain analytical results due to the potential to volatilize sulfides to the atmosphere during field sampling.

Ozone Production Trends – OU Ratio Method

The ozone utilization (OU) ratio method relies on historical daily ozone production data from the OUC plants for the years 2004 through 2009. Table III presents the average daily flow rates, average daily ozone production rates, and the OU ratio, normalized by flow, for OUC's seven WTPs. As expected, the OU ratios vary as a function of hydrogen sulfide concentration in the plant well supplies, with the lowest ratios at Pine Hills (5 to 39 lb/MG) and the highest ratios at Sky Lake (87 to 164 lb/MG).

For each plant, the ozone production rate operating envelope was calculated by multiplying historical and design plant flows for the five-year operating period by the 1st and 99th percentile OU ratios, respectively, and plotting this information on an ozone production frequency diagram. These conservative design values were selected to provide a wide operating envelope to define the ozone generator turndown requirements for each plant.

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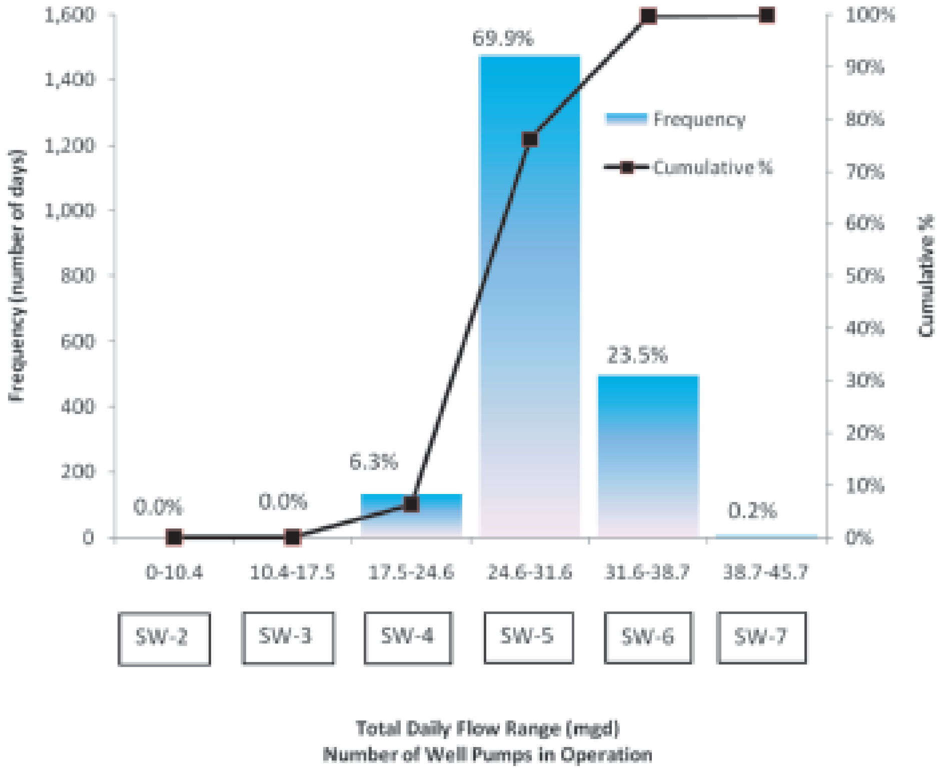

Figure 5 - Southwest WTP – Design Flow Frequency Histogram

TABLE IV - SOUTHWEST WTP - OZONE GENERATOR RIGHT-SIZING ANALYSIS (OZONE UTILIZATION RATIO METHOD)

