APPENDICES

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Appendix A: Water Treatment Terms and Abbreviations

Acidic: A solution having an excess of hydrogen (H^+) ions, and thus with a pH less than 7.0.
Adsorption: Non-permanent attachment of a particular molecule to a solid substrate
Advisory Alarm: A process alarm that alerts the operator to evaluate the condition of the system, without an automatic response.
Alkaline: A solution having an excess of hydroxyl (OH^-) ions, and thus with a pH greater than 7.0.
Alkalinity: A measure of the amount of HCO_3 present in water, generally expressed as an amount of $CaCO_3$ equivalent.
Anion: A negatively charged ion resulting from the dissociation of salts, minerals, or acids in water.
Antiscalant: A compound added to feed water to a membrane system to increase concentrations at which scalants will precipitate, increasing efficiency.

Biocide: A chemical preventing biological growth
Brine: (usually Concentrate) The stream into which ions or solids are concentrated.

CIP: Clean In Place
Clean In Place (CIP): Circulation of chemicals through the RO or EDI system to remove scale and fouling from the piping and stacks.
CIP Mode: The EDI operating mode in which the unit is undergoing the CIP procedure.
CMU: Concentrate Make-up.
Coagulant: A chemical added to water to aid in flocculation.
Co-Current Flow: Flow across and through a membrane where the feed/reject and permeate flow in the same direction and parallel to the membrane surface.
Composite Membrane: Membrane having two or more distinct layers.
Concentrate (RO): In reverse osmosis the retentate or reject not passing the membrane in which ions are at an increased concentration.
Concentrate Make-up (CMU): Portion of feed stream added to the concentrate recycle stream in order to control ionic concentrations in the concentrate stream.
Concentrate Recycle (CR): A method in which overall recovery is increased by re-using a fraction of the concentrate stream.
Concentrate Stream: Process stream flowing through the concentrating compartments of the membrane stack.

Concentration Factor: The amount of a given compound in the reject as a multiple of the amount in the feed stream.
CR: Concentrate Recycle
Critical Failure: A condition causing a process alarm that causes the unit to shut down immediately, because continued operation could cause damage to the equipment.
Cross Flow Filtration: Flow across and through a membrane where the feed/reject stream flows parallel to the membrane while the permeate stream flows perpendicular. The flow pattern reduces fouling on the media surface. Cross flow filtration necessitates a certain amount of the feed being lost to maintain flow.
Cross Leak: Hydraulic transfer of water between manifolds in the stack (from the demineralizing stream to the concentrate stream).

DCS: Distributed Control System
Deionization: The removal of ions by ion exchange processes.
Demineralize: To reduce the quantity of minerals or salts in an aqueous solution.
Distributed Control System: A centralized electronic monitoring and control system for unit operations.

ESD: Emergency Shutdown.

Feed (F): A water stream entering a unit treatment process.
Filtrate: Liquid exiting a filtration process with reduced content of solids or contaminants.
Flocculation: Gathering of many small particles into a larger conglomeration or floc. Often aided by coagulant addition.
Flux: A measure of the flow through a filter relative to the size of the media. Usually expressed in gallons per square foot per day or liters per square meter per hour.
Fouling: A phenomenon in which organic or other materials are deposited on a membrane and cause blockage.

gpm: Gallons per minute

Hardness: A measure of the amount of calcium and magnesium present in water.
HMI: Human Machine Interface
Human Machine Interface: A panel that allows interactive monitoring and control of system conditions and settings.
Hydraulic Staging: Multiple passes of water through a treatment system to provide additional treatment.

Ion: An electrically charged particle, with a positive or a negative charge, formed by the dissociation of a salt, mineral or acid in water.

Langelier Saturation Index (LSI): A measure of the tendency of water to dissolve or deposit calcium carbonate (scaling). The LSI is calculated from the total alkalinity, hardness, total dissolved solids (TDS), pH, and temperature of the water.
LSI: Langelier Saturation Index

Manifold: A flow path the feeds several other flow paths.
Man Machine Interface (MMI): See Human Machine Interface.
MCC: Motor Control Center
Membrane: A material allowing mass transfer of some compounds while rejecting other, which is constructed to allow separation of feed and a permeate streams.
mgd: Million gallons per day
Mho: A measure of conductance. The ratio of the current flowing through a conductor, measured in amperes, to the potential difference between the end to the conductor, measured in volts, is the conductance in mhos. A mho is a unit of conductance equal to the reciprocal of the ohm, expressed as amperes/volt.
Micromho (μmho): One millionth of a mho.
Microsiemens (μS): A measure of conductance equivalent to a micromho.
MMI: Man Machine Interface. See Human Machine Interface.
MOV: Motor Operated Valve

Non-Critical Failure: A process alarm condition which starts an orderly shut-down of the unit.
NTU: Nephelometric Turbidity Unit. A measurement of the turbidity (opacity) of water.

Off-Spec Product (OSP): Portion of product stream sent to the feed tank or waste tank for not meeting product quality standards.
OI: Operator Interface
O&M: Operation and Maintenance
Operator Interface: Also called Human Machine Interface or Man Machine Interface. A display or screen through which system conditions can be monitored and controlled.
OSP: Off-Spec Product.

Percent Recovery: The percent of feed water which becomes product water.
Permeate: Water flowing through a membrane, such as demineralized process stream leaving the RO unit.
PFD: Process Flow Diagram.
pH: The measure of the acidity or basicity of a solution, based on the concentration of hydrogen ions. pH values are expressed as numbers on a scale of 0 to 14. With values less than 7 acidic, and greater than 7 basic.
P&ID: Piping and Instrumentation Diagram
PLC: Programmable Logic Controller
POV: Pneumatically Operated Valve

Power Supply: A device that converts an AC input to a DC output.
ppm: Parts per million
Product: A treated water stream exiting a unit treatment process.
Programmable Logic Controller: Computer system used to record and manipulate unit conditions
psi: Pounds per square inch

Recovery: The amount of feed collected as product as a percent of the total feed.
Reject: Also called retentate. In reverse osmosis, the concentrated liquid not passing the membrane.
Rejection: The amount of a given compound or material in the reject as a percentage of the amount on the feed.
Retentate: See Reject
Reverse Osmosis (RO): A process using pressure to purify water by driving it through a semi-permeable membrane excluding selected components.
RO: Reverse Osmosis

SCADA: Supervisory Control and Data Acquisition
Scale: Precipitate of calcium carbonate or calcium sulfate.
Scaling: The formation of a precipitate on a surface in contact with water as the result of scale deposit.
Scfm: standard cubic feet per minute
SDI: Silt Density Index
Silt Density Index (SDI): A measure of particle density in water.
Solute: Material (such as salts) dissolved by a solvent (such as water).

TDS: Total Dissolved Solids
TMP: Trans Membrane Pressure
Total Dissolved Solids: The concentration of all solids dissolved in a solution (normally expressed in ppm).
Trans Membrane Pressure: The pressure drop across a filtration membrane.
Turbidity: The clarity of water.

Valve Test: The process in which the operation of motor operated valves may be manually tested.
VFD: Variable Frequency Drive

Water Softener: Cation resin in the sodium form the removes cations such as calcium and magnesium from the water, and releases sodium ions.

Appendix B: Forms and Data Sheets

The following pages present a number of log sheets and forms that are expected to be of use to monitor and record system operational information.

