
Water Treatment

Review Class Notes

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Water Treatment

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Drinking Water Standards

Drinking water standards are promulgated by the United States Environmental Protection Agency (EPA) to protect public health from waterborne diseases.

Maximum Contaminant Level Goal (MCLG)

The maximum concentration of a contaminant in drinking water at which no known or anticipated adverse health effects on persons occurs and which allows for an adequate margin of safety. MCLG's are determined for non-carcinogenic toxic substances based on the Reference dose, RfD. The RfD is the daily exposure level to a substance that with a factor of safety will not cause adverse health effects over the lifetime of a person. The RfD is determined based on the No Observed Adverse Effect Level (NOAEL) which is determined for toxicological studies of the substance in humans and/or animals. The RfD is computed by dividing the NOEL by an uncertainty factor (UF). RfD's are usually reported in milligrams per kilogram per day (mg/kg · day), which requires conversion to a concentration for use as an MCLG. Thus the Drinking Water Equivalent Level (DWEL) is calculated based on the NOAEL, the UF, the average weight of a person, and the average daily water consumption of a person:

$$DWEL = \frac{[NOAEL \text{ in } mg/(kg \cdot \text{day})](70 \text{ kg})}{(UF)(2 \text{ L/day})}$$

Where:

NOAEL = No observed adverse effect level.

70 kg = Assumed weight of an adult.

2 L/day = Assumed daily water consumption of an adult.

UF = Uncertainty factor (usually 10, 100, or 1000).

To determine the MCLG, the exposure to the substance from drinking water, food and air must be considered so that the total exposure does not exceed the RfD. Since exposures from food and air are often not quantified the MCLG is calculated:

$$MCLG = DWEL(\text{Percentage contribution from drinking water})$$

The percentage contribution from drinking water is often assumed to be 20% in the absence of other data.ⁱ

Maximum Contaminant Level (MCL)

The maximum concentration of a contaminant allowed in drinking water to meet regulatory standards which is set as close to the MCLG as is feasible. Feasibility takes into account the best available technology (BAT) and the cost of treatment. MCL's are included in the Primary Drinking Standards.

Maximum Residual Disinfectant Level Goal (MRDLG)

The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.

Maximum Residual Disinfectant Level (MRDL)

The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.

Public Health Goal

See Maximum Contaminant Level Goal.

Treatment Technique

A required process intended to reduce the level of a contaminant in drinking water.

Best Available Technology (BAT)

The best available technologies are listed by the EPA for control and/or removal of regulated contaminants. Alternate technologies for small systems may also be specified by the EPA and other restrictions on the use of certain BATs may exist in certain circumstances; refer to the National Primary Drinking Water Standards in 40 CFR §141.

National Primary Drinking Water Standards

The national primary drinking water standards are the federally enforceable standards for drinking water in the United States. MCL's are set by the US EPA to protect public health as described above. The standards are summarized in Table 1, below. In addition to the MCL for each contaminant, the potential health effects, common sources, and MCLG are presented. In addition, the EPA listed Best Available Technology (BAT) is provided for each contaminant as applicable. The contaminants are grouped by type by EPA as shown in the Legend. The contaminants in Table 1 are listed in alphabetical order. Footnotes to the table are provided below the table.

Table 1 - National Primary Drinking Water Standards

Legend	Contaminant	MCL or TT¹ (mg/L)²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
OC	Acrylamide	TT ³	Nervous system or blood problems;	Added to water during sewage/wastewater increased risk of cancer treatment	zero	TT
OC	Alachlor	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops	zero	4
R	Alpha particles	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation	zero	7
IOC	Antimony	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder	0.006	2,7
IOC	Arsenic	0.010	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass & electronics production wastes	zero	1,2,5,6,7,9,12
IOC	Asbestos (fibers >10 micrometers)	7 million fibers per Liter (MFL)	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits	7 MFL	2,3,8
OC	Atrazine	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops	0.003	4
IOC	Barium	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits	2	5,6,7,9
OC	Benzene	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills	zero	4,13
OC	Benzo(a)pyrene (PAHs)	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines	zero	4
IOC	Beryllium	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries	0.004	1,2,5,6,7
R	Beta particles and photon emitters	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation	zero	5,7
DBP	Bromate	0.010	Increased risk of cancer	Byproduct of drinking water disinfection	zero	TT

Legend	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
IOC	Cadmium	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints	0.005	2,5,6,7
OC	Carbofuran	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa	0.04	4
OC	Carbon tetrachloride	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities	zero	4,13
D	Chloramines (as Cl ₂)	MRDL=4.0 ¹	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes	MRDLG=4 ¹	TT
OC	Chlordane	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide	zero	4
D	Chlorine (as Cl ₂)	MRDL=4.0 ¹	Eye/nose irritation; stomach discomfort	Water additive used to control microbes	MRDLG=4 ¹	TT
D	Chlorine dioxide (as ClO ₂)	MRDL=0.8 ¹	Anemia; infants & young children: nervous system effects	Water additive used to control microbes	MRDLG=0.8 ¹	TT
DBP	Chlorite	1.0	Anemia; infants & young children: nervous system effects	Byproduct of drinking water disinfection	0.8	TT
OC	Chlorobenzene	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories	0.1	4,13
IOC	Chromium (total)	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits	0.1	2,5,6,7
IOC	Copper	TT ² ; Action Level = 1.3	Short term exposure: Gastrointestinal distress. Long term exposure: Liver or kidney damage. People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits	1.3	TT
M	Cryptosporidium	TT ²	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero	TT
IOC	Cyanide (as free cyanide)	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories	0.2	5,7,10
OC	2,4-D	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops	0.07	4
OC	Dalapon	0.2	Minor kidney changes	Runoff from herbicide used on rights of way	0.2	4
OC	1,2-Dibromo-3-chloropropane (DBCP)	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards	zero	4,13
OC	o-Dichlorobenzene	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories	0.6	4,13

Legend	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
OC	p-Dichlorobenzene	0.075	Anemia; liver, kidney or spleen damage; changes in blood	Discharge from industrial chemical factories	0.075	4,13
OC	1,2-Dichloroethane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	zero	4,13
OC	1,1-Dichloroethylene	0.007	Liver problems	Discharge from industrial chemical factories	0.007	4,13
OC	cis-1,2-Dichloroethylene	0.07	Liver problems	Discharge from industrial chemical factories	0.07	4,13
OC	trans-1,2-Dichloroethylene	0.1	Liver problems	Discharge from industrial chemical factories	0.1	4,13
OC	Dichloromethane	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories	zero	13
OC	1,2-Dichloropropane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	zero	4,13
OC	Di(2-ethylhexyl) adipate	0.4	Weight loss, live problems, or possible reproductive difficulties	Discharge from chemical factories	0.4	4,13
OC	Di(2-ethylhexyl) phthalate	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories	zero	4
OC	Dinoseb	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables	0.007	4
OC	Dioxin (2,3,7,8-TCDD)	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories	zero	4
OC	Diquat	0.02	Cataracts	Runoff from herbicide use	0.02	4
OC	Endothall	0.1	Stomach and intestinal problems	Runoff from herbicide use	0.1	4
OC	Endrin	0.002	Liver problems	Residue of banned insecticide	0.002	4
OC	Epichlorohydrin	TT ³	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals	zero	TT
OC	Ethylbenzene	0.7	Liver or kidneys problems	Discharge from petroleum refineries	0.7	4,13
OC	Ethylene dibromide	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries	zero	4,13

Legend	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
M	Fecal Coliform and <i>E. Coli</i>	MCL ⁵	Fecal Coliforms and <i>E. coli</i> are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Microbes in these wastes may cause short term effects, such as diarrhea, cramps, nausea, headaches, or other symptoms. They may pose a special health risk for infants, young children, and people with severely compromised immune systems.	Human and animal fecal waste	Zero ⁵	TT
IOC	Fluoride	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories	4.0	7
M	Giardia lamblia	TT ³	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero	TT
OC	Glyphosate	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use	0.7	12
DBP	Haloacetic acids (HAA5)	0.060	Increased risk of cancer	Byproduct of drinking water disinfection	n/a ⁶	4,14
OC	Heptachlor	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide	zero	4
OC	Heptachlor epoxide	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor	zero	4
M	Heterotrophic plate count (HPC)	TT ³	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is.	HPC measures a range of bacteria that are naturally present in the environment	n/a	
OC	Hexachlorobenzene	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories	zero	4
OC	Hexachlorocyclopentadiene	0.05	Kidney or stomach problems	Discharge from chemical factories	0.05	4,13
IOC	Lead	TT ⁷ ; Action Level = 0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities; Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits	zero	TT
M	Legionella	TT ³	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems	zero	TT
OC	Lindane	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens	0.0002	4
IOC	Mercury (inorganic)	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands	0.002	2,4,6,7