Parameter	Well Pumping Configuration						
	Units	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7
Ozone Production Analysis							
In-Service Well Pumping Capacity							
Well No. 1 Capacity	gpm		4900	4900	4900	4900	4900
Well No. 2 Capacity	gpm			4900	4900	4900	4900
Well No. 3 Capacity	gpm				4900	4900	4900
Well No. 4 Capacity	gpm					4900	4900
Well No. 5 Capacity	gpm						4900
Well No. 6 Capacity	gpm	2450	2450	2450	2450	2450	2450
Well No. 7 Capacity	gpm	4800	4800	4800	4800	4800	4800
Combined Well Capacity	gpm	7250	12150	17050	21950	26850	31750
Combined Well Capacity	mgd	10.4	17.5	24.6	31.6	38.7	45.7
Frequency of Occurrence							
Percent Time Wells in Operation- Historical Flows	%	0%	13%	84.9%	2.1%	0%	0%
Percent Time Wells In Operation- Design Flows	%	0%	0%	6.3%	70%	23.5%	0.2%
Ozone Utilization Ratio							
99th Percentile	lb/mg	82	82	82	82	82	82
50th Percentile	lb/mg	70	70	70	70	70	70
1st Percentile	lb/mg	62	62	62	62	62	62
Required Ozone Dose							
Maximum	mg/L	9.8	9.8	9.8	9.8	9.8	9.8
Average	mg/L	8.4	8.4	8.4	8.4	8.4	8.4
Minimum	mg/L	7.4	7.4	7.4	7.4	7.4	7.4
Required Ozone Production							
Maximum	lb/day	856	1435	2013	2592	3170	3749
Average	lb/day	731	1225	1719	2213	2706	3200
Minimum	lb/day	647	1085	1522	1960	2397	2835
Ozone Generator Capacity Analysis							
Generator Quantity and Rated Capacity[1]							
Generator Rated Capacity	ppd	900	900	1080	900	1080	1260
Ozone-in-Oxygen Concentration	%wt	12%	12%	10%	12%	10%	8%
No. of Installed Generators	No.	4	4	4	4	4	4
No. of Operating Generators:							
At Maximum Production	No.	1	2	2	3	3	3
At Average Production	No.	1	2	2	3	3	3
At Minimum Production	No.	1	2	2	3	3	3
Generator Production-to-Capacity Ratio:[1]							
At Maximum Production	%	95%	80%	93%	96%	98%	99%
At Average Production	%	81%	68%	80%	82%	84%	85%
At Minimum Production	%	72%	60%	70%	73%	74%	75%
Ozone Gas Flowrate:[2]							
Generator Minimum Gas Flow Limit	scfm	12	12	12	12	12	12
At Maximum Production	scfm	60	100	168	181	265	392
At Average Production	scfm	51	85	144	154	226	335
At Minimum Production	scfm	45	76	127	137	201	296

[1] Generator rated capacity is based on 12% ozone concentration; higher production rates at lower ozone concentrations are based on performance data provided by Ozonia and ITT-WEDECO.

[2] Generator gas flow limit is based on the selected generator size and was based on data provided by ITT-Wedeco which had the highest requirements.

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An advantage of the OU ratio method is that it does not rely on hydrogen sulfide concentration measurements for calculating ozone production requirements. Instead, the ozone production rates and plant flows recorded at each plant can be used directly. This approach assumes that the ozone concentration analyzers and ozone mass flow meters for calculating ozone production rates are calibrated, ozone mass transfer rates are acceptable (e.g., > 92 percent), and ozone production rates are adjusted daily by plant operators to ensure complete oxidation of hydrogen sulfide in finished water leaving the plant.

Ozone Production vs. Generator Capacity Analysis

Due to measurement uncertainties associated with the OSD method, the OU ratio method was selected for matching ozone generation equipment capacities to ozone production requirements in the generator right-sizing analysis. While both methods were used to plot historical and design ozone production frequency curves for comparison purposes, only the OU method was used for ozone generator capacity selection. For most (but not all) plants, the OSD method resulted in higher ozone production rates than the OU method, which could have led to over-sizing the ozone generators at certain OUC plants, if this method was used for design.

Ozone Generator Right-Sizing Analysis—Southwest WTP

The ozone generator right-sizing analysis is presented in this section for OUC's Southwest WTP, which has a rated capacity of 40 mgd. The same approach was used to size and select ozone generation equipment for OUC's other six plants.

Well Field Flow Analysis

Figures 4 and 5 present historical and design flow frequency histograms, respectively, for the Southwest WTP. The well field flow analysis included six pumping configurations, ranging from two to seven wells per configuration with combined pumping rates from 10.4 to 45.7 mgd. The pumping rates for each configuration were used to set histogram flow intervals, which were then populated with "historical" and "design" average daily flow values. The historical flow frequency analysis indicates that the predominant pumping configuration was SW-4, which operated 85 percent of the time. The design flow frequency analysis showed a significant shift toward higher flows, with the SW-5 and SW-6 configurations (in combination) operating almost 94 percent of the time. The largest pumping configuration (SW-7), with all pumps in service, will only be required to meet < 0.2 percent of predicted future water demands, and was considered to be a low priority in the generator right-sizing analysis for this plant. As shown in Figure 5, almost 70 percent of the future demands will operate between 24.6 and 31.6 mgd.

Generator Right-Sizing Analysis

Table IV presents the ozone generator right-sizing analysis for the Southwest WTP. The OU ratio method was used for determining ozone production rates for the six well field pumping configurations. As shown, the three configurations (SW-4, SW-5, and SW-6) are expected to operate at cumulative frequency intervals ranging from 6 to 70 percent of the time (or a total of 99.8 percent of the time in those three configurations), and thus were considered for sizing the ozone generation equipment for the plant. The ozone generator capacity analysis is presented at the bottom of the table. It involved an iterative process to select the optimal number and rated capacity ozone generators to meet ozone production requirements for the plant and project design constraints (see Table I).

