AQUARIUS
TECHNOLOGIES PTY LTD
WATER QUALITY CONTROL

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Aquarius Technical Bulletin - No. 24

Understanding Oxidising Biocides and ORP Control.

Oxidising biocides such as chlorine, bromine and ozone have been used for disinfection of water for almost 100 years due to their great efficiency and ease of use. Chlorine either as gas, or liquid hypochlorite solutions is the most commonly used disinfectant in both potable water and in swimming pools. Bromine is proving to be the oxidising biocide of choice for disinfection of comfort cooling systems operating at pH values of 8.0 - 9.0.

Chemistry of oxidising biocides in water

Chlorine Gas - $Cl_2 + H_2O$ ----> HOCl + HCl
Liq. Chlorine - NaOCl + H_2O --->HOCl + NaOH

Hypochlorous Acid (HOCl) is a weak acid and dissociates in water as follows
HOCl <-----> OCl^- + H^+ pK_a = 7.5 approx.
Hypochlorous Acid <----->Hypochlorite ion & Hydrogen ion, similarly bromine dissociates as follows
HOBr <-----> OBr^- + H^+ pK_a = 8.5 approx.
Hypobromous Acid <----> Hypobromite ion & Hydrogen Ion. See Figure 1

The disassociation of HOCl and HOBr is effected by the following

1. ***The pH value***, lower pH's result in more HOCl and HOBr being available.
2. ***Temperature,*** increasing the temperature from 25 oC results in more OCl^- and OBr being formed.
3. ***The Ionic Concentration*** or T.D.S. of the system, higher T.D.S. will reduce the amount of HOCl or HOBr formed.
4. ***The effect of complexing ions*** such as cyanuric acid with chlorine in swimming pools, or dimethylhydantoin with bromine, reduce the amount of HOCl or HOBr respectively.

The pH value is by far the major factor in the amount of HOCl or HOBr formed. HOCl and HOBr are about 80 - 100 times more effective disinfectants than are the OCl and OBr ions. HOCl and HOBr have the ability to penetrate the bacteria cell structure and cause it to rupture and die. As pH values increase less HOCl or HOBr is available and disinfection efficiency is reduced - Fig 2.

Bromine having a higher disassociation constant - pK_a = 8.7 approx. has much more HOBr available at pH values from 8.0 - 9.0.