Legend	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
OC	Methoxychlor	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock	0.04	4
IOC	Nitrate (measured as Nitrogen)	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	10	5,7
IOC	Nitrite (measured as Nitrogen)	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	1	5,7,9
OC	Oxamyl (Vydate)	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes	0.2	4
OC	Pentachlorophenol	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories	zero	4
OC	Picloram	0.5	Liver problems	Herbicide runoff	0.5	4
OC	Polychlorinated biphenyls (PCBs)	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals	zero	4
R	Radium 226 and Radium 228 (combined)	5 pCi/L	Increased risk of cancer	Erosion of natural deposits	zero	5,6,7
IOC	Selenium	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines	0.05	1,2,6,7,9
OC	Simazine	0.004	Problems with blood	Herbicide runoff	0.004	4
OC	Styrene	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills	0.1	4,13
OC	Tetrachloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners	zero	4,13
IOC	Thallium	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories	0.0005	1,5
OC	Toluene	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories	1	4,13
M	Total Coliforms	5.0% ⁴	Coliforms are bacteria that indicate that other, potentially harmful, bacteria may be present. See also Fecal Coliform and <i>E. Coli</i>	Coliforms are naturally present in the environment as well as feces; fecal coliforms and <i>E. coli</i> only come from human and animal fecal waste.	zero	TT

Legend	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal	Best Available Technology (BAT)
DBP	Total Trihalomethanes (TTHMs)	0.10 0.080 after 12/31/03	Liver, kidney or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection	n/a6	4,14
OC	Toxaphene	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle	zero	4
OC	2,4,5-TP (Silvex)	0.05	Liver problems	Residue of banned herbicide	0.05	4
OC	1,2,4-Trichlorobenzene	0.07	Changes in adrenal glands	Discharge from textile finishing factories	0.07	4,13
OC	1,1,1-Trichloroethane	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories	0.20	4,13
OC	1,1,2-Trichloroethane	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories	0.003	4,13
OC	Trichloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories	zero	4,13
M	Turbidity	TT ³	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing micro-organisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff	n/a	TT
R	Uranium	30 ug/L as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits	zero	2,5,6,7
OC	Vinyl chloride	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories	zero	13
M	Viruses (enteric)	TT ³	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero	TT
OC	Xylenes (total)	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories	10	4,13

Legend: **D** Disinfectant **IOC** Inorganic Chemical **OC** Organic Chemical **DBP** Disinfection Byproduct **M** Microorganism **R** Radionuclides

NOTES

1 Definitions

- **Maximum Contaminant Level Goal (MCLG)**—The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.

- Maximum Contaminant Level (MCL)—The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
- Maximum Residual Disinfectant Level Goal (MRDLG)—The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.
- Maximum Residual Disinfectant Level (MRDL)—The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.
- Treatment Technique (TT)—A required process intended to reduce the level of a contaminant in drinking water.

2 Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (ppm).

3 EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to (1) disinfect their water, and (2) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- Cryptosporidium (as of 1/1/02 for systems serving >10,000 and 1/14/05 for systems serving <10,000) 99% removal.
- Giardia lamblia: 99.9% removal/inactivation
- Viruses: 99.99% removal/inactivation
- Legionella: No limit, but EPA believes that if Giardia and viruses are removed/inactivated, Legionella will also be controlled.
- Turbidity: At no time can turbidity (cloudiness of water) go above 1 nephelometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 0.3 NTU in 95% of the daily samples in any month.
- HPC: No more than 500 bacterial colonies per milliliter
- Long Term 1 Enhanced Surface Water Treatment (Effective Date: January 14, 2005); Surface water systems or (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long Term 1 Enhanced Surface Water Treatment Rule provisions (e.g. turbidity standards, individual filter monitoring, Cryptosporidium removal requirements, updated watershed control requirements for unfiltered systems).
- Filter Backwash Recycling: The Filter Backwash Recycling Rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

4 No more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E. coli* fecal coliforms, system has an acute MCL violation. See also Fecal Coliform and *E. Coli*.

5 A routine sample that is fecal coliform-positive or *E. coli*-positive triggers repeat samples—If any repeat sample is total coliform-positive the system has an acute MCL violation. A routine sample that is total coliform-positive and fecal coliform-negative or *E. coli*-negative triggers repeat samples—If any repeat sample is fecal coliform-positive or *E. coli*-positive, the system has an acute MCL violation. See also Total Coliform.

6 Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

- Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.3 mg/L)
- Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L)

7 Lead and copper are regulated by a Treatment Technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 mg/L, and for lead is 0.015 mg/L.

8 Each water system must certify, in writing, to the state (using third-party or manufacturers certification) that when it uses acrylamide and/or epichlorohydrin to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows: Acrylamide = 0.05% dosed at 1 mg/L (or equivalent); Epichlorohydrin = 0.01% dosed at 20 mg/L (or equivalent).

Best Available Technology Key

The following best available technologies are listed by the EPA for control and/or removal of the contaminants as shown in the table above. Alternate technologies for small systems may also be specified by the EPA and other restrictions on the use of these BATs may exist in certain circumstances; refer to the National Primary Drinking Water Standards in 40 CFR §141.

- 1 – Activated Alumina
 - 2 – Coagulation/Filtration (not BAT for systems <500 service connections)
 - 3 – Direct and Diatomite Filtration
 - 4 – Granular Activated Carbon
 - 5 – Ion Exchange
 - 6 – Lime Softening (not BAT for systems <500 service connections)
 - 7 – Reverse Osmosis
 - 8 – Corrosion Control
 - 9 – Electro dialysis
 - 10 – Chlorine
 - 11 – Ultraviolet Light
 - 12 – Oxidation/Filtration
 - 13 – Packed Tower Aeration
 - 14 – Enhanced Coagulation or Enhanced Softening
- TT – Control of contaminant is related to controlling treatment techniques.

National Secondary Drinking Water Standards

National Secondary Drinking Water Standards are non-enforceable guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. EPA recommends secondary standards to water systems but does not require systems to comply. However, states may choose to adopt them as enforceable standards.

Table 2 - National Secondary Drinking Water Standards

Contaminant	Secondary MCL	Noticeable Effects above the Secondary MCL
Aluminum	0.05 to 0.2 mg/L*	colored water
Chloride	250 mg/L	salty taste
Color	15 color units	visible tint
Copper	1.0 mg/L	metallic taste; blue-green staining
Corrosivity	Non-corrosive	metallic taste; corroded pipes/ fixtures staining
Fluoride	2.0 mg/L	tooth discoloration
Foaming agents	0.5 mg/L	frothy, cloudy; bitter taste; odor
Iron	0.3 mg/L	rusty color; sediment; metallic taste; reddish or orange staining
Manganese	0.05 mg/L	black to brown color; black staining; bitter metallic taste
Odor	3 TON (threshold odor number)	"rotten-egg", musty or chemical smell
pH	6.5 - 8.5	low pH: bitter metallic taste; corrosion high pH: slippery feel; soda taste; deposits
Silver	0.1 mg/L	skin discoloration; graying of the white part of the eye
Sulfate	250 mg/L	salty taste
Total Dissolved Solids (TDS)	500 mg/L	hardness; deposits; colored water; staining; salty taste
Zinc	5 mg/L	metallic taste

Example Problem No. 1

(PM)The EPA has determined that the No observed adverse effect level (NOAEL) for a contaminant is 300 mg/kg-d (reference dose) with an uncertainty factor of 100. Given that an average adult weighs 70 kg, drinks 2 L of water per day, and 20% of the total exposure to the contaminant comes from drinking water; EPA should set the MCLG for this contaminant at:

- a) 7mg/L b) 21 mg/L c) 105 mg/L d) 300 mg/L

Demands

Quantity of water expected by customers to be available at the tap for use. Also, the quantity of water required to satisfy the needs of a community.