GE Water & Process Technologies

Reverse Osmosis Data Normalization

Parameters					
Date / time			Units	Instrument #	
RO Feed Water	Conductivity		µS/cm	AIT 1201	
	ORP		mvolts		
	SDI				
	pH		pH		
	Temperature		Deg F		
Machine Readings:	RO				
Run Time Meter	Elapsed Hours		Hrs		
Flows	Pressure Exchangers	Feed Water Inlet	gpm	FI 0902	
		Feed Water Outlet	gpm	FI 0903	
	RO	Reject	gpm	FIT 0904	
		Permeate	gpm	FIT 0901	
		Feed	gpm	Calculate	
Pressures	Pressure Exchangers	Feed Water Inlet	psig	PI 0901	
		Feed Water Outlet	psig	PI 0902	
		Reject Water Outlet	psig	PI 0901	
	RO	Feed	psig	PI 0902	
		Reject	psig	PI 0902	
		Permeate	psig	PI 0904	
Conductivity	Permeate		µS/cm	AIT 0901	

Comments / Adjustments Made

Appendix C: Scientific and Design Principles

The sections below outlined the scientific principles of operation for the technologies used in the water treatment system. Please keep in mind that these descriptions are general, and thus may not reflect the system as designed in all details.

The sections below cover the following processes in the water treatment system:

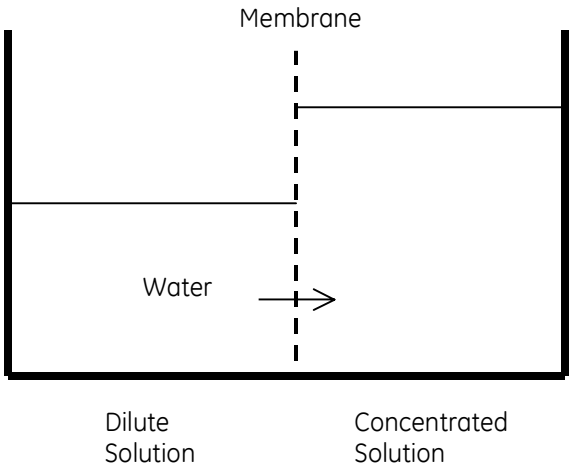
- Reverse osmosis.

Appendix C.1 Reverse Osmosis Principles

Reverse Osmosis (RO) is a process used to remove dissolved ions from water. In RO, Pressure forces the water through a semi-permeable membrane element. The. Thus the permeate water which has passed the membrane contains a relatively low concentration of ions compared to the reject (or concentrate) which contains all of the ions which did not pass the membrane in a reduced quantity of water.

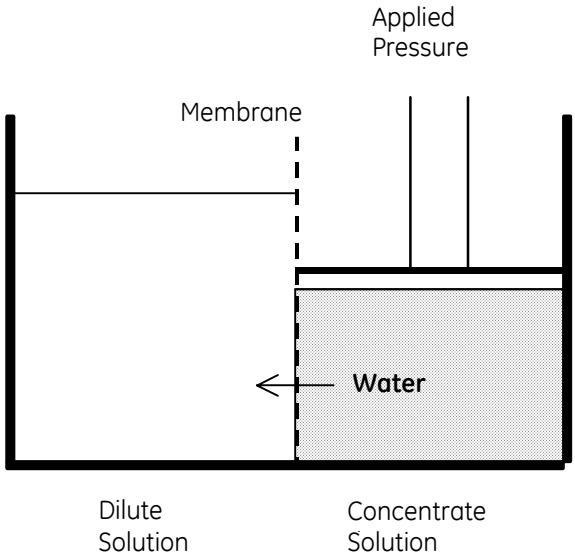
To understand reverse osmosis, the naturally occurring phenomenon of osmosis must be understood. Osmosis can be defined as the spontaneous passage of a liquid solvent from a dilute solution to a more concentrated solution across a semi-permeable membrane. The driving force behind this transfer is the osmotic pressure; osmotic pressure is higher the more concentrated a solution is, and water will flow into a more concentrated solution to reduce the osmotic pressure to a level equal to that in the less concentrated solution. The transfer of the solvent (water) but not the solutes (dissolved solids) will continue until the concentrations of the solution on both sides of the membrane are in equilibrium (the osmotic pressures are equal). The flow rate of the water is directly proportional to the concentrations of the two solutions. The osmotic pressure in one solution rises (water leaves and ions become more concentrated) while that in the other decreases. Osmosis is illustrated in Figure C-1.

Figure C-1: Osmosis



The osmotic pressure can be measured, and the resulting flow of solute from high low concentration to high can be halted by applying a pressure equal to the osmotic pressure on the side of the more concentrated solution. If this external pressure is increased further, the flow of water will be reversed from its natural flowing direction and towards the more dilute solution. The reversing of the flow is the process of **reverse osmosis**, and is illustrated in Figure C-2.

Figure C-2: Reverse Osmosis



For example, if a variable pressure (applied pressure P) were applied on the more concentrated solution side of a semi-permeable membrane element, the following conditions could be realized:

1. If P equals the osmotic pressure of the solution, the solvent flows at the same rate in both directions; i.e., there is no net change in water volumes. This condition represents the phenomenon of osmosis.
2. If P is greater than the osmotic pressure of the solution, the solvent flows from the more concentrated solution to the "pure" solvent side of the membrane. This condition represents the phenomenon of reverse osmosis. This is the process illustrated in Figure C-2.

There are many membrane elements that have good qualities of rejection (salt separation) allowing water to pass freely but limiting other compounds from passing. The main problem with the early membrane elements was that the water flow rate (flow per unit area) was very low at any reasonable pressure drop across the membrane element.

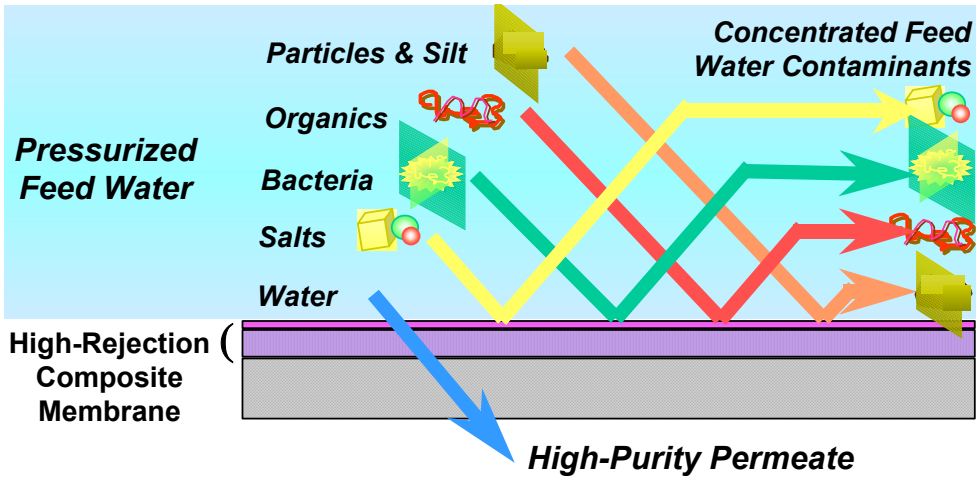
The breakthrough that made RO commercially feasible was the creation of an asymmetric cellulose acetate membrane element: one surface of the element having a dense but very thin layer of skin (0.2 micron thick), and the remainder being a relatively spongy porous mass. If this element was magnified many times its actual size, it would be seen that the initial pore size in the dense skin is very small.