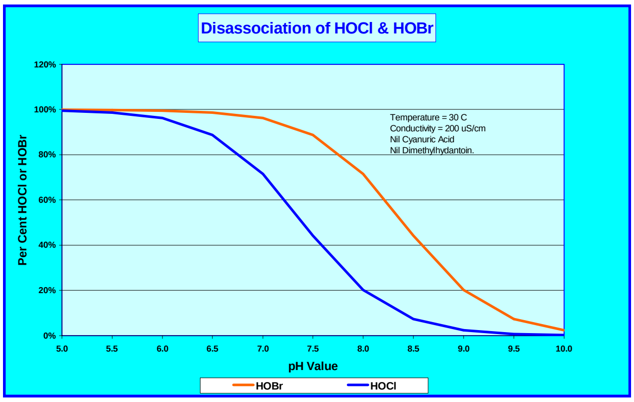

Figure 1

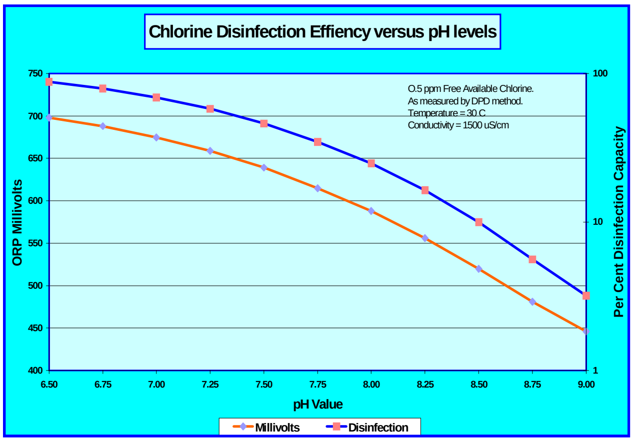

Figure 2

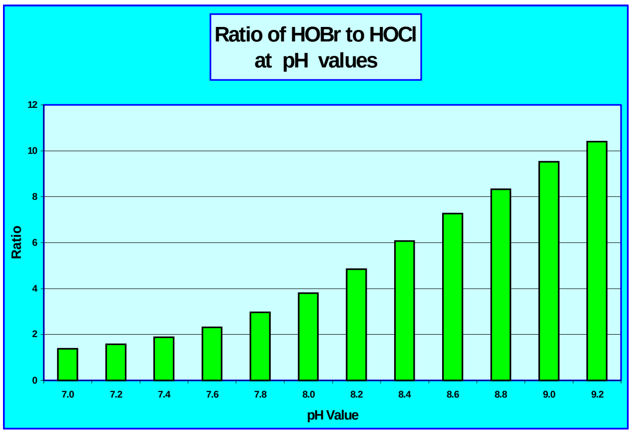

Figure 3

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Looking at the history of oxidising biocides, most chlorine applications are in, potable water where the pH values are normally 7.0 - 7.3, in swimming pools where pH is controlled to 7.2 - 7.6 and in large industrial cooling towers where pH is controlled to pH 6.8 - 7.2. At these pH values 50 - 75% of the chlorine dosed is available as HOCl and thus very good disinfection is normally achieved. Refer to Figure 1.

Chlorine or Halogen Demand

Chlorine, Bromine and Ozone (Halogens) are consumed in the destruction of bacteria, algae, organic matter, Fe^{++}, NO_3^-, S^{--}, and SO_3^- and NH_3 (organic nitrogen). This is termed the ***Chlorine or Halogen Demand,*** and sufficient halogen must be dosed to satisfy this demand, plus a small excess or residual.

NH_3 compounds react with chlorine to form chloramines which are very ineffective biocides, and with bromine to form bromamines. The excess chlorine or residual is termed ***Free Available Chlorine, FAC or Free Available Halogen, FAH.***

The dosage of halogen required is proportional to the sum of the Chlorine Demand and Free Available Chlorine or residual. The halogen demand in swimming pools will depend on, bather load, bather hygiene, temperature, sunlight and the make up water, whilst the demand on cooling towers will vary with evaporative load, the wind direction, amount of pollen or "food" in the incoming air, the temperature, and the make up water supply.

It is essential to be able to automatically dose the halogens based on the varying demand from the system, and this is where the ORP sensor is ideally suited.

Overdosing with halogens, whilst being wasteful of product can also result in serious corrosion problems especially to copper pipe work.

Measurement of Free Available Chlorine

The standard method for measurement of free available chlorine (halogen) is based on the DPD reagent, buffered to 6.3 - 6.5, which is added to a sample of the water to give a pink colour, the intensity of the pink colour being proportional to the Free Available Chlorine level, which is then read off by comparison with a colour chart (cheap chlorine test kits) or photometrically in e.g. Hanna C104 meter.

The DPD test method for Free Available Chlorine (a) DPD measures the total HOCl + OCl in the sample. (b) "Cheap test kits" have an accuracy of about +/- 0.5 ppm. (c) Photometric test kits have an accuracy of about +/- 0.2 ppm(d) With high chlorine levels the red colour can "bleach" to colourless to give a false reading as very low levels.

Measurement of free available chlorine is definitely not a measure of disinfection, even though it is written into regulations world wide for both potable water and for swimming pools and spas, at 0.5 -1.0 ppm and 1.5 - 3.0 ppm respectively.

It is taken for granted that the pH is close to pH 7.0 and thus the majority of Free Available Chlorine is present as HOCl - see figure 1.

What should the Free Available Chlorine level be ?