Factors affecting demand

1. Population
2. Season, Time of year
3. Weather
4. Time of day
5. Land Use
6. Population density

Demand used for Design

Use annual average day demand to size water supply:

$$\text{Annual average day demand} = \frac{\text{Total demand for one year}}{365 \text{ days in one year}}$$

Use maximum day demand to design production facilities:

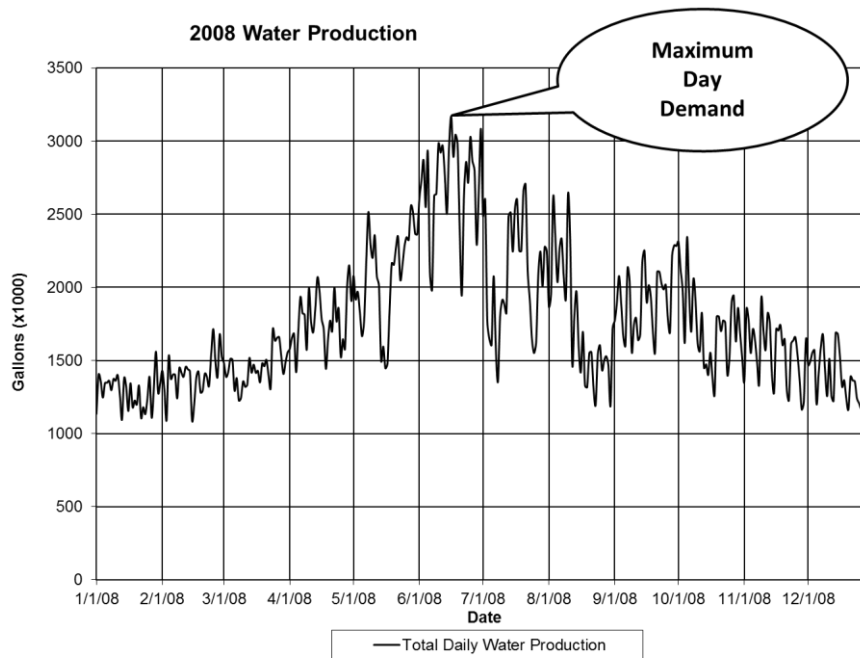


Figure 1 - Daily Demand Records for 2008

Use maximum hour demand to design distribution facilities:

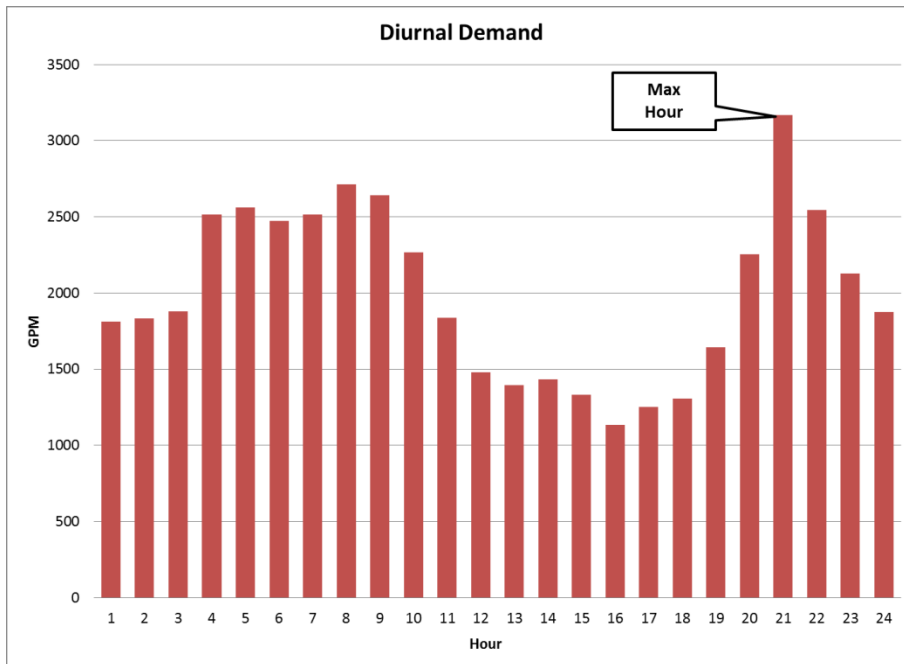


Figure 2 - Diurnal Demand for Maximum Day

Demands can be expressed in gallons per minute (GPM), gallons per day (GPD), and million gallons per day (MGD). Demands may also be expressed as a function of population in gallons per capita per day (GPCD) or gallons per person per day (GPPD). Annual demands are often expressed in acre-feet or million gallons (MG).

Example Problem No. 2

A community of 20,000 people uses an average of 3,360 acre-feet of water per year. The maximum recorded daily consumption was 6 million gallons and the maximum hour consumption was 7,000 gallons per minute.

- A. (AM)The average demand for water per person is most nearly:
 - a) 80 GPCD b) 100 GPCD c) 150 GPCD d) 200 GPCD

- B. (AM)Population projections show a population of 50,000 people by the year 2040. Assuming that water demand patterns do not change, the total water treatment capacity needed to serve the 2040 population is most nearly:
 - a) 5 MGD b) 7.5 MGD c) 10 MGD d) 15 MGD

C. (AM) Assuming demand patterns do not change, the maximum hour consumption in 2040 will be most nearly:

- a) 1.0 MG b) 3.0 MG c) 6.0 MG d) 10.0 MG

Distribution System

A distribution system is a network of pipes, pumps and storage tanks used to deliver drinking water to homes and businesses. Distribution systems usually include provisions for fire fighting.

Design network to provide maximum hour demands and maintain a minimum of 35 psig in all parts of the distribution system.

Design network to operate under emergency conditions and maintain a minimum of 20 psig in all parts of the distribution system.

Emergencies include:

1. Fire
2. Natural disaster
3. Transmission main break
4. Power outage
5. Terrorist attack

Typical design for emergency conditions is to consider fire flow with maximum month demand.

Hydraulic design is performed usually using Hazen-Williams formula and Hardy Cross method for network analysis.

Storage

Raw water storage

Storage of untreated water designed to meet demands during times of low supply (drought). Raw water is often stored in lakes, reservoirs, and aquifers.

Firm yield

The maximum average annual demand that can be served from raw water storage during the drought of record.

Treated water storage

Storage of treated water designed to meet daily and hourly demands.

Production storage

A clear well is storage tank used to store effluent from a water treatment facility prior to transmission and distribution. Production facilities are typically designed to meet maximum day demands, and clear wells are designed to provide storage between low demand periods and high demand periods of the maximum day. Clear wells often have additional storage to provide treated water during short term shut downs of the water treatment facility.

Distribution storage

Treated water stored in the distribution system to provide for variations in diurnal demand and maintain pressure in the system. These facilities typically include storage to provide flow to fight fires. The flow and duration for firefighting capacity depends upon the type, height and density of structures in the community. Elevated storage is used to maintain pressures within the distribution system within a normal operating range. Figure 3 shows how elevated storage maintains pressure in the system. Most elevated storage has between 30 and 50 feet of operating head range. Typically half or more of the operating head range is reserved for emergency conditions.

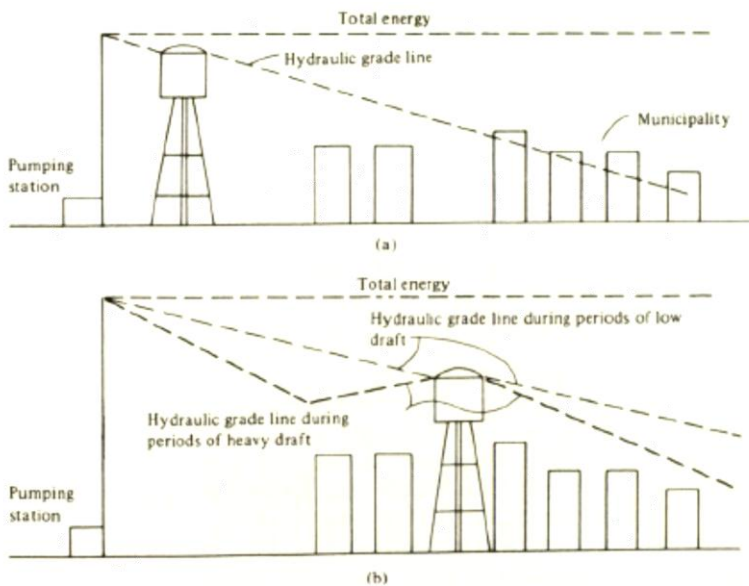


Figure 3 - Distribution system pressure as influenced by location of elevated storageⁱⁱ

Total storage includes production storage, emergency storage and equalizing storage. Production storage is provided to allow for plant shut downs to last 1-3 days. Emergency storage is used for firefighting. Often 10 to 12 hours of storage is provided in reserve for firefighting. Equalization storage is used to allow for constant rate pumping instead of variable rate pumps that constantly change flow rate to match demand. Use of variable rate pumping is often considered uneconomical and cumbersome. With equalizing storage, on the design maximum demand day, the high service pumps constantly provide water to the distribution system at a constant rate. When the hourly demand exceeds the rate of pumping the distribution storage is emptied to supply the demand. When the pumping rate exceeds the demand the storage is refilled. A mass diagram or cumulative demand diagram similar to a Ripple diagram can be used to determine the required storage as shown in Figure 4. The variation in demand shown in Figure 2 is accumulated in a running total volume in Millions of gallons in Figure 4. The steep areas of the demand curve indicate high

demand periods while the flatter areas indicate low demand periods. Constant pumping is shown as a straight line. Since the total pumping equals the total demand on maximum demand day, the curves end at the same total volume for the day. Using two lines parallel to the pumping line, the volume is found as difference between the lines when placed tangent to the demand curve at the inflections between high and low demand periods as shown in Figure 4.