Based on this analysis, four ozone generators (three duty, one standby) are recommended for the Southwest plant, each with a rated capacity of 900 ppd at an ozone-in-oxygen concentration of 12 weight percent. The generators will operate most of the time at this optimal ozone concentration, with a slightly lower concentration of 10 percent to meet peak future ozone demands. The recommended generator capacity for Southwest is the same as two other OUC plants (Conway and Navy).

Figure 6 plots the recommended ozone generation equipment for Southwest against the ozone production operating envelopes developed using the OU and OSD methods. As shown, the three duty ozone generators are capable of covering the entire operating envelope for meeting ozone production requirements using the OU method, but would be undersized with respect to the OSD method.; the latter method is not recommended for right-sizing the generators.

Conclusion

By applying the ozone utilization (OU) ratio to the design and sizing of the ozone generation equipment for all of OUC's water treatment plants, there is a direct cost savings benefit for capital cost and operations and maintenance costs. Both methods were applied to the sizing of the generators and compared, and the results are depicted in Table V.

For two of the facilities, the generator sizes actually increased slightly with the OU method; for two of the plants, there was no change between the two methods; and, for three of the seven plants, there were either significantly smaller ozone generators or fewer ozone generators required using the OU method.

By utilizing the OU methodology for ozone generator sizing, OUC will save an estimated $1.4 million in capital costs when procuring the equipment for this project. These findings would then imply that it is advantageous to perform pilot testing to get accurate ozone utilization ratios when implementing ozone for water treatment, and when upgrading existing systems, to utilize previous SCADA information to help finalize ozone generator design sizes.

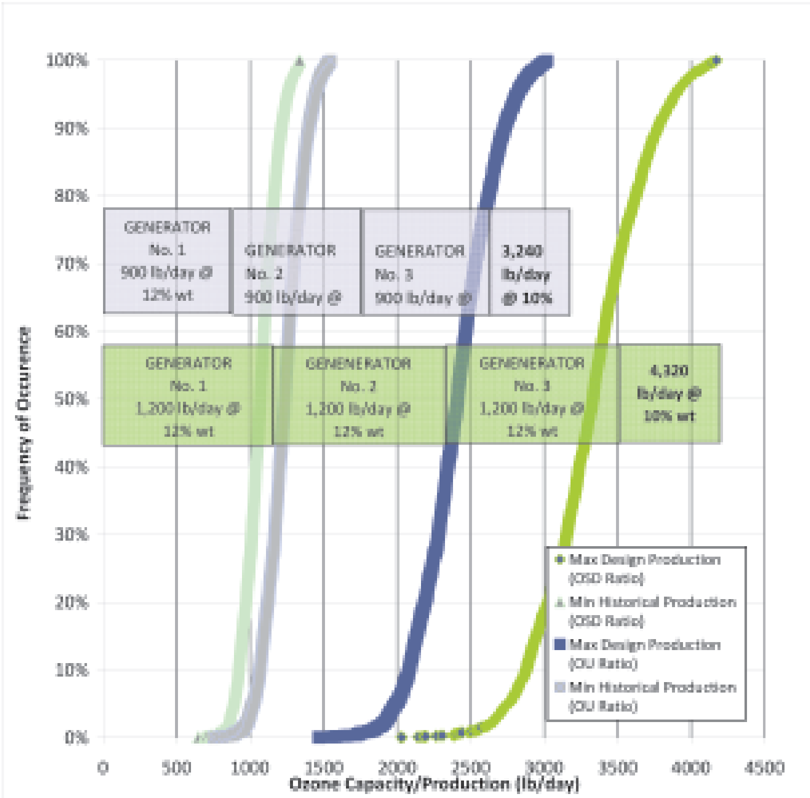

Figure 6 - Southwest WTP – Ozone Production vs. Generator Capacity Curves

TABLE V – GENERATOR SIZING COMPARISON

WTP	Ozone Production Design Range, ppd		Ozone Generator Quantity and Size, ppd		Size or Quantity Change
	OSD Method	OU Method	OSD Method	OU Method	
Southwest	537 - 5,120	650 - 3,750	4 x 1,500	4 x 900	smaller
Pine Hills	60 - 1,773	60 - 891	4 x 600	2 x 600	fewer
Conway	228 - 3,823	353 - 3,127	4 x 1,200	4 x 900	smaller
Navy	252 - 653	252 - 857	2 x 900	2 x 900	----------
Lake Highland	337 - 3,824	625 - 3,881	4 x 1,200	4 x 1,200	----------
Kirkman	275 - 1,499	333 - 1,884	2 x 1,500	2 x 1,800	larger
Sky Lake	400 - 2,992	726 - 3,382	3 x 1,500	3 x 1,800	larger