The pore size increases greatly further away from the outer skin toward the spongy backing membrane. Thus, once a particle passes through the initial skin, there will be no

means for the particle to be trapped and plug the element. This dense skin serves as the rejecting surface (is located on the side of the concentrated solution), but since this layer is very thin, the resistance to flow is greatly reduced. Salt rejection takes place at or within a few molecules of the surface. Thus, the rejection characteristics are the same with a thin-skinned element as with a much thicker element. Through variation of manufacturing raw materials and process techniques, the properties of the element can be changed to suit the rejection requirements.

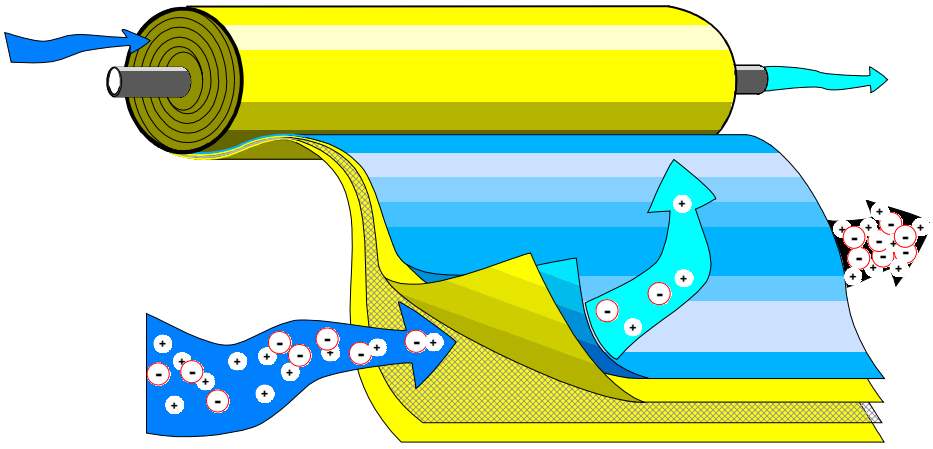
An Illustration of the operation of an RO membrane is given in Figure C-3.

Figure C-3: RO Membrane Cross-Section



The ability to process a significant volume of water is dependent on having a large amount of membrane surface area available for processing. One way of maximizing the amount of membrane surface area available for processing is by winding a membrane sheet around a cylindrical core, with the layers of membrane separated by feed and concentrate spacers providing flow channels. This arrangement is the spiral wound membrane that is the core of most RO plants. An illustration of a typical spiral wound RO membrane element is given as Figure C-4.

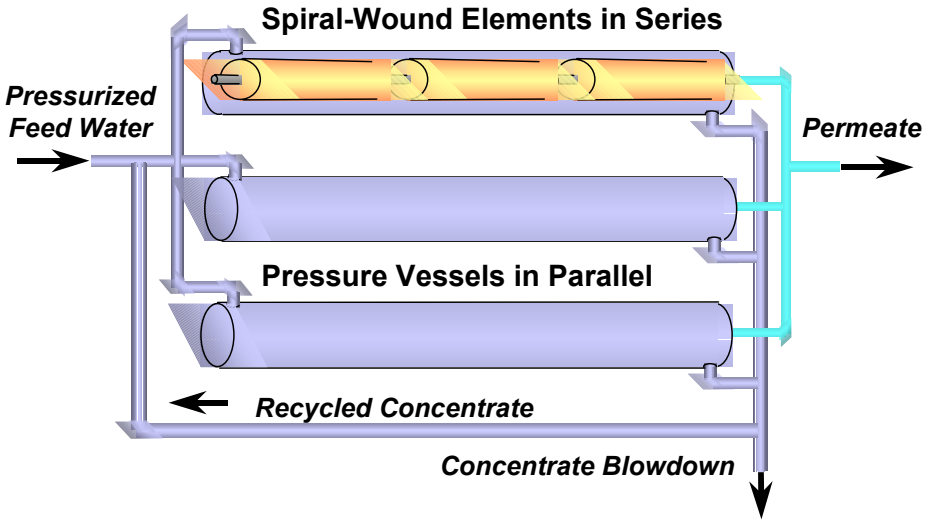
Figure C-4: RO Membrane Element



An RO system is composed of two major parts: the high-pressure pump, and the pressure tubes containing membrane elements. The supply water, pressurized by the pump, flows over the membrane elements, and the permeate (product) and reject (retentate) streams are collected separately.

Because feed water is at high pressure, the elements are contained in pressure vessels. A pressure vessel will typically contain 4 to 6 elements, and a number of pressure vessels are arranged in parallel to process the desired flow. The arrangement of membranes and vessels in an RO unit is shown in Figure C-5.

Figure C-5: RO System Arrangement

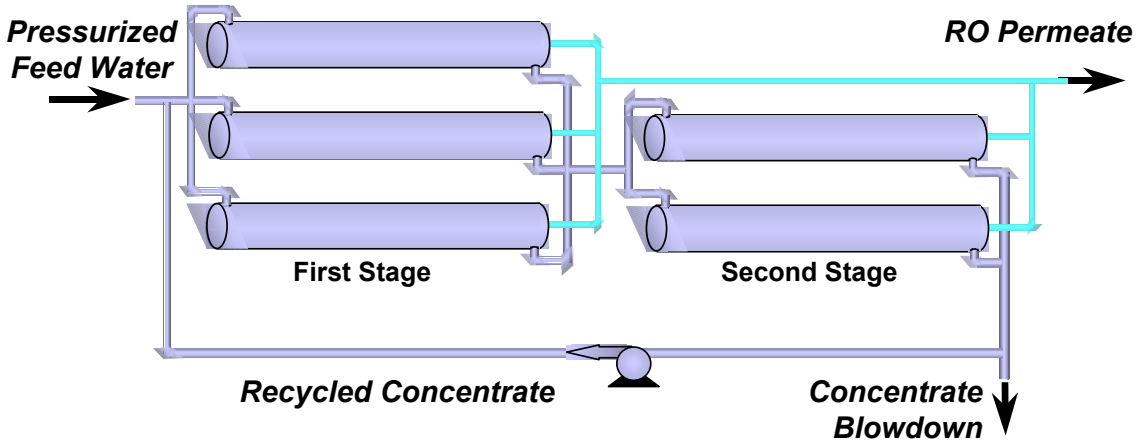


RO systems are typically designed with multiple passes and/or stages, as required to best meet product water requirements based on input water quality.

- Multiple passes are used when higher product water quality is required. In a multiple-pass system, the permeate from one pass (which has passed through the membrane) is used as higher quality feed for a subsequent pass. In multiple-pass systems, different pressures and RO membranes are typically used to optimize the system.
- Multiple stages are used to increase recovery within a pass, and do not typically have a significant effect on product water quality. In staging, the reject from the first stage feeds the second stage, and the second stage reject feeds the third stage (if present). Permeate from all stages is combined as product. Only the reject from the final stage is sent to waste.

An example of a single-pass system with two stages is given in Figure C-6.

Figure C-6: RO Staging



The RO system is carefully designed to make certain that minimum flow rates over the elements are maintained. This is critical to efficient RO operation. The reason for this is that as pure water passes through the element under pressure, it leaves a very high concentration of the supply water dissolved substances behind at the element surface. This phenomenon, where the water near the membrane is more highly concentrated than the bulk of the water, is called the boundary layer.