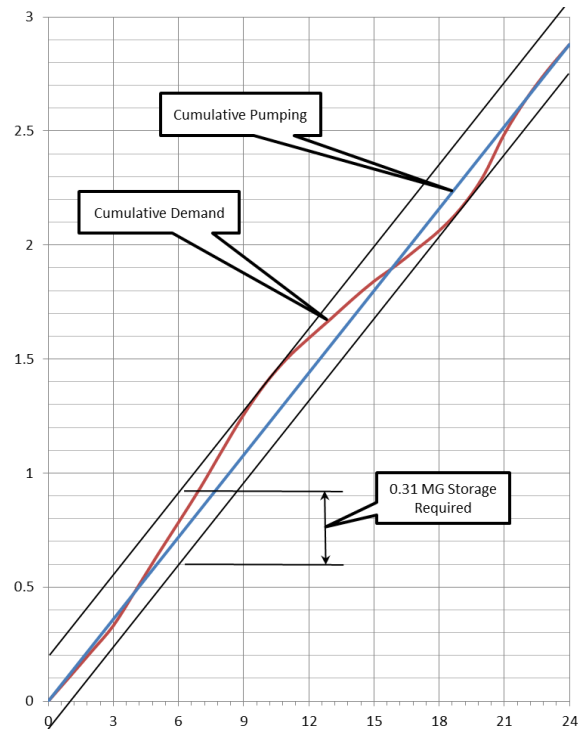


Figure 4 – Using cumulative demand and pumping curves to determine volume in MG of equalizing storage required on the maximum demand day

Example problem No. 3

The topography of an area served by a community water system varies in ground elevation from 800 FT above Mean Sea Level (MSL) to 900 FT above MSL. The water system demands require an equalizing storage of 0.5 MG in an elevated water storage tank.

- A. (AM)The elevation of the overflow of the elevated storage tank to maintain a static water pressure in the distribution system of between 40 and 90 PSI at ground level through out the area is most nearly:
 - a) 890 FT MSL
 - b) 945 FT MSL
 - c) 1000 FT MSL
 - d) 1090 FT MSL

B. (AM) To avoid a static water pressure at ground level less than 35 PSI in the system, the diameter of the cylindrical elevated tank must be at least (Use the correct answer from A as the overflow elevation of the elevated tank):

a) 99 FT

b) 67 FT

c) 54 FT

d) 33 FT

Hydraulic Loading

Hydraulic retention time: *HRT*

$$HRT = \frac{Volume}{Flow} = \frac{V}{Q}$$

HRT may be expressed in units of seconds, minutes, hours or days. Volume may be in cubic feet, gallons, or million gallons. Flow may be in units of million gallons per day (MGD), gallons per day (GPD), gallons per minute (GPM) or cubic feet per second (CFS). Unit conversions are almost always required to solve.

Hydraulic surface loading rate: *HLR*

$$HLR = \frac{Flow}{Surface Area} = \frac{Q}{A_s}$$

HLR may also be referred to as an overflow rate in the case of sedimentation facilities. The loading rate is typically expressed in gallons per day per square foot (GPD/FT²) or in gallons per minute per square foot (GPM/FT²). Flow may be expressed in MGD, GPD, GPM, or CFS. Area is typically expressed in square feet (FT²). Unit conversions are sometimes necessary to solve.

Weir loading rate: *WLR*

$$WLR = \frac{Flow}{Weir Length} = \frac{Q}{L_w}$$

WLR is the flow per unit length of weir usually expressed in gallons per day per foot (GPD/FT). Flow is usually expressed in MGD, GPD, GPM or CFS and the length is expressed in feet (FT). Unit conversions are sometimes necessary to solve.

Example Problem No. 4

A treatment unit is 100 FT long, 40 FT wide, and 20 FT deep. It treats a flow of 2.5 MGD. It has effluent weirs with a total length of 80 FT.

- A. (AM)The hydraulic retention time (HRT) is most nearly:
- a) 5.7 hours b) 6.3 hours c) 6.9 hours d) 7.4 hours
- B. (AM)The hydraulic surface loading rate (HLR) is most nearly:
- a) 980 GPD/FT² b) 625 GPD/FT² c) 460 GPD/FT² d) 315 GPD/FT²
- C. (AM)The weir loading rate (WLR) is most nearly:
- a) 15,000 GPD/FT b) 31,000 GPD/FT c) 43,000 GPD/FT d) 62,000 GPD/FT

Sedimentation

Sedimentation is the process of settling solid particles from suspension in the water. This is achieved by providing a long hydraulic retention time under quiescent conditions to allow the solids to fall to the bottom of the basin. Solids are collected with mechanical equipment and removed from the tank as concentrated slurry. Settling basins may be circular or rectangular.

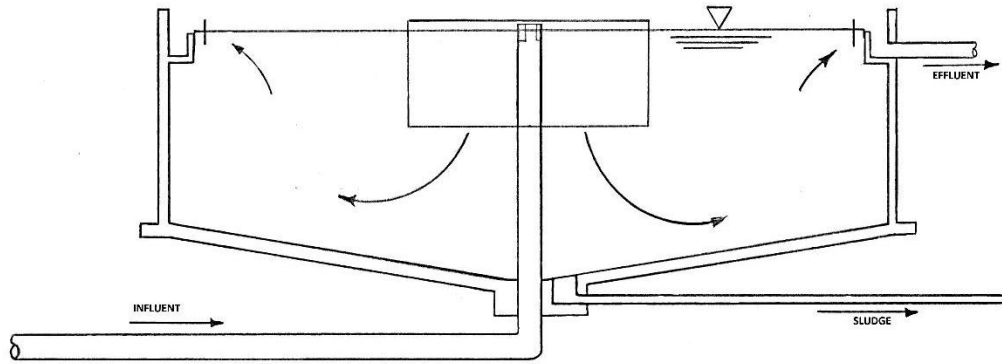


Figure 5 - Circular Sedimentation Basin, Clarifier

Design is based on hydraulic loading criteria: *HLR* and *HRT*. The *HLR* determines the required surface area and the *HRT* determines the required volume. Since surface area multiplied by depth is volume, the *HRT* is used to determine the depth. Effluent weirs are designed based on a weir loading rate. *HLR* is sometimes called the overflow rate.

Design *HLR* may be determined based on the settling velocity of a design particle as described below.

Discrete Settling

Discrete settling is based on Stoke's Law for individual particles. Stoke's Law is derived from Newton's Law equating drag force to gravitational force to determine the particle terminal velocity. Stoke's Law is valid for Reynold's Numbers less than 0.3 and is calculated:

$$V_c = \frac{g(\rho_s - \rho)d^2}{18\mu}$$

where:

V_c = particle settling velocity, terminal velocity, (FT/s)

d = diameter of the particle, (FT)

g = acceleration due to gravity, (FT/s²)

ρ_s = mass density of particle, (slug/FT³)

ρ = mass density of fluid, (slug/FT³)

μ = dynamic viscosity of fluid (LB-s/FT²)

Theoretically, the flowrate, Q , is equal to the velocity, V , times area, A . If we substitute the particle velocity for V and the basin surface area for A , we get:

$$Q = A_s \bullet V_c, \text{ and}$$

$$V_c = \frac{Q}{A_s}$$

which is the same definition for *HLR*. Thus the particle settling velocity is equal to the *HLR*. Theoretically, to obtain 100% removal of a given particle, the basin must be sized with an *HLR* less than or equal to the particle's settling velocity. In water treatment, particle settling velocities are determined through pilot testing.

Example Problem No. 5

A water treatment plant is designed with rectangular sedimentation basins. The sedimentation basins must have a 5:1 length to width ratio and a maximum length of 300 FT. The design *HLR* is 800 GPD/FT² and the minimum HRT is 4.0 hours.