The disinfection efficiency of Free Available Chlorine is reduced as pH values increase upwards towards 9.0. If we accept 0.33 ppm FAC as an acceptable level of disinfection in a system operating at pH at 7.5, we need 0.5 ppm at pH 8.0, 1.4 ppm at pH 8.5 and 4.3 ppm at pH 9.0 to achieve the same level of disinfection. (The same level of HOCl) See Figure 4.

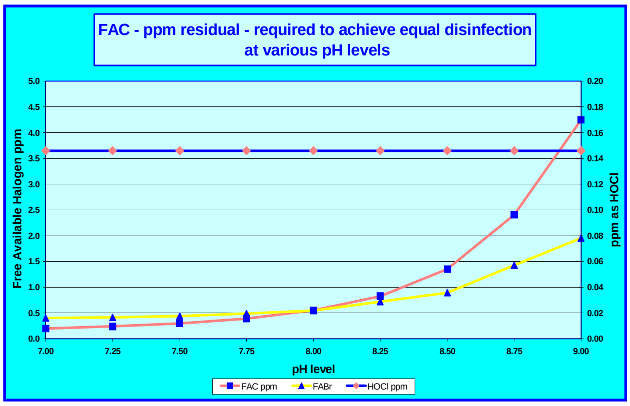

Figure 4

The above graph shows it is HOCl that is responsible for disinfection as this amount is kept constant at all pH values.

The ORP sensor is a very sensitive sensor for low levels of HOCl or HOBr in most water systems, and is sensitive to levels from less than 0.001 to above 5.0 ppm .

As far back as 1968 the German Federal Health Office concluded that the kill time for E. Coli is just a fraction of a second at an ORP (redox) value of 650 mV. independent of the pH value.

In 1971 the World Health Organisation (WHO) adopted an ORP standard of 700 mV. for drinking water disinfection. A study in the USA of water in commercial spas, by Oregon State Health Department and Yale University concluded that ORP was the only significant predictor of bacterial quality of the water.

NSW Health Department Guidelines (June 1996) recommend a minimum ORP level of 720 mV. for chlorination of public swimming pools, with pH range of 7.2 - 7.8 - this equates to 1.5 ppm FAC at pH 7.2 and 3.3 ppm FAC at pH 7.8 which in turn calculates to 0.58 ppm of HOCl in both cases.

These levels are intended to meet the bacteriological criteria of - less than 10^{-3} Heterotrophic Plate Count per 100 ml, zero Thermotolerant Coliforms per 100 ml, and zero Pseudomonas Aerugina per 100 ml as per test methods AS 4276.3.1, AS 4267.7, and AS 4276.12 1995 respectively.

In cooling water where the bacteriological criteria is 10^{-3} - 10^{-5} Heterotrophic Plate Counts per ml, it can be extrapolated that a residual of 0.1 ppm as HOCl or HOBr will be sufficient to meet this criteria. This is equivalent to 500 - 550 mV. ORP reading.

If we continue to use Free Available Chlorine or Free available Halogen as our criteria for bacteriological standards and degree of disinfection, ***then we must take into account the system operating pH value and set our FAC targets for chlorine or bromine as per the graph in Figure 4.***

Effectiveness of Halogens as disinfectants.

Chlorine, Bromine, and Ozone are universally used for disinfection in potable water, public swimming pools and large industrial cooling systems.

The Cooling Tower Institute Guideline: Best Practice for Control of Legionella - Feb. 2000 recommends halogens such as chlorine and bromine as best practice disinfectants for cooling systems.

The Australian Institute of Refrigeration, Air-conditioning and Heating - Application Manual No. DA18 - "Management Specifically for Legionella Control" states that only BCD and CTPE were effective in specifically controlling Legionella. BCD is more commonly known as "Bromine Tablets", a concentrated source of bromine.

The "kill rate" of biocides is a function of concentration and contact time or "CT" . Halogens are effective biocides at very low concentrations, and have a rapid kill rate with time, in the order of seconds to minutes, and are very quickly consumed, and/or the residual lost from the system. Therefore continuous treatment is beneficial in almost every instance to maintain a high degree of disinfection.