For example, if the water upstream of the element is 500 ppm, then the product water passing through the membrane will be about 2 ppm, while the water at the membrane surface will be about 510 ppm. A little further along the membrane, the water in contact with the membrane may be concentrated to 1,000 ppm, and the water passing through will be about 10 - 20 ppm.

By maintaining the water flow velocity across the element surface above a critical value, this concentrated boundary layer is kept at a minimum and high-quality product water can be produced. The other benefit of proper flow rates is that suspended matter tends to be carried out of the system more effectively. For these reasons, the design flow rates should not be changed except in the "safe" direction. The "safe" direction, in general, increases the concentrate flow and the water velocity, reducing the boundary layer.

It should be noted that the less concentrated the supply water is in the RO system, the better the quality of the product water. In other words, the lower the water recovery rate, the lower the concentration of the water in the system, and thus the better the product water quality (as long as the driving pressure is maintained). For some applications, the economic benefits of better quality product water far outweigh the extra cost of rejected water. An example of this is where RO water is further demineralized.

Antiscalants (acids and chemical antiscalants) and dispersants may be added to the RO feed stream to prevent the formation and nucleation of scales; dispersants prevent

scaling compounds from agglomerating together, while antiscalants artificially raise the saturation level for a scale.

Sodium bisulfite is often added to RO feed streams to remove residual chlorine. Most RO membranes are sensitive to the presence of chlorine and are damaged by high levels or continual contact with chlorine in the feed water.

Product water from RO systems often ahs a low pH. In many cases the product is pH adjusted with caustic prior to downstream processing or use.

RO membranes can become fouled or scaled in several ways:

- Certain ions have limited solubility when present in combination with each other, when their concentration is high enough, these salts can precipitate and scale RO membranes.
- Higher concentrations of ions in the reject stream can take certain species above their solubility limits, which will also result in fouling
- Because RO membranes are damaged by chlorine, it cannot be used as a disinfectant within the confines of the RO system. In some cases biological fouling may occur.

When RO system become fouled, they must be cleaned. The need for cleaning can be detected by reviewing pressure and water quality trends. The type of fouling that has occurred can be derived from the type of problems seen and knowledge of feed water characteristics. This cleaning is almost always achieved with a Clean In Place (CIP) procedure.

A typical CIP procedure is as follows:

1. The type of fouling and the appropriate chemical treatment is determined.
2. The chemical solution is mixed (and often heated to provide more effective cleaning) in a CIP tank.
3. The RO unit to be cleaned is taken off-line, and connections are made (if required) and valves set for CIP. Most units are cleaned one pass and stage at a time.
4. The RO solution is circulated from the CIP tank through the membranes in a closed loop.
5. The CIP solution is allowed to soak in the membranes for a time.
6. The CIP solution is rinsed form the membranes.
7. The procedure is repeated until all membrane are cleaned and the unit may be brought back on line.

RO systems offer the following advantages:

1. Flexibility: varying element sizes and membrane types allow the designer/end user to tailor a system to meet specific site water requirements.
2. Durability: RO element systems have proven to be operable after varying feed TDS, pH, and temperature conditions.
3. Energy efficiency: RO element systems can produce volumes of high quality water with low power input.
4. Water efficiency: RO systems run at high recovery rates. The system recovery rate is dependent upon feed water quality.

Appendix D: Calculations

The sections below present information on units, conversions, and calculations that may be used for system operation. The sections include:

- RO recovery calculations,
- LSI calculations,
- Chemical addition calculations,
- SBS mixing and addition,
- RO data normalization,
- CIP chemical use calculations, and
- Common units and conversions.

Appendix D.1 RO Recovery Calculations

RO membrane system performance calculations are made as follows:

Percent recovery is calculated as:

Percent Recovery = (Total Product Flow)/(Total Feed Flow) * 100

To make this calculation, divide the total product flow by the total feed flow, and then multiply by 100.

Example #1:

Product Flow Rate = 15 GPM
Total Feed Flow = 30 GPM (15 GPM Reject Flow)
Recovery = 15/30 * 100 = 50%

Example #2:

Product Flow Rate = 100 GPM
Total Feed Flow = 118 GPM (18 GPM Reject Flow Rate)
Recovery = 100/118 * 100 = 85%

Percent rejection is calculated as:

Percent Rejection = (1-(Product TDS/Feed TDS)) *100
Product TDS / Feed TDS = Decimal 1
1 - Decimal 1 = Decimal 2
Decimal 2 * 100 = Percent Rejection

Example #1:

Product TDS = 33, Feed TDS = 300
Decimal 1 = 33 / 300 = .11
Decimal 2 = 1 - Decimal 1 = .89
Percent Rejection = Decimal 2 * 100 = 89% Rejection

Example #2:

Product TDS = 28, Feed TDS = 300
Decimal 1 = 28 / 300 = .09
Decimal 2 = 1 - Decimal 1 = .91
Percent Rejection = Decimal 2 * 100 = 91% Rejection

RO reject concentration is calculated as:

Reject TDS = CF * Feed TDS
Concentration Factor (CF) = 1/(100% - Percent Recovery)

For all examples: Feed TDS = 100 ppm

Example #1:

Recovery = 50%
CF = 1 / (1.0 -0.5) = 2
Reject TDS = 2 * 100ppm = 200 ppm Reject Concentration

Example #2:

Recovery = 85%
CF = 1 / (1.0 -0.85) = 6.7
Reject TDS = 6.7 * 100ppm = 670 ppm Reject Concentration

Appendix D.2 SDSI Calculation

The Stiff and Davis Stability Index is used to determine the need for calcium carbonate scale control in the operation and design of reverse osmosis installations. This practice is applicable for concentrate streams containing more than 10,000 mg/L of total dissolved solids.

This index is used in preference to the LSI, which is inaccurate for concentrate due to high TDS and common ion effects.

To calculate the SDSI, ASTM Method D4582-91 is used, which is available under licnse from ASTM.

Appendix D.3 Chemical Addition Calculations

The equations below may be used to calculate volumes or weights for chemical solution mixing and addition. For greatest accuracy, control, and monitoring of chemical solutions, the user should calculate and measure chemical dosing rates in milliliters per minute, not gallons per day.

There are two key aspects in making chemical addition calculations:

1. Calculating the amount of concentrated chemical to be added to water to form a solution of the correct strength, and
2. Calculating the amount of solution to be dosed to the process flow to achieve the required dosing concentration.

Both of these is detailed below.

Appendix D.3.1 Chemical Solution Calculations

In most cases, chemicals that are used in water treatment systems are delivered to the site as concentrated solutions and then diluted to a working solution in a day tank prior to dosing to the process. A dilute solution is preferable for dosing because dosing rates tend to be relatively low, and when a concentrated solution is used, very small errors in dosing rates can lead to very large differences in dosed concentration.

The concentration of chemical solutions can be measured in several ways, as weight/weight weight/volume, or as volume/volume. In order to make accurate calculations it is necessary to understand which basis is being considered. The reason this difference is important is because different chemicals have different densities (specific gravities). Water has a specific gravity of 1.0, a specific gravity of less than 1 indicates a materials less dense than water, while a specific gravity greater than indicates a material more dense than water. For example, percentage compositions a "5.25% NaOCl" solution (sodium hypochlorite, bleach) may mean any of the following:

Measure	Interpretation for "5.25% NaOCl"	Notation
mass/mass	5.25 g of NaOCl dissolved in every 100 g of solution	5.25 (w/w)% NaOCl
mass/volume	5.25 g of NaOCl are dissolved in every 100 mL of solution	5.25 g NaOCl/100 mL solution
volume/volume	5.25 mL of NaOCl are dissolved in every 100 mL of solution	5.25 (v/v)% NaOCl

For dilute solutions around room temperature, mass and mass/volume percentages agree to two or three figures, when the latter is expressed in g/mL. Volume percentages are convenient for liquid or gaseous solutes. In accurate work you must always specify which type of percentage is being used: the three are not equivalent. It's best to avoid mass/volume percentages entirely.