- A. (AM)The minimum number of sedimentation basins required to treat 25 MGD is:
- a) 4 b) 3 c) 2 d) 1
-
- B. (AM)If 3 identical basins are used to treat 35 MGD, each has a length most nearly:
- a) 300 FT b) 270 FT c) 225 FT d)195 FT
-
- C. (AM)The depth required to treat 25 MGD with three basins that are 46 FT by 230 FT is most nearly:
- a) 12 FT b) 15 FT c) 18 FT d) 22 FT

Taste and Odor Control

Bad tastes and foul odors may not be indicative of health risks, but make water unpleasant to drink and use for domestic purposes. Tastes and odors generate more customer complaints than virtually any other characteristic of drinking water. Bad tastes and foul odors can be caused by algae, organic matter, chemical contaminants, chlorine, hydrogen sulfide, and other contaminants. Excessive quantities of chlorides and dissolved solids give water a salty flavor. Metals such as aluminum and zinc can give water a metallic taste. Hydrogen sulfide gives a rotten egg smell.

Controlling taste and odor means removing the causes. For example, **micro-straining** can be employed to remove algae and other organisms. Micro-straining is filtering raw water through a 35 µm or finer metal filter cloth.

Activated carbon can be used to remove tastes and odors and a variety of chemical contaminants.

Aeration is effective at stripping hydrogen sulfide from water as well as providing oxygen to waters low in dissolved oxygen.

Chlorine can be used to oxidize organic matter and industrial wastes. However, very high doses are often required resulting in a need for dechlorination. This is referred to as super chlorination.

Chlorine dioxide has been found to be effective in oxidizing organic matter without creating large quantities of by-products when carefully controlled.

Odor is measured by the Threshold Odor Number (TON). The **TON** is determined by adding increasing amounts of odor-free dilution water to a sample until the combination is virtually odor free. Then the TON is computed:

$$TON = \frac{V_{sample} + V_{dilute}}{V_{sample}}$$

A TON of 3 or less is considered ideal. Generally a TON of 5 or more will generate customer complaints. Untreated river waters have a TON between 6 and 24. Treated water can have a TON less than 6.

Example Problem No. 6

(PM)A laboratory technician at a water treatment plant checks a 200 mL sample of finished water for odor. After adding 550 mL of odorless dilution water to the sample, the technician no longer detects any odor. The threshold odor number for the finished water is:

- a) 2.75 b) 3.0 c) 3.50 d) 3.75

Rapid Mix

Rapid mixing is the process of mixing raw water with chemicals for coagulation, disinfection, pH adjustment, etc. Rapid mixing usually occurs only prior to flocculation, but may occur at several points within the system. For example, rapid mixing may be used prior to flocculation to mix alum and polymer with the raw water; and rapid mixing may be used in the disinfection step to mix filtered water with liquid sodium hypochlorite.

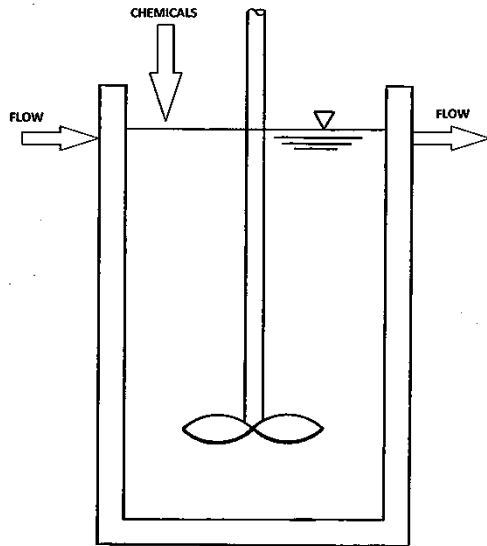


Figure 6 - Section of Rapid Mix Basin

Mixing energy is described based on the velocity gradient imparted to the fluid. The mean velocity gradient is the average change in velocity throughout the mixing basin. The velocity gradient is calculated:

$$G = \sqrt{\frac{P}{\mu V}}$$

Where:

G = velocity gradient (s^{-1})

P = power requirement (FT-LB/s)

μ = dynamic viscosity of liquid (LB-s/FT²)

V = volume mixed (FT³)

Thus the more power input to the rapid mixing process, the greater the velocity gradient and thus the energy of mixing. Typical rapid mixing processes for chemical addition use hydraulic retention times (HRT) between 5 and 20 seconds and G values between 250 and 1500 s^{-1} . Turbine or propeller mixers are used to provide the mixing power.

Turbine Mixers and Propeller Mixers

Turbine and propeller mixers include a turbine or propeller on a straight motor driven shaft, usually oriented vertically in a mixing chamber. A turbine may have straight or curved blades mounted to a flat plate perpendicular to the shaft. Propellers are angle blades similar to airplane propellers.

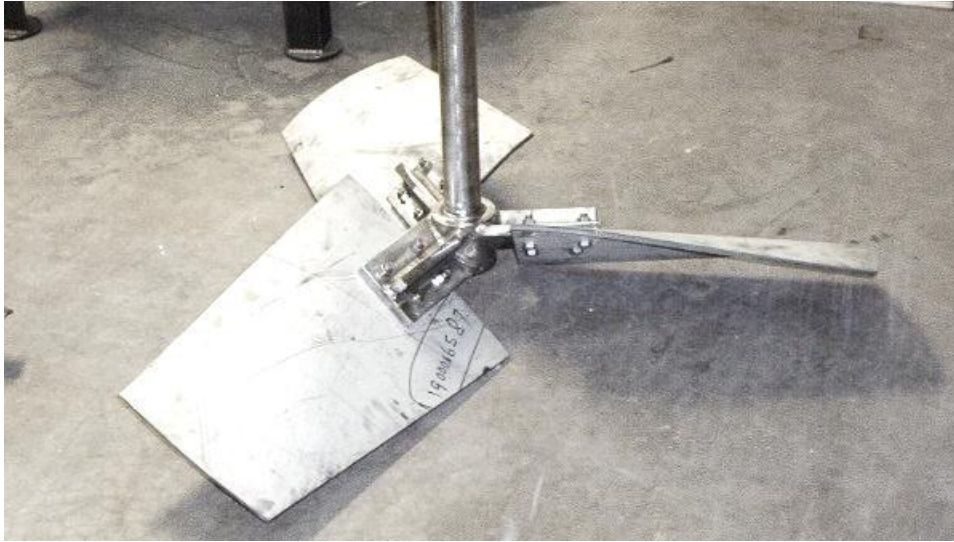


Figure 7 - Hybrid propeller/turbine mixer, known as a Hydrofoil impeller.

Power imparted by turbines and propellers are determined by controlled testing of individual designs within a laboratory. The following equation can be used to calculate the power imparted by turbines and propellers under turbulent conditions when the constants for the particular device design are known.

$$P = k\rho n^3 D^5 \quad \text{Turbulent Mixing } N_R > 10,000$$

where:

P = power (FT-LB/s)

k = constant

μ = dynamic viscosity (LB-s/FT²)

ρ = mass density (slug/FT³)

D = diameter of impeller (FT)

n = speed of revolution (rev/s)

N_R = Reynold's Number

$$N_R = \frac{D^2 n \rho}{\mu}$$

Turbulent mixing is used for rapid mix, the mixing of chemicals with water.

Example Problem No. 7

A 5 MGD water treatment plant is designed with a rapid mix basin to incorporate coagulants into the raw water. To achieve a complete mix, a minimum hydraulic retention time (HRT) of ten seconds is required and a velocity gradient of 1000 s^{-1} is required. The mixer will be a turbine mixer with an impeller that is 2.0 FT in diameter with a mixer constant of 1.25. The dynamic viscosity of the water is $2.05 \times 10^{-5} \text{ lb}\cdot\text{s}/\text{ft}^2$ and the fluid density is $1.936 \text{ slugs}/\text{FT}^3$.

A. (AM) The volume of the rapid mix basin is most nearly:

- a) 70 FT³ b) 77 FT³ c) 83 FT³ d) 96 FT³

B. (PM) The design speed of the turbine is most nearly:

- a) 191 RPM b) 184 RPM c) 164 RPM d) 148 RPM

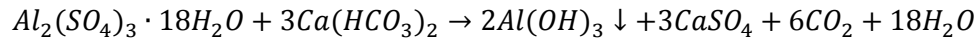
Coagulation and Flocculation

Colloids do not settle out of solution and range in size from 1 to 500 millimicrons (nanometers). Colloids are classified as hydrophobic (water hating) and hydrophilic (water loving). Hydrophilic colloids are stable because of their attraction to water, e.g. soap, soluble starch, blood serum. Hydrophobic colloids depend on their electric charge to maintain stability. The natural force of attraction between colloidal particles is offset by repulsive forces developed by positive ions adsorbed onto their surfaces in solution. The magnitude of this repulsive force is called the Zeta Potential.