Halogens attack and oxidise all bacteria and organic matter, and bacteria are not able to build up an immunity to oxidising agents. Some bacteria, amoeba or protozoa may require higher concentrations to penetrate the cell, such as Giardia or Crytosporidium.

Halogens such as chlorine and bromine revert back to the chlorides (common salt) and bromides respectively after oxidising the bacteria and are a minimum environmental discharge hazard.

Safety, handling and dosage of Halogens.

Halogens in the concentrated form are hazardous chemicals, and will react violently with acids or reducing agents. Proper storage and safety equipment should be afforded by reference to the MSDS for each particular chemical.

Chlorine gas at low concentrations in air will seriously damage the lungs and can be fatal, thus Sodium Hypochlorite solution is a less hazardous form of chlorine for pools and general use.

Dosage of hypochlorite can be unreliable due to "gassing off" which air locks electromagnetic dosage pumps. Peristaltic dose pumps with the appropriate squeeze tube is the dose pump of choice.

BCD dosage is usually via a dissolution feeder, but care is required in dosage as the solution exiting the feeder has a pH of about 2.5 and an ORP value of approx. 1200 mV. and at this level is highly corrosive.

Dosage via PVC lines to an area of very good mixing and dilution, usually in the tower basin is strongly recommended.

The ORP (or Redox) Sensor.

ORP is a measure of a solutions oxidising or reducing strength. An oxidising agent has a potential to acquire electrons and become reduced. When electrons are transferred from one species to another in a chemical reaction, the reaction is called an oxidation reduction reaction.

When halogens react with bacteria, the bacteria act as the reducing agents, donating electrons to the halogen, and the bacteria is oxidised, the halogen being reduced. This flow of electrons from bacteria to halogen is sensed as a small voltage by the ORP electrode.

The oxidation - reduction potential (ORP) of a specific reaction can be determined using the Nernst equation similar to the pH reaction.

$$\mathbf{E_m = E^0 + RT/nF \log A_{ox}/A_{red}}$$

$\mathbf{E_m}$ is the measured oxidation-reduction potential of the reaction, $\mathbf{E^0}$ is the standard potential which is referenced to the hydrogen potential, **RT/nF** is the Nernst value, and $\mathbf{A_{ox}}$ and $\mathbf{A_{red}}$ are the activities of the oxidant and reductant.

ORP measures the ratio of the activities of the oxidising and reducing species in a solution. This indicates the solutions electron activity, i.e. its ability to oxidise or reduce other substances. It does not directly indicate the concentration of the predominant oxidising or reducing agent. Concentrations can however be deduced by solving the Nernst equation if enough of the variables are known.

ORP electrodes used in water treatment applications are usually composed of either platinum or gold, which allows electrons to exchange between the oxidised and reduced species in the solution. Silver/ Silver chloride is normally used as the reference electrode to complete the circuit.

The electron exchange produces a millivolt potential in the range of -1000 to + 1000 millivolts but having a current output in the pica amp range (0.0000000000001 amps), which necessitates high impedance circuitry for accurate measurement without polarising the electrode.

As electrons are being exchanged at the platinum surface, it is essential that the electrode is subject to a flow of water past the electrode, and that it is maintained reasonably clean and free from contamination. Whilst calibration is not necessary, it is prudent to periodically verify the operation of the electrode in standard ORP solutions such as 250 mV. and 475 mV. standard solutions.

It is essential to keep the electrode wet at all times to prevent the junction to the reference electrode drying out. Electrode life is at least 2 - 3 years with due care and service.

See our operating instructions manuals for full recommended cleaning and verification details.

Requirements of an ORP measurement and control system.

1. As the ORP sensor operates at picoamp currents to output voltages from - 1000 to + 1000 millivolts, ***it is essential to have a high impedance measurement circuit*** to prevent polarising the sensor.