At low concentrations, the difference in specific gravity between a compound and the water it is mixed into is negligible, but at higher concentrations it becomes important. For example a chemical with a specific gravity of 1.5, 1 gallon of 100% solution weighs 12.5 pounds (compared to 8.33 lb/gallon for water), a 50% by volume solution weighs 10.4 lb/gal, a 10% by volume solution weighs 8.75 lb/gal, and a 1% by volume solution weighs 8.37 lb/gal (only 0.5% more than a 100% water solution.

The same example can be used to show the difference between wt% (percent composition by weight) and vol% (percent composition by volume). The example above is vol%. The same composition as above in wt% would compare as follows: a 50% solution by weight of the example chemical would be 40% chemical by volume (60% water), a 10% solution by weight would be 6.9% by volume, and 1% by weight would be 0.67% by volume.

At higher chemical concentrations, wt% is most commonly used, but vol% may also be used, at lower concentrations ppm is usually used. Unless otherwise specified ppm is mg/l.

The quick way to convert from wt% to ppm is by the dilution factor method. Think of percentages as 'parts per hundred' and one part per hundred is 10,000 parts per million.

For example to create 10 liters of a 200 ppm solution from 5.25% bleach (sodium hypochlorite). You must dilute some of the bleach by adding water to it. If we rephrase the question we ask how much bleach (5.25% NaOCl) should be diluted to 1000 mL to make a 200 ppm NaOCl solution.

Since you know that the bleach solution is 5.25% NaOCl, there is 5.25 g of NaOCl in each in 100 g (total) of solution. Since you want 200 ppm NaOCl, that translates to 0.02%, or for 10,000 ml (10 liters) 2 grams total (10,000 grams x 200/1,000,000 grams/gram).

Because it is a dilute solution, we can ignore the specific gravity. So you will need 38 ml of bleach (2 grams * / (5.25 gm/100 ml) diluted to 10 liters with water.

If you have some doubt about your calculations, look at the problem using different logic. The next best way is to see if the answer is consistent with the given information.

Appendix D.3.2 Chemical Dosing Calculations

The first step is to convert flow rate from gallons per minute to milliliters (ml) per minute. The formula for conversion is:

Feed Flow in gallons per minute (gpm) x 3,785 ml /gal. = ml/min.

Since solutions and water are typically expressed and measured by volume (in gallons or liters), not weight, the user must understand that:

- Water weighs 8.33 lbs/gal,
- A chemical solution weighs (8.33 * specific gravity) lbs./gal., and
- Gallons x 3785 = milliliters (ml).

A dilution equation is used to determine the amount in volume of chemical solution to chemically inject on a milliliter per day basis. For example, if a solution with a specific gravity of 1.1 is added:

Feed Flow (GPD)	x 8.33 lbs/gal. x 1,000,000 gals.	2 ppm x 3785 ml/gal 9.16 lbs/gal	= flow of concentrated Hypersperse (ml/day)

Example: For 1000 GPD of feed water,

1000 GPD	x 8.33 lbs/gal. x 1000,000	2 ppm x 3785 ml/gal 9.6 lbs/gal.
= 6.57 ml of	Hypersperse/day	

The user must understand that there are 1440 minutes in a day, so to convert Gallons per Minute (GPM) to Gallons per Day (GPD), multiply by 1440. Likewise, to convert GPD to GPM, divide by 1440.

Appendix D.4 SBS Mixing and Addition

Sodium bisulfite is used in many RO systems as a pretreatment chemical to remove residual chlorine. It is also used as a preservative to protect membranes when the system is out of service for a significant period of time. The section below presents information to mix 1% SBS solutions for membrane storage as well as 5% or 10% solutions for chemical addition. All solutions are calculated on a by weight basis

Fluid Systems recommends a 1.0 to 1.5 wt% solution of metabisulfite (sodium metabisulfite) at a pH of 4 for membrane storage. This will serve the same anti-oxidant role as the 1.0% SBS solution, and either is suitable for the supplied membranes. Solution mixing for sodium metabisulfite may be calculated using the information presented above.

Table D-1 gives amounts for addition of dry bisulfite to water to form 1%, 5% and 10% storage solutions. To get the required volume of solution, measure the indicated amount of bisulfite, add water, and mix until the volume is reached.

Table D-1: Storage Solution from Dry Bisulfite

Solution Required (gal)	For 1% Solution, Bisulfite (lb)	For 5% Solution, Bisulfite (lb)	For 10% Solution, Bisulfite (lb)
1	0.09	0.43	0.89
2	0.18	0.86	1.78
3	0.27	1.29	2.68
4	0.36	1.73	3.57
5	0.45	2.16	4.46
10	0.89	4.31	8.92
15	1.34	6.47	13.38
20	1.78	8.63	17.84
25	2.23	10.78	22.30
30	2.68	12.94	26.76
35	3.12	15.10	31.22
40	3.57	17.26	35.68
45	4.01	19.41	40.14
50	4.46	21.57	44.60
55	4.91	23.73	49.06
60	5.35	25.88	53.52
65	5.80	28.04	57.98
70	6.24	30.20	62.44
75	6.69	32.35	66.90
80	7.14	34.51	71.36
85	7.58	36.67	75.82
90	8.03	38.82	80.28
95	8.47	40.98	84.74
100	8.92	43.14	89.20

Table D-2 gives the amount of concentrated bisulfite solution (25%) to add to water to make 1%, 5%, and 10% solutions by weight. This solution cannot be diluted by volume (adding one part to four parts for 5% solution) because the density changes significantly during dilution. (Diluting by volume assumes that the density stays about the same.) The following chart takes this change into account.

Table D-2: Solutions from 25% Bisulfite

Volume of Solution (gal)	1% Bisulfite Solution		5% Bisulfite Solution		10% Bisulfite Solution	
	(gal)	(ml)	(gal)	(ml)	(gal)	(ml)
1	0.034	129	0.17	643	0.36	1360
2	0.068	257	0.35	1330	0.72	2730
4	0.136	515	0.70	2650	1.44	5450
5	0.170	643	0.87	3290	1.81	6850
10	0.341	1290	1.75	6620	3.61	13700
15	0.511	1930	2.62	9170	5.42	20500
20	0.682	2580	3.49	13200	7.22	27300
25	0.852	3230	4.37	16500	9.03	34200
30	1.02	3860	5.24	19800	10.84	41000
35	1.19	4504	6.11	23100	12.64	4780
40	1.36	5150	6.99	26500	14.45	54700
45	1.53	8860	7.86	29800	16.25	61500
50	1.70	6430	8.73	33000	18.06	68400

Table D-3 gives the injection rates for sodium bisulfite solutions of 5% and 10% to achieve a 2 ppm concentration in process water (before reaction). The specific gravity of the 5% solution is 1.035 and the specific gravity of the 10%solution is 1.07.