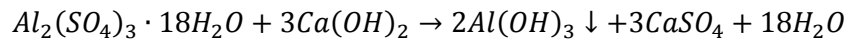
Chemical coagulation destabilizes colloidal particles. Hydrophobic particles are destabilized by salts of aluminum and iron. These salts form metal ions in water which compress the diffuse double layer surrounding individual particles. Slow mixing, called flocculation, allows particles to contact each other and stick together. Organic polymers can be used to provide bridging between particles by attaching themselves to the adsorbant surfaces of the particles, thus creating larger flocculated masses that will then settle out.

Coagulation is a process including the addition of a chemical to destabilize colloids causing them to settle. Flocculation is the process of slow mixing to allow particles to stick together to form larger particles that settle more easily. Aluminum or iron salts are commonly used coagulants added to water sometimes with polymers and other coagulant aids. Commonly used metal salts include alum (aluminum sulfate, $Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), ferrous sulfate ($FeSO_4$) and lime ($Ca(OH)_2$), and chlorinated copperas. The coagulation process is heavily dependent upon pH and alkalinity, and involves dissolution, hydrolysis, and polymerization.

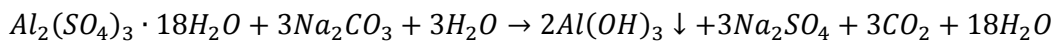
Chemical coagulation with alum can be simplified to the following chemical equation:



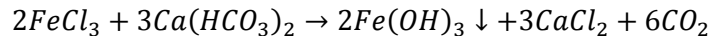
When insufficient alkalinity is available, then lime or soda ash is added and the reactions are as follows for lime ($Ca(OH)_2$):



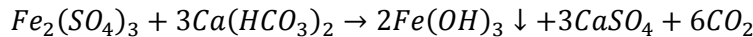
And for soda ash (Na_2CO_3):



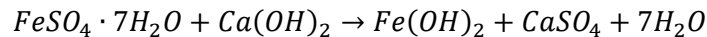
Ferric Chloride reacts with alkalinity as follows:



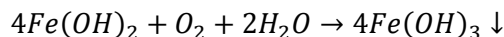
Ferric Sulfate reacts with alkalinity as follows:



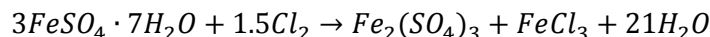
Ferrous Sulfate and Lime reacts as follows:



And then the Ferrous hydroxide ($Fe(OH)_2$) can be oxidized by free dissolved oxygen to produce insoluble Ferric hydroxide ($Fe(OH)_3$) as shown:



Chlorinated copperas is Ferrous sulfate (copperas) oxidized with Chlorine to produce Ferric sulfate and Ferric chloride:



This is followed by reactions with alkalinity as shown previously to produce Ferric hydroxide precipitants.

Example Problem No. 8

(PM) A water treatment plant doses 65 mg/L of alum ($\text{Al}_2(\text{SO}_4)_3$) to the raw water for coagulation. The alkalinity in mg/L as CaCO_3 needed to provide for a complete conversion of the alum to aluminum hydroxide is most nearly:

- a) 32 b) 57 c) 75 d) 96

Flocculation design

Flocculation is a special type of mixing characterized by gentle laminar conditions. The purpose of flocculation is to provide mixing needed to allow colloidal particles to contact each other and coalesce with the aid of coagulation chemicals. Velocity gradients used for flocculation typically vary between 20 and 100 s^{-1} with hydraulic retention times (*HRT*) from 5 to 30 minutes.

The velocity gradient is calculated:

$$G = \sqrt{\frac{P}{\mu V}}$$

where:

G = velocity gradient (s^{-1})

P = power requirement (FT-LB/s)

μ = dynamic viscosity of liquid (LB-s/FT²)

V = volume mixed (FT³)

While a variety of mixers can be used for flocculation, the most common are paddle wheel mixers.

Paddle wheel mixers

Paddles are mounted on horizontal motor driven shafts to provide mixing energy. Paddle mixers are typically designed for a tip speed of 2 to 3 ft/s. The following expression is used to calculate the power imparted by paddle wheel mixers:

$$P = F_D V_p = \frac{C_D A_p \rho V_p^3}{2}$$

where:

P = power (LB-FT/s)

F_D = drag force (LB)

C_D = drag coefficient for paddle

A_p = cross-sectional area of paddles (FT²)

ρ = mass density of fluid (slug/FT³)

v_p = relative velocity of paddles with respect to fluid (FT/s).

The value of v_p is usually assumed to be 0.6 to 0.75 times the paddle tip speed.

Turbine Mixers and Propeller Mixers

Turbine and propeller mixers may also be used for flocculation in smaller basins. Since laminar mixing is required for flocculation, the power provided by a turbine or propeller mixer is given by:

$$P = k\mu n^2 D^3 \quad \text{Laminar Mixing } N_R < 10$$

where:

P = power (FT-LB/s)

k = constant

μ = dynamic viscosity (LB-s/FT²)

ρ = mass density (slug/FT³)

D = diameter of impeller (FT)

n = speed of revolution (rev/s)

N_R = Reynold's Number

$$N_R = \frac{D^2 n \rho}{\mu}$$

Only very small capacity plants have flocculation basins small enough to make use of propeller or turbine mixers, typically less than 1 MGD.

Example Problem No. 9

A 10 MGD water treatment plant has a flocculation basin that is 25 FT wide by 62 FT long by 12 FT deep. The basin is designed for a velocity gradient of mixing of 80 s⁻¹ in water with a dynamic viscosity of 2.05x10⁻⁵ LB·s/FT² and density of 1.936 slugs/FT³. The equipment is a paddle wheel type flocculator with a drag coefficient of 1.8 and paddle tip speed of 2.0 FT/s. Assume the relative velocity of the paddles is 0.7 times the paddle tip speed.

- A. (AM) The hydraulic retention time (HRT) of the flocculation basin is most nearly:
- a) 30 min. b) 25 min. c) 20 min. d) 15 min.

B. (PM)The power required in LB·FT/s for flocculation is most nearly:

- a) 2440 b) 3680 c) 1220 d) 1840

C. (PM)The total surface area of paddles required on the flocculator is most nearly:

- a) 255 FT² b) 510 FT² c) 990 FT² d) 1254 FT²

Filtration

Filtration is the process to remove particles from water by straining the water through a filter medium. Sand is the most common filtration medium. Other mediums include anthracite and garnet. Filtration technologies include:

- Gravity Filtration Systems
 - Rapid rate gravity filtration
 - Slow sand filtration
- Pressure Filtration Systems
 - Rapid rate pressure filtration
 - Diatomaceous earth filtration
 - Membrane filtration
 - Cartridge filtration

Gravity filtration systems operate with relatively low headloss through the unit and pressure filters operate with higher headloss. Pressure filters can be economical in small plants while the limitations on vessel size make gravity filters more economical in large plants. The major disadvantage of pressure filters is the inability to view the filter operation and cleaning.ⁱⁱⁱ

Rapid rate gravity filtration is the most commonly used technology for water treatment. Flow is normally downward through a bed of granular media. Solids lodge in the pore spaces between the granules and on top of the media bed. As the bed clogs, the headloss increases resulting in either an increased water level over the bed or a reduced flow rate through the bed. Before the filter unit

reaches its limiting headloss or before a reduction in quality is observed, the filter bed is cleaned by backwashing: forcing a high volume flow of water upward through the filter to expand the bed and wash the solids from the bed.

Slow sand filters operate similar to rapid rate filters except at a much lower capacity. Slow sand filters operate without facilities for backwashing and thus at hydraulic and solids loading rates at least 50 to 100 times lower than rapid rate filters. When the limits of headloss or acceptable effluent quality are reached, the filter unit is removed from service scraped. Scraping involves removal of the top inch of sand. Following a scraping, slow sand filters require a ripening period of one to two days during which, the filtrate is wasted. When the total depth of the filter media has been reduced to about half of the design depth due to scraping, the media is removed and replaced. Following media replacement, the filter must be operated to establish a biological population within the media before it will produce consistently good quality effluent. This is called curing and involves wasting the filtrate for about 30 days.