2. The ORP sensor is very sensitive to stray currents in the water, even the effect of dissimilar metals can set up an unwanted voltage, or use of Electrolytic Chlorinators will pose unwanted voltages. ***It is imperative that the sensor input to the circuitry is of the differential input type with a ground reference electrode*** to ensure the accuracy of measurement from the sensor. See Technical Bulletin No. 21.

3. ***The circuitry needs to be better than C-Tick Standard with regard to electromagnetic interference***. Variable speed drives on pumps and fans can cause interference on the power supply and effect or "crash" the microprocessor program routines.

4. ***Dosage control should be P.I.D. based***, as the demand for halogens is variable, and there is significant lag time between dosage to the system, and circulation of this dose to provide feedback to the sensor. Feed back time lags vary from minutes in cooling systems to hours in large swimming pools. P.I.D. allows for dosage to accelerate or deaccelerate based on demand and feedback algorithms without overshoot of the desired set point value. ON/OFF dosage control on dosage results in "saw- tooth" over and undershoots of the set point and is archaic in this era of microprocessors.

5. ***ORP readings provide for a easy historical record of degree of disinfection, or alarms*** when relayed back to a DDC or BMS system. Computers are inherently noisy and ***it is imperative that the 4 - 20 mA signal is Loop Isolated from the ORP circuitry***. Refer to Technical Bulletin No. 21.

6. ***DDC Interfacing should be via differential inputs with a 10K resistor tied to analog ground***, to ensure accurate and pure signals are available at the BMS unit. Refer to Technical Bulletin No. 22

7. Dosage Pumps need careful consideration and specification, ***Liquid Halogens are prone to give off gas which "air locks" electromagnetic or solenoid dose pumps***, and results in unreliable dosage and control. Unless dose rates are in excess of 5 lts./hr., ***peristaltic dose pumps which are self priming should be used assuming dose head pressure is less than 250 kPa.***

Bromine tablets feeders, are re-engineered from pool filter casings, with pressure ratings of 280 kPa.. Note that the ***effluent exiting the BCD feeder has a pH of about 2.5 and a FAC of about 300 ppm - highly corrosive.*** PVC dosage lines to an area of rapid mixing is essential.

8. ***Is pH control and dosage necessary***, for the particular system? The degree of disinfection "drops off" at higher pH values. Control and dosage on pH should be considered dependant on the system and the make up water. If liquid chlorine is chosen then the pH should be controlled between 7.0 and 7.5 however on cooling towers where pH's are usually between 8.0 and 9.0, BCD tablets are the preferred oxidising agent, without any pH control. See Figure 1.

Relationship of ORP to Free Available Chlorine

As outlined in chemistry of Chlorine or halogens in water in the beginning of this article, Chlorine dissociates to HOCl + OCl ions and Bromine to HOBr and OBr ions.

The disassociation rate of Chlorine or Bromine in water is proportional to the following.

(a) the operating pH value.
(b) the temperature of the solution
(c) the ionic concentration, conductivity or T.D.S
(d) the concentration of complexing agents such as Cyanuric Acid with Chlorine, or dimethylhydantoin with Bromine.

R& D carried out by Aquarius has shown that Free Available Chlorine can be reliably calculated from ORP millivolts readings by inserting the above known variables into an equation.

The full equation is quite complicated, requires fourth order polynomials, as well as log and exponential formulae, but is fairly easily calculated by either a microprocessor or on a spreadsheet such as Excel.

The charts on the next pages have been calculated from this information and have been verified via in house research and "in the field" results.

ORP has many advantages -

1. It is a very accurate measure of disinfection.
2. It is many times more accurate that DPD test for free available chlorine.
3. Very low levels of FAC can be accurately measured by ORP and not by DPD
4. ORP readings can signal alarms on High or Low readings - e.g. empty tank will run to low ORP
5. ORP can be data logged to provide historical records of disinfection.
6. Sufficient R & D has been carried out in the last five years by Aquarius to ensure accuracy, reliability and with an in depth understanding of the chemistry of ORP as applied to swimming pools, spas, fountains and to cooling towers.
7. ***A properly engineered and serviced ORP system could guarantee the prevention of Legionella in cooling towers,*** and is gaining acceptance in pools, spas, and fountains.