Table D-3: Sodium Bisulfate Injection Rates for 2 ppm

Feed Flow (gpm)	5% Bisulfite Solution (wt)		10% Bisulfite Solution (wt)	
	Volume (gpd)	Volume (ml/min)	Volume (gpd)	Volume (ml/min)
5	0.28	0.7	0.13	0.4
10	0.56	1.5	0.27	0.7
20	1.1	2.9	0.54	1.4
30	1.67	4.4	0.81	2.1
40	2.23	5.9	1.08	2.8
50	2.78	7.3	1.35	3.5
60	3.34	8.8	1.61	4.2
70	3.90	10.2	1.88	5.0
80	4.45	11.7	2.15	5.7
90	5.01	13.2	2.42	6.4
100	5.57	14.6	2.69	7.1
110	6.12	16.1	2.96	7.8
120	6.68	17.6	3.23	8.5
130	7.23	19.0	3.50	9.2
140	7.79	20.5	3.77	9.9
150	8.35	21.9	4.04	10.6
160	8.90	23.4	4.31	11.3
170	9.46	24.9	4.58	12.0
180	10.02	26.3	4.84	12.7
190	1057	27.8	5.11	13.4
200	11.13	29.3	5.38	14.1
210	11.69	30.7	5.65	14.9
220	12.24	32.2	5.92	15.6
230	12.8	33.6	6.19	16.3
240	13.36	35.1	6.46	17.0
250	13.91	36.6	6.73	17.7
300	16.7	43.9	8.07	21.2
350	19.48	51.2	9.42	24.8
400	22.26	58.5	10.77	28.3
450	25.04	65.8	12.11	31.8
500	27.83	73.1	13.46	35.4

Table D-4 gives the injections rates for sodium bisulfite solutions of 5% and 10% to achieve a 3 ppm concentration (before reaction). The specific gravity of the 5% solution is 1.035 and the specific gravity of the 10%solution is 1.07.

Table D-4: Sodium Bisulfate Injection Rates for 3 ppm

Feed Flow (gpm)	5% Bisulfite Solution (wt)		10% Bisulfite Solution (wt)	
	Volume (gpd)	Volume (ml/min)	Volume (gpd)	Volume (ml/min)
5	0.42	1.1	0.20	0.5
10	0.83	2.2	0.40	1.1
20	1.67	4.4	0.81	2.1
30	2.50	6.6	1.21	3.2
40	3.34	8.8	1.61	4.2
50	4.17	11.0	2.02	5.3
60	5.01	13.2	2.42	6.4
70	5.84	15.4	2.83	7.4
80	6.68	17.6	3.23	8.5
90	7.51	19.7	3.63	9.6
100	8.35	21.9	4.04	10.6
110	9.18	24.1	4.44	11.7
120	10.02	26.3	4.84	12.7
130	10.85	28.5	5.25	13.8
140	11.69	30.7	5.65	14.9
150	12.52	32.9	6.06	15.9
160	13.36	35.1	6.46	17.0
170	14.19	37.3	6.86	18.0
180	15.03	39.5	7.27	19.1
190	15.86	41.7	7.67	20.2
200	16.7	43.9	8.07	21.2
210	17.53	46.1	8.48	22.3
220	18.37	48.3	8.88	23.3
230	19.2	50.5	9.29	24.4
240	20.03	52.7	9.69	25.5
250	20.87	54.9	10.09	26.5
300	25.04	65.8	12.11	31.8
350	29.22	76.8	14.13	37.1
400	33.39	87.8	16.15	42.4
450	37.57	98.7	18.17	47.8
500	41.74	109.7	20.19	53.1

Appendix D.5 RO Data Normalization

The operation and performance of RO systems will vary as the feed quality changes. In addition, as RO systems operate they will eventually become fouled with deposited material that may include precipitated compounds, particulates, or biological foulants. In order to understand that changes in system performance and attribute them to feed changes or to fouling, operational data is normalized. This can be done by hand, but is more easily accomplished using a data normalization program.

The majority of Reverse Osmosis (RO) systems normally will operate with consistent results over long periods of time if operating parameters (particularly feed quality) remain constant. Fouling does not occur or occurs slowly, and membrane damage is avoided.

When operating parameters (e.g. temperature, feed TDS, permeate flow, recovery) change or fluctuate, fouling of the membrane and element feed paths can occur. Data normalization is a technique that allows the user to compare operations under different conditions to a reference set of conditions. This allows the user to determine whether changes in flow or rejection are caused by fouling, damage to the membranes, or are just due to different operating conditions.

Appendix D.5.1 Performance Calculations

The calculations for RO performance monitoring are outlined below. For long-term use we recommend placing the data and equations into a spreadsheet and using the graphing capabilities to visually track performance.

Table D-5: RO Performance Tracking Data Points

Point	Units	Abbreviation	Sample Data Startup	Sample Data Now
Time	Hrs	---	241	250
Temperature	C	---	16	12
Feed Pressure	Psi	P_f	230	270
Feed Conductivity	µS/cm	K_f	500	550
Feed Flow	Gpm	Q_f	133	138
Reject Pressure	Psi	P_b	200	330
Reject Conductivity	µS/cm	K_b	2000	2200
Reject Flow	Gpm	Q_b	33	33
Permeate Pressure	Psi	P_p	20	20
Permeate Conductivity	µS/cm	K_p	8.5	9.5
Permeate Flow	Gpm	Q_p	100	105

Table D-6: RO Performance Tracking Calculations

Calculation	Equation	Sample Data Startup	Sample Data Now
Recovery (Y%)	Y% (Q_p/Q_r) * 100	75.2	76.1
Rejection (R%)	R = (1 – ((K_p*k_{TDS}) / (K_f*k_{TDS})))*100	98.3	98.3
Salt Passage (SP%)	SP = (K_p*k_{TDS} / (K_f*k_{TDS}) * 100	1.70	1.73
Differential Pressure (dP)	DP = P_f - P_b	30	50
Transmembrane Pressure (TPD)	TPD = P_f - P_p	210	250
Concentration Factor (CF)	CF = (1 / (1 – Y))	4.0	4.2
Mean Concentration Factor (CFM)	CFM = ln (1 / (1 – Y))/Y	1.85	1.88
Feed/Brine Concentration (C_{FB})	C_{FB} = C_r * CFM	927	1034
Brine Stream Concentration (C_b)	C_b = C_f/(1-Y)	2016	2301
Feed/Brine Osmotic Pressure (π_{fb})	π_{fb} = C_{FB}/k_π	9.3	10.3
Net Driving Pressure (NDP)	NDP = (P_f – P_p – ((P_f – P_b)/2) - π_{fb}	185.7	215.7
NOTE: Sea Water conductivity to TDS correction constant k_{TDS} = 0.50 Brackish Water conductivity to TDS correction constant k_{TDS} = 0.65 Sea Water Osmotic Pressure Constant k_π = 95 Brackish Water Osmotic Pressure Constant k_π = 100			

Table D-7: RO Performance Tracking Normalization Equations

Calculation	Sample Data Now
Temperature Correction Factor (TCF)	TCF Toray < 25 °C = exp (0.0372)(T-25) TCF Toray > 25 °C = exp (0.0343)(T-25) TCF Hydranautics < 25 °C = 0.35 + (0.026*T) TCF Hydranautics > 25 °C = exp 2640(1/298-1/(T+273))
Flow Rate (Q_N)	Q_N = [$(Q_p)_t$ * $(NDP)_i$ / $(NDP)_t$ * $(TCF)_i$ / $(TCF)_t$]
Salt Passage (SP_N)	SP_N = [$(SP\%)_t$ * $(NDP)_t$ / $(NDP)_i$]
Differential Pressure (dP_N)	DP_N = [dP * $(Q_p)_i$ / $(Q_p)_t$ * TCF]

Appendix D.5.2 Change in Apparent Membrane Performance

Changes in operating parameters will have a normal effect on membrane performance. These influences can result in either an apparent reduction of permeate flow or of quality. This section will enumerate those effects that normally affect membrane performance.