Rapid rate pressure filtration is similar to rapid rate gravity filtration except that the flow is pumped through the media within a pressure vessel. Pressure filters also require periodic backwash.

Diatomaceous earth (DE) filters are also called precoat filters and use diatomaceous earth as a filter medium. Diatomaceous earth is a sedimentary rock formed from deposits of diatoms (microscopic aquatic plants). Diatoms have the ability to remove silica from water to produce a skeletal structure, thus the remains of diatoms form a deposit that is about 85% silica. A DE filter includes a media support called a septum which can be flat or cylindrical. About a 3 to 5 mm cake of DE called the precoat is applied to the septum. A continuous feed of Diatomite, the body feed, is required to maintain the porosity of the filter cake. Operating requirements for DE filters include:

- Preparation of body feed and precoat.
- Verification that dosages are proper.
- Periodic backwashing and disposal of spent filter cake.
- Periodic inspection of septum for cleanliness and damage.
- Verification that the filter is producing the quality of effluent that meets performance criteria.

Membrane filtration uses a plastic or rubber membrane fabricated to have uniformly sized pores. Membrane filtration is considered an advanced treatment process, thus details of membrane processes are presented in that section of the notes.

Cartridge filters typically are made with one of two types of media, surface or depth media. Surface media is usually a membrane with uniform pores of a particular to exclude larger particles. Depth media traps particles within the depth of the media. An example of a depth type cartridge is made of spun fibers wrapped around a central core support structure.

Cartridges are usually hollow cylinders designed to filter water passed from the outside of the cylinder to the inside. The cartridge is housed in a metal or plastic cylinder with influent and

effluent connections. This allows for the removal of the main housing and thus replacement of the cartridge when it is exhausted.

Cartridge filters are manufactured in a variety of sizes to provide filtration for many different size applications. They can also contain other media such as granular activated carbon and activated alumina which are discussed under advanced treatment. In addition, some membranes are used for media in cartridge filters. Higher particulate removal is typically a goal for laboratory and pharmaceutical use.

Design sizing of filters is based on a hydraulic loading rate per unit surface area or *HLR*. Units are usually gallons per minute per square foot of filter area. For granular media filters, the filter area is the surface area of the bed of filter media. For membrane and cartridge filters, the filter area is the membrane or fiber surface area exposed to water to be filtered. Backwash rates are measured in terms of *HLR* as well. Common loading rates for different filters is presented in Table 3.

Table 3 - Typical Hydraulic Loading Rates for Different Filter Types

Filter Type	Hydraulic Loading Rate (HLR)	Backwash Rate
Rapid Rate Gravity Filter	2 - 4 GPM/FT ²	10 - 20 GPM/FT ²
Slow Sand Filter	45 - 150 GPD/FT ²	Not Applicable
Rapid Rate Pressure Filters	< 3 GPM/FT ²	10 - 20 GPM/FT ²
Diatomaceous Earth Filters	1 - 1.5 GPM/FT ²	Sufficient to remove precoat
Membrane Filters	50 - 100 GPD/FT ²	50 - 100 GPD/FT ²
Cartridge Filters	0.1 - 2 GPM/FT ²	Not Applicable

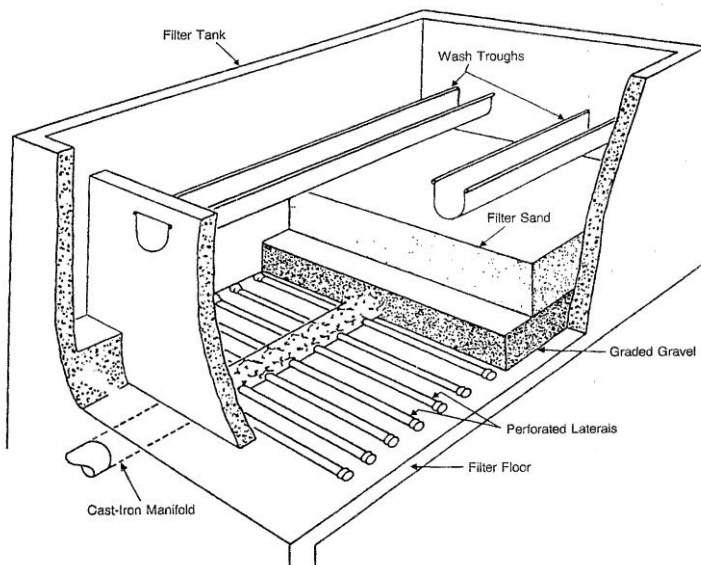


Figure 8 - Typical Rapid Rate Gravity Filter Cut-Away View

Example Problem No. 10

A water treatment plant uses rapid sand gravity filters to treat surface water. Each filter bed is 11 FT by 22 FT with sand 2.0 FT deep and anthracite 1.0 FT deep. The design filtration rate is 3 GPM/FT² and the backwash rate is 18 GPM/FT². The filters are backwashed daily. The backwash lasts about 20 minutes and the filter is ripened by filtering to drain for 20 to 30 minutes of the run following a backwash. About 10 more minutes is used in transitioning the filter from in service to backwash to ripen to back in service. Thus, a filter is out of service for about one hour to perform a backwash. So that the backwash process can be easily accommodated in one 8 hour shift, the plant includes a total of 6 filters.

A. (AM) The maximum capacity of the filters in MGD is most nearly:

- a) 2.0 b) 5.8 c) 6.0 d) 6.3

B. (PM) The quantity of backwash water used each day is most nearly:

- a) 0.09 MG b) 0.16 MG c) 0.34 MG d) 0.52 MG

C. (PM) The backwash pump used to supply the backwash water has a capacity in GPM of most nearly:

- a) 8712 b) 4356 c) 4170 d) 726

Disinfection

Disinfection is a process used to inactivate pathogens. By inactivation, we mean to render them harmless or non-disease causing. Disinfection with chemicals achieves inactivation through one or more of three main mechanisms:

- Destroy or impair cellular structure by attacking major cell constituents. This involves destroying the cell wall or impairing the functions of semipermeable membranes.
- Interfere with the energy-yielding metabolism by rendering the enzymes nonfunctional.
- Interfere with biosynthesis and growth by preventing synthesis of normal proteins, nucleic acids, coenzymes, or the cell wall.^{iv}

Common chemical disinfectants include chlorine, chloramines, chlorine dioxide, and ozone. Ultraviolet light can also be used as a disinfectant.

In water treatment disinfection effectiveness depends on several factors:

- *Disinfectant type.* Each type of disinfectant inactivates an organism at a different rate.
- *Disinfectant dose.* Higher dose increases the inactivation rate.
- *Type of organism and its physiological condition.* In general, protozoa are more resistant to disinfectants than bacteria or viruses. Some organisms form resistant forms (for example, cysts).
- *Contact time.* Increasing the contact time will increase pathogen inactivation.
- *pH.* The effectiveness of certain disinfectants (such as Chlorine) is highly pH dependent. Others (such as monochloramine and Ozone) are not pH dependent.
- *Temperature.* Typically, increasing the temperature will increase the rate of disinfection.
- *Turbidity.* Particles causing turbidity can shield pathogenic microorganisms from disinfectants. Particles also increase the disinfectant demand and reduce the concentration.
- *Dissolved organics.* Dissolved organics can interfere with disinfection by consuming the disinfectants to produce compounds with little or no microbiocidal activity.^v

In water treatment, the effectiveness of a disinfection process is described the product of the concentration of disinfectant and the contact time of the disinfectant. This product is called *CT*:

$$CT = C \times T$$

Where:

CT = a measure of the effectiveness of a disinfection process, mg/L·min.

C = disinfectant concentration in mg/L.

T = disinfectant contact time in minutes.

The *CT* required to achieve disinfection differs by pathogen and by disinfectant. Also, the required *CT* may be affected by pH and temperature for certain disinfectants, such as chlorine. Table 4 and Table 5 provide *CT* values for inactivation of Giardia and viruses.