Author

The author is Bert Topping - Managing Director of Aquarius Technologies Pty Ltd. - a Quality Assured manufacturer of automatic dosage and control equipment for the Water Treatment Industry.

Theoretical FAC ppm - Free Available Chlorine
Typical Swimming pool

Temp = 27 C, T.D.S. = 2000 ppm and Cyanuric Acid = 40 ppm

	pH	7.00	7.20	7.40	7.60	7.80	8.00	8.20	8.40	8.60	8.80	9.00
ORP												
375		0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.08	0.13	0.20	0.31
400		0.02	0.02	0.02	0.03	0.04	0.06	0.09	0.13	0.20	0.32	0.49
425		0.02	0.03	0.04	0.05	0.07	0.09	0.14	0.21	0.32	0.50	0.78
450		0.04	0.04	0.06	0.07	0.10	0.14	0.21	0.32	0.49	0.76	1.18
475		0.06	0.07	0.08	0.11	0.15	0.21	0.31	0.47	0.73	1.13	1.77
500		0.08	0.10	0.12	0.16	0.22	0.31	0.46	0.69	1.06	1.65	2.58
525		0.12	0.14	0.17	0.23	0.31	0.45	0.66	0.99	1.52	2.37	3.70
550		0.17	0.20	0.25	0.32	0.44	0.63	0.93	1.40	2.15	3.34	5.22
575		0.23	0.28	0.34	0.45	0.61	0.87	1.29	1.95	2.99	4.64	7.26
600		0.32	0.38	0.47	0.61	0.84	1.20	1.76	2.67	4.09	6.36	9.94
625		0.43	0.51	0.63	0.83	1.13	1.62	2.39	3.61	5.54	8.60	13.45
650		0.58	0.68	0.85	1.10	1.51	2.16	3.19	4.82	7.40	11.49	17.98
675		0.77	**0.90**	**1.12**	**1.46**	2.00	2.86	4.22	6.37	9.79	15.20	23.77
700		1.00	**1.18**	**1.46**	**1.91**	2.62	3.74	5.52	8.34	12.81	19.89	31.12
725		1.30	**1.53**	**1.90**	**2.48**	3.39	4.85	7.16	10.81	16.61	25.79	40.34
750		1.67	1.97	2.44	3.18	4.36	6.23	9.20	13.89	21.34	33.14	51.85
775		2.13	2.51	3.11	4.06	5.56	7.94	11.72	17.71	27.20	42.24	66.08
800		2.69	3.17	3.93	5.13	7.03	10.05	14.83	22.40	34.40	53.43	83.58
825		3.38	3.98	4.93	6.44	8.83	12.62	18.62	28.13	43.20	67.09	104.9
850		4.22	4.97	6.15	8.03	11.01	15.73	23.22	35.08	53.88	83.68	130.9
875		5.23	6.15	7.62	9.95	13.65	19.50	28.77	43.47	66.77	103.7	162.2
900		6.44	7.58	9.39	12.26	16.81	24.02	35.44	53.55	82.25	127.7	199.8