If a loss in permeate flow is observed, it may be caused by the following changes in operating parameters:

- A decrease in feed water temperature with no change in feed pump pressure.

- A decrease in RO feed pressure by throttling down the feed valve.
- An increase in permeate back pressure with no change in feed pump pressure.
- An increase in the feed TDS (or conductivity) since this increases the osmotic pressure that has to be overcome to permeate water through the membrane.
- An increase in the system recovery rate. This increases the average feed/concentrate TDS, which then increases the osmotic pressure.
- Fouling of the membrane surface.
- Fouling of the feed spacer that results in an increase of feed-to-concentrate pressure drop (delta P) which starves the back-end of the system of net driving pressure (NDP) to produce permeate water.

If a loss of permeate water quality is observed, it may be caused by the following changes in operating parameters. The water quality can be monitored as an increase in permeate TDS as ppm or conductivity:

- An increase in feed water temperature with the system adjusted to maintain the same permeate flow (or flux).
- A decrease in the system permeate flow, which reduces the water flux, and results in less permeate water to dilute the amount of salts that have passed through the membrane.
- An increase in the feed TDS (or conductivity) since the RO will always reject a set percentage of the salts.
- An increase in the system recovery rate since this increases the average feed/concentrate TDS of the system.
- Fouling of the membrane surface.
- Damaged o-rings seals.
- Damage to the membrane surface (such as exposure to chlorine) which allows more salts to pass.

Use of data normalization “factors out” the effects of changing feed pressure, concentration, and temperature. Factors related to fouling, degradation, or systemic factors (ie, blown o-rings) can thus be more clearly discerned. Normalized data that is graphed will show not only the instantaneous condition of the RO system at any given time, but also shows the detailed operating history.

These graphs can be a useful tool for troubleshooting.

Appendix D.5.3 Normalization Data

The normalized data graphs that may be of use include:

- Normalized Salt Passage vs. Time: This graph plots the normalized percent salt passage of the system relative to the System Reference Data at start-up.
- Normalized Permeate Flow vs Time: This graph plots the normalized permeate flow in gpm or m 3 /hr, relative to the System Reference Data at start-up.
- Salt Transport Coefficient vs. Time: This graph plots Salt Transport Coefficient (STC) for "membrane technophiles". The importance of this number is that it measures the efficiency of the membrane in how fast it allows the passage of salts. The value is reported as m/sec (meters per second). This number allows the comparison of membranes from site to site, independent of what the on-site operating conditions are. This number will be affected by changes in the ionic makeup of the feed water. For example, an increase in divalent ions (like hardness or sulfate) will result in a lower Salt Transport Coefficient.
- Water Transport Coefficient vs. Time: This graph plots the Water Transport Coefficient (WTC) for "membrane technophiles". The importance of this number is that it measures the efficiency of the membrane in how fast it allows the passage of water. The value is reported as m/sec-kPa (meters per second per kilopascal). This number allows the comparison of membranes from site-to-site, independent of what the on-site operating conditions are.
- Normalized Delta P vs. Time: This graph plots the normalized feed-to-concentrate pressure drop in PSI or Bar relative to the System Reference Data at start-up. The normalized Delta P value reflects adjustments to pressure drop due to varying feed and concentrate flows.

Appendix D.6 RO CIP Chemical Use Calculations

The sections below detail the calculation of the amounts of chemical to be used in CIP procedures.

The total volume of chemical solution required depends on the water volume in the portion of the system being cleaned. Because each system is different, some calculations will be required.

The total volume of liquid in the RO unit is derived as follows:

$$V_t = V_s + V_p + A$$

Where:

V_t = Total volume of liquid in the membranes (liters),

V_s = Volume of water in the membrane housings (liters),
V_p = Volume of water in the piping (liters),
A = The amount of hydrochloric acid (38%) to create a 5% solution (liters).

The liquid volume in the piping is completely dependent on the configuration of the unit as installed. The volumes in are given Table D-8 to aid in calculating total piping volume. To calculate the piping volume, sum the volumes for the lengths of piping of various sizes. Frequently, small size piping does not contain significant volume and can be included with a single allowance.

Table D-8: Pipe Volume Calculations

Pipe Size	Volume (liters/foot)
1"	0.155
1 ½"	0.348
2"	0.617
2 ½"	0.965
3"	1.39
4"	2.47
6"	5.56
8"	9.88

Appendix D.6.1 Derivation of Hydrochloric Acid Quantity

The amount of hydrochloric acid (HCl) required for CIP is derived from the total volume of liquid in the RO unit and the concentration of the HCl solution available. Hydrochloric acid is typically added as a 38% wt solution.

We know that a 5% solution contains 50 grams/liter hydrochloric acid and a 38% solution contains 450 grams/liter hydrochloric acid (not 380 due to differences in density). Therefore,

$$A = (50/450)\, V_t$$

Since the equation is iterative in that V_t depends on A and A depends on V_t, we solve the equations for A, resulting in:

$$A = 0.125\, (Vs + Vp)$$

Appendix D.6.2 Derivation of NaCl Quantities

NaCl is added to form a 100 gram per liter solution. Because the NaCl is solid, and will dissolve in the liquid to make the required solution the calculations do not need to include the volume of NaCl added. NaCl is added as a pure solid.

The mass of NaCl added in kilograms needed to create a 100 gram per liter solution is thus calculated as follows:

$$S = (100/1000)\, V_t$$

Where:

S = Mass of NaCl added (grams)

Appendix D.6.3 Derivation of Chlorine Quantities

Chlorine is added as a liquid to obtain a 200 ppm chlorine solution. Although the added chlorine will increase the total volume in the unit, the amount added is very small relative to the total volume and can be ignored. Chlorine is added as a 5.25% bleach solution.

We know that a 200 ppm solution contains 0.2 grams/liter chlorine and a 5.25% solution contains 52.5 grams/liter chlorine. Therefore, the amount of chlorine added in milliliters to create a 200 ppm solution is thus calculated as follows:

$$C = (0.2/52.5)\, V_t$$

Where:

C = Amount of 5.25% chlorine solution added (milliliters).

Appendix D.7 Units and Conversions

The sections below provide a brief summary of major units in various measurement systems, and a conversion table providing conversion factors between major units.

Appendix D.7.1 Metric System

Basic measures in the metric system and their relationships are outlined in the tables below.