Theoretical FAC ppm - Free Available Chlorine
Typical Hydrotherapy pool

Temp = 32 C, T.D.S. = 2000 ppm and Cyanuric Acid = NIL ppm

	pH	7.00	7.20	7.40	7.60	7.80	8.00	8.20	8.40	8.60	8.80	9.00
ORP												
375		0.01	0.01	0.01	0.02	0.02	0.03	0.05	0.08	0.12	0.18	0.29
400		0.01	0.02	0.02	0.03	0.04	0.06	0.08	0.12	0.19	0.30	0.47
425		0.02	0.03	0.03	0.04	0.06	0.09	0.13	0.19	0.30	0.47	0.73
450		0.03	0.04	0.05	0.07	0.09	0.13	0.20	0.30	0.46	0.71	1.12
475		0.05	0.06	0.07	0.10	0.14	0.20	0.29	0.44	0.68	1.06	1.66
500		0.07	0.09	0.11	0.14	0.20	0.29	0.43	0.65	1.00	1.55	2.43
525		0.10	0.12	0.16	0.21	0.29	0.41	0.61	0.93	1.43	2.23	3.49
550		0.15	0.18	0.22	0.29	0.40	0.58	0.86	1.31	2.02	3.14	4.92
575		0.21	0.24	0.31	0.41	0.56	0.81	1.20	1.82	2.81	4.37	6.84
600		0.28	0.34	0.42	0.56	0.77	1.11	1.64	2.50	3.84	5.98	9.37
625		0.38	0.45	0.57	0.75	1.04	1.50	2.22	3.38	5.20	8.09	12.68
650		0.51	0.61	0.76	1.00	1.39	2.00	2.97	4.51	6.95	10.82	16.94
675		0.67	0.80	1.00	1.33	1.84	2.65	3.93	5.97	9.19	14.30	22.4
700		0.88	**1.05**	**1.31**	**1.74**	2.41	3.47	5.15	7.81	12.03	18.72	29.3
725		1.14	**1.36**	**1.70**	**2.25**	3.12	4.49	6.67	10.12	15.60	24.27	38.0
750		1.47	**1.75**	**2.19**	**2.89**	4.01	5.77	8.57	13.01	20.04	31.19	48.8
775		1.87	**2.23**	**2.79**	**3.69**	5.11	7.36	10.93	16.58	25.55	39.76	62.3
800		2.36	2.82	3.53	4.66	6.46	9.31	13.82	20.98	32.31	50.28	78.8
825		2.97	3.54	4.43	5.86	8.11	11.69	17.36	26.34	40.58	63.14	98.9
850		3.70	4.41	5.53	7.31	10.12	14.58	21.65	32.85	50.61	78.75	123.3
875		4.59	5.46	6.85	9.05	12.54	18.07	26.83	40.71	62.72	97.59	152.8
900		5.65	6.73	8.44	11.15	15.45	22.26	33.05	50.15	77.25	120.2	

Theoretical FAC ppm - Free Available Chlorine
Typical Potable or Drinking Water System

Temp = 18 C, Conductivity = 250 uS/cm

	pH	7.00	7.20	7.40	7.60	7.80	8.00	8.20	8.40	8.60	8.80	9.00
ORP												
375		0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.05	0.07	0.11	.18
400		0.01	0.01	0.01	0.02	0.03	0.04	0.05	0.08	0.12	0.18	0.28
425		0.02	0.02	0.02	0.03	0.04	0.06	0.08	0.12	0.18	0.29	0.45
450		0.03	0.03	0.04	0.05	0.06	0.08	0.12	0.18	0.28	0.44	0.58
475		0.04	0.04	0.05	0.07	0.09	0.13	0.18	0.28	0.42	0.65	1.02
500		0.06	0.06	0.08	0.10	0.13	0.19	0.27	0.40	0.62	0.95	1.48
525		0.08	0.09	0.11	0.14	0.19	0.27	0.39	0.58	0.88	1.36	2.13
550		0.11	0.13	0.16	0.20	0.27	0.37	0.55	0.82	1.25	1.93	3.00
575		0.16	0.18	0.22	0.28	0.37	0.52	0.76	1.13	1.73	2.68	4.17
600		0.21	0.25	0.30	0.38	0.51	0.71	1.04	1.55	2.37	3.67	5.72
625		0.29	0.33	0.40	0.51	0.69	0.97	1.41	2.10	3.21	4.96	7.73
650		0.39	0.44	0.54	0.69	0.92	1.29	1.88	2.81	4.29	6.63	10.3
675		0.51	0.59	0.71	0.91	1.22	1.71	2.48	3.72	5.67	8.76	13.7
700		0.67	**0.77**	**0.93**	**1.19**	**1.59**	2.23	3.25	4.86	7.42	11.47	17.4
725		0.87	**1.00**	**1.21**	**1.54**	**2.06**	2.90	4.22	6.31	9.62	14.87	23.2
750		1.11	**1.28**	**1.55**	**1.98**	**2.65**	3.72	5.42	8.10	12.36	19.11	29.8
775		1.42	1.63	1.98	2.52	3.38	4.74	6.91	10.33	15.76	24.36	38.0
800		1.79	2.07	2.50	3.19	4.28	6.00	8.73	13.07	19.93	30.81	58.0
825		2.25	2.60	3.14	4.00	5.37	7.53	10.97	16.41	25.03	38.69	50.3
850		2.81	3.24	3.92	4.99	6.70	9.40	13.68	20.46	31.22	48.26	75.4
875		3.48	4.01	4.85	6.19	8.30	11.65	16.95	25.36	38.68	59.80	93.3
900		4.29	4.94	5.98	7.62	10.22	14.34	20.88	31.24	47.65	73.66	