Table D-9: Metric Length and Area Measures

Length	Area
10 millimeters = 1 centimeter	100 sq. mm = 1 sq. cm
10 centimeters = 1 decimeter	10,000 sq. cm = 1 sq. meter
10 decimeters = 1 meter	100 sq. meters = 1 are
10 meters = 1 decameter	100 ares = 1 hectare
10 decameters = 1 hectometer	10,000 sq. meters = 1 hectare
10 hectometers = 1 kilometer	100 hectares = 1 sq. kilometer
1000 meters = 1 kilometer	1,000,000 sq. meters = 1 sq. kilometer

Table D-10: Metric Volume and Capacity Measures

Volume	Capacity
1000 cu. mm = 1 cu. cm	10 milliliters = 1 centiliter
1000 cu. cm = 1 cu. decimeter	10 centiliters = 1 deciliter
1000 cu. dm = 1 cu. meter	10 deciliters = 1 liter
1000 liters = 1 cu. meter	
1 million cu. cm = 1 cu. meter	

Table D-11: Metric Mass Measures

Mass
1000 grams = 1 kilogram
1000 kilograms = 1 tonne

Appendix D.7.2 The US System of Measurements

Most of the US system of measurements is the same as that for the UK. The biggest differences to be noted are in capacity, where there are both liquid and dry measures as well as being based on a different standard - the US liquid gallon is smaller than the UK gallon. There is also a measurement known at the US survey foot. It is gradually being phased out as the maps and land plans are re-drawn under metrication. (The changeover is being made by putting 39.37 US survey feet = 12 meters)

Table D-12: US Length and Area Measures

Length	Area
12 inches = 1 foot	144 sq. inches = 1 square foot
3 feet = 1 yard	9 sq. feet = 1 square yard
5280 feet = 1 mile	4840 sq. yards = 1 acre
1760 yards = 1 mile	640 acres = 1 square mile

Table D-13: US Volume and Capacity Measures

Volume	Capacity (Dry)	Capacity (Liquid)
1728 cu. inches = 1 cubic foot	16 fluid ounces = 1 pint	2 pints = 1 quart
27 cu. feet = 1 cubic yard	2 pints = 1 quart	4 quarts = 1 gallon (8 pints)

Table D-14: US Mass Measures

Mass
16 ounces = 1 pound
2000 pounds = 1 ton

Appendix D.7.3 The UK (Imperial) System of Measurements

The old Imperial (now UK) system was originally defined by three standard measures - the yard, the pound and the gallon, which were held in London. They are now defined by reference to the S I measures of the meter, the kilogram and the liter. These equivalent measures are exact.

- 1 yard = 0.9144 meters - same as US
- 1 pound = 0.453 592 37 kilograms - same as US
- 1 gallon = 4.546 09 liters

Note particularly that the UK gallon is a different size to the US gallon so that NO liquid measures of the same name are the same size in the UK and US systems. Also that the ton (UK) is 2240 pounds while a ton (US) is 2000 pounds. These are also referred to as a long ton and short ton respectively.

Table D-15: UK (Imperial) Length and Area Measures

Length	Area
12 inches = 1 foot	144 sq. inches = 1 square foot
3 feet = 1 yard	9 sq. feet = 1 square yard
5280 feet = 1 mile	4840 sq. yards = 1 acre
1760 yards = 1 mile	640 acres = 1 square mile

Table D-16: UK (Imperial) Volume and Capacity Measures

Capacity	Volume
20 fluid ounces = 1 pint	1728 cu. inches = 1 cubic foot
4 gills = 1 pint	27 cu. feet = 1 cubic yard
2 pints = 1 quart	
4 quarts = 1 gallon (8 pints)	

Table D-17: UK (Imperial) Mass Measures

Mass (Avoirdupois)
16 ounces = 1 pound
14 pounds = 1 stone
8 stones = 1 hundredweight [cwt]
20 cwt = 1 ton (2240 pounds)

Appendix D.7.4 Conversion Factors

Summary table of conversion factors most often required.

Table D-18: Conversion Factors

To change	into	do this	To change	into	do this
acres	hectares	x 0.4047	kilograms	ounces	x 35.3
acres	sq. kilometers	/ 247	kilograms	pounds	x 2.2046
acres	sq. meters	x 4047	kilograms	tonnes	/ 1000
acres	sq. miles	/ 640	kilograms	tons (UK/long)	/ 1016

To change	into	do this	To change	into	do this
barrels (oil)	cu.meters	/ 6.29	kilograms	tons (US/short)	/ 907
barrels (oil)	gallons (UK)	x 34.97	kilometers	meters	x 1000
barrels (oil)	gallons (US)	x 42	kilometers	miles	x 0.6214
barrels (oil)	liters	x 159	liters	cu.inches	x 61.02
centimeters	feet	/ 30.48	liters	gallons (UK)	x 0.2200
centimeters	inches	/ 2.54	liters	gallons (US)	x 0.2642
centimeters	meters	/ 100	liters	pints (UK)	x 1.760
centimeters	millimeters	x 10	liters	pints (US liquid)	x 2.113
cubic cm	cubic inches	x 0.06102	meters	yards	/ 0.9144
cubic cm	liters	/ 1000	meters	centimeters	x 100
cubic cm	milliliters	x 1	miles	kilometers	x 1.609
cubic feet	cubic inches	x 1728	millimeters	inches	/ 25.4
cubic feet	cubic meters	x 0.0283	ounces	grams	x 28.35
cubic feet	cubic yards	/ 27	pints (UK)	liters	x 0.5683
cubic feet	gallons (UK)	x 6.229	pints (UK)	pints (US liquid)	x 1.201
cubic feet	gallons (US)	x 7.481	pints (US liquid)	liters	x 0.4732
cubic feet	liters	x 28.32	pints (US liquid)	pints (UK)	x 0.8327
cubic inches	cubic cm	x 16.39	pounds	kilograms	x 0.4536
cubic inches	liters	x 0.01639	pounds	ounces	x 16
cubic meters	cubic feet	x 35.31	square cm	sq. inches	x 0.1550
feet	centimeters	x 30.48	square feet	sq. inches	x 144
feet	meters	x 0.3048	square feet	sq. meters	x 0.0929
feet	yards	/ 3	square inches	square cm	x 6.4516
fl.ounces (UK)	fl.ounces (US)	x 0.961	square inches	square feet	/ 144
fl.ounces (UK)	milliliters	x 28.41	square km	acres	x 247
fl.ounces (US)	fl.ounces (UK)	x 1.041	square km	hectares	x 100 #
fl.ounces (US)	milliliters	x 29.57	square km	square miles	x 0.3861
gallons	pints	x 8	square meters	acres	/ 4047
gallons (UK)	cubic feet	x 0.1605	square meters	hectares	/ 10 000
gallons (UK)	gallons (US)	x 1.2009	square meters	square feet	x 10.76
gallons (UK)	liters	x 4.54609	square meters	square yards	x 1.196
gallons (US)	cubic feet	x 0.1337	square miles	acres	x 640
gallons (US)	gallons (UK)	x 0.8327	square miles	hectares	x 259
gallons (US)	liters	x 3.785	square miles	square km	x 2.590
grams	kilograms	/ 1000	square yards	square meters	/ 1.196
grams	ounces	/ 28.35	tonnes	kilograms	x 1000
hectares	acres	x 2.471	tonnes	tons (UK/long)	x 0.9842
hectares	square km	/ 100	tonnes	tons (US/short)	x 1.1023
hectares	square meters	x 10000	tons (UK/long)	kilograms	x 1016
hectares	square miles	/ 259	tons (US/short)	kilograms	x 907.2

To change	into	do this	To change	into	do this
hectares	square yards	x 11 960	tons (UK/long)	tonnes	x 1.016
inches	centimeters	x 2.54	tons (US/short)	tonnes	x 0.9072
inches	feet	/ 12	yards	meters	x 0.9144

Appendix E: System Drawings

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