Theoretical FAC ppm - Free Available Chlorine
Typical Cooling Tower Water System

Temp = 30 C, Conductivity = 1000 uS/cm.

	pH	7.00	7.20	7.40	7.60	7.80	8.00	8.20	8.40	8.60	8.80	9.00
ORP												
375		0.01	0.01	0.01	0.02	0.02	0.03	0.04	0.07	0.10	0.16	0.25
400		0.01	0.01	0.02	0.02	0.03	0.05	0.07	0.11	0.17	0.26	0.41
425		0.02	0.02	0.03	0.04	0.05	0.08	0.11	0.17	0.26	0.41	0.64
450		0.03	0.04	0.04	0.06	0.08	0.12	0.17	0.26	0.40	0.62	0.98
475		0.04	0.05	0.07	0.09	0.12	0.17	**0.26**	**0.39**	**0.60**	**0.93**	**1.46**
500		0.07	0.08	0.10	0.13	0.18	0.25	**0.37**	**0.57**	**0.87**	**1.36**	**2.13**
525		0.09	0.11	0.14	0.18	0.25	0.36	**0.54**	**0.81**	**1.25**	**1.95**	**3.06**
550		0.13	0.16	0.20	0.26	0.36	0.51	**0.76**	**1.15**	**1.77**	**2.75**	**4.31**
575		0.18	0.22	0.27	0.36	0.50	0.71	1.05	1.60	2.46	3.82	5.98
600		0.25	0.30	0.37	0.49	0.68	0.98	1.44	2.19	3.37	5.24	8.20
625		0.34	0.41	0.51	0.67	0.92	1.32	1.95	2.96	4.55	7.08	11.0
650		0.46	0.54	0.68	0.89	1.23	1.76	2.61	3.96	6.09	9.47	14.8
675		0.60	0.72	0.89	1.18	1.62	2.33	3.45	5.23	8.05	12.52	19.6
700		0.79	0.94	1.17	1.54	2.12	3.05	4.52	6.85	10.54	16.38	25.6
725		1.03	1.22	1.52	2.00	2.75	3.96	5.86	8.88	13.66	21.24	33.2
750		1.32	1.56	1.95	2.57	3.54	5.08	7.53	11.41	17.55	27.29	42.7
775		1.68	1.99	2.49	3.27	4.51	6.48	9.60	14.54	22.37	34.79	54.5
800		2.13	2.52	3.15	4.14	5.71	8.20	12.14	18.39	28.30	44.00	68.9
825		2.67	3.16	3.95	5.19	7.17	10.29	15.24	23.09	35.54	55.26	86.5
850		3.33	3.95	4.93	6.48	8.94	12.83	19.01	28.80	44.32	68.91	107.8
875		4.13	4.89	6.10	8.03	11.08	15.91	23.56	35.69	54.92	85.40	133.7
900		5.08	6.02	7.52	9.89	13.64	19.59	29.02	43.97	67.65	105.2	