Table 4 - Values of CT for 3-Log Inactivation of Giardia Lambli

Disinfectant mg/L	pH	Temperature, °C					
		0.5	5	10	15	20	25
Free Chlorine ≤0.4	6	137	97	73	49	36	24
	7	195	139	104	70	52	35
	8	277	198	149	99	74	50
	9	390	279	209	140	105	70
1.0	6	148	105	79	53	39	26
	7	210	149	112	75	56	37
	8	306	216	162	108	81	56
	9	437	312	236	156	117	78
1.6	6	157	109	83	56	42	28
	7	226	155	119	79	59	40
	8	321	227	170	116	87	58
	9	466	329	236	169	126	82
2.0	6	165	116	87	58	44	29
	7	236	165	126	83	62	41
	8	346	263	182	122	91	61
	9	500	353	265	177	132	88
3.0	6	181	126	95	63	47	32
	7	261	182	137	91	68	46
	8	382	268	201	136	101	67
	9	552	389	292	195	146	97
ClO ₂	6-9	63	26	23	19	15	11
Ozone	6-9	2.9	1.9	1.43	0.95	0.72	0.48
Chloramine	6-9	3800	2200	1850	1500	1100	750

Table 5 - Values of CT for the Inactivation of Viruses at pH between 6 and 9

Disinfectant	Log Inactivation	Temperature, °C					
		≤1	5	10	15	20	25
Free Chlorine	2	6	4	3	2	1	1
	3	9	6	4	3	2	1
	4	12	8	6	4	3	2
Chlorine Dioxide	2	8.4	5.6	4.2	2.8	2.1	1.4
	3	25.6	17.1	12.8	8.6	6.4	4.3
	4	50.1	33.4	25.1	16.7	12.5	8.4
Ozone	2	0.9	0.6	0.5	0.3	0.25	0.15
	3	1.4	0.9	0.8	0.5	0.4	0.25
	4	1.8	1.2	1.0	0.6	0.5	0.3
Chloramine	2	1243	857	643	428	321	214
	3	2063	1423	1067	712	534	356
	4	2883	1988	1491	994	746	497

The diagram below shows a typical disinfection process. The disinfectant is added before the treatment unit at some set dose. The water and disinfectant flow into the treatment unit and the residual concentration of disinfectant is measured on the flow exiting the treatment unit.

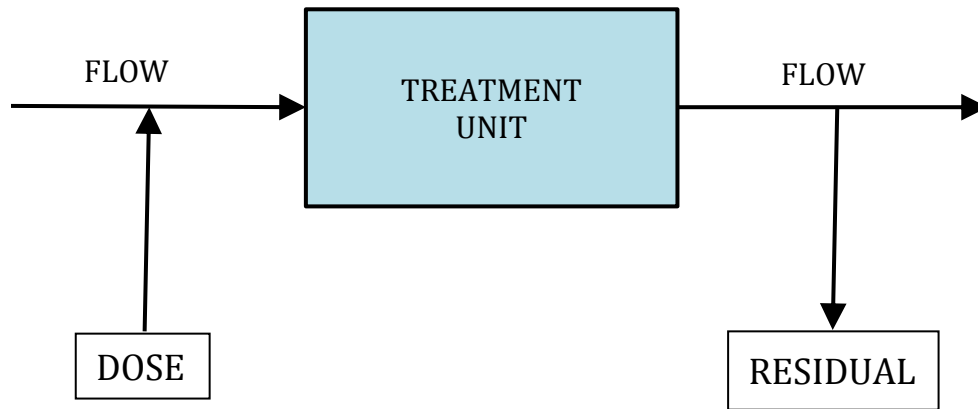


Figure 9 - Typical Disinfection Flow Sheet

The difference between the dose and the residual is called the disinfectant demand:

$$Demand = Dose - Residual$$

Use the residual concentration for the concentration, C , in the equation for CT . The time, T , in the CT equation is the 10th percentile of the hydraulic retention time in the treatment unit or T_{10} . T_{10} can be calculated using the mean hydraulic retention time, HRT :

$$T_{10} = HRT \times B_f = \frac{V}{Q} \times B_f$$

The baffling factor, B_f , is a function of the hydraulic characteristics of the treatment unit or contactor. Higher baffling factors result from units that come closest to achieving plug flow. Units with a high degree of hydraulic short-circuiting use a low baffling factor. Perfect plug flow uses a baffling factor of one, as shown in Table 6 with other baffling conditions.

Table 6 - Baffling Factors for Calculation of Contact Time

Baffling Condition	Baffling Factor T_{10}/T	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow), perforated inlet, outlet and intra basin baffles

Primary Disinfection

Regulatory standards for drinking water require that certain levels of removal and/or inactivation be achieved for certain pathogens. The Surface Water Treatment Rule (SWTR) specified target pathogens and required level of removal/inactivation include:

- Cryptosporidium: 99% or 2-Log.
- Giardia Lamblia: 99.9% or 3 Log.
- Viruses: 99.99% or 4 Log.

Legionella is another regulated pathogen; but it is removed or inactivated more easily than Giardia Lamblia, and thus if a sufficient degree of Giardia Lamblia removal/inactivation is achieved, then a sufficient level of removal/inactivation of Legionella has also been achieved to prevent spread of disease. Higher removal/inactivation levels may be required for source waters with high concentrations of pathogens.

The level of disinfection required depends upon the removal of the target pathogens in the filtration and associated treatment processes. Different processes achieve varying levels of pathogen removal. The above regulatory levels of removal/inactivation must be achieved through the combined processes of filtration and disinfection. If no filtration is used, then the inactivation achieved by disinfection must meet or exceed the same level. The level of removal from filtration is added to level of inactivation by disinfection to determine compliance with the requirements of SWTR. Table 7 summarizes the requirements for Giardia and viruses. **All the processes listed in Table 7 will provide a 2 Log removal of Cryptosporidium and thus meet those minimum requirements.**

Table 7 - Pathogen Removal and Inactivation Requirements for Various Treatment Processes

Treatment Process	Expected Log Removal		Required Log Inactivation	
	Giardia	Viruses	Giardia	Viruses
Conventional filtration	2.5	2.0	0.5	2.0
Direct filtration	2.0	1.0	1.0	3.0
Slow sand filtration	2.0	2.0	1.0	2.0
Diatomaceous earth filtration	2.0	1.0	1.0	3.0

Conventional filtration includes coagulation, flocculation and sedimentation prior to filtration as shown below in Figure 10.

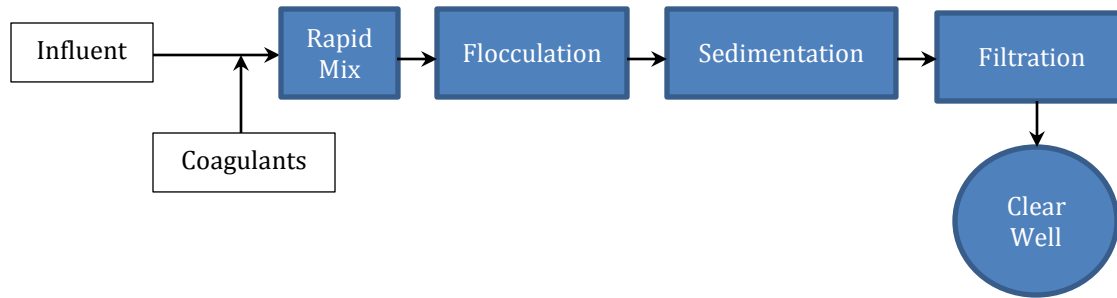


Figure 10 - Conventional Filtration Flow Sheet

Direct filtration is filtration with little or no pretreatment. The filters may be preceded by a coagulant addition and sometimes flocculation as shown below in Figure 11.

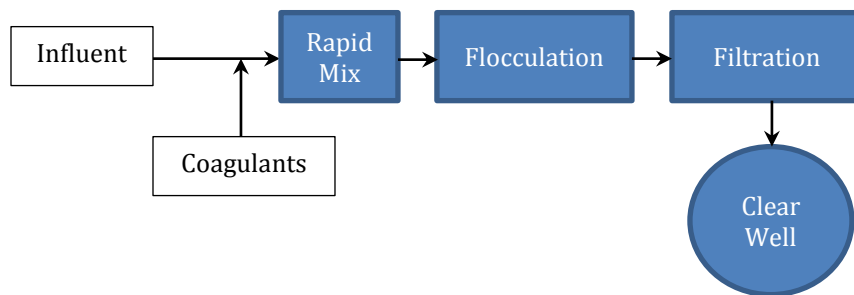


Figure 11 - Flow Sheet for Direct Filtration with Flocculation

Slow sand filtration is discussed in the filtration section of the notes. Slow sand filters typically require pretreatment such as a roughing filter or sedimentation similar to conventional filtration. Diatomaceous earth filtration is also discussed in the filtration section of the notes. DE filters should be preceded by coagulant feed of alum or polymer to enhance removal of viruses, bacteria and turbidity.

Treatment plants must determine the compliance with pathogen removal/inactivation requirements daily. Compliance is determined by calculating the actual CT, CT_{cal} , for various units in the process to determine the total CT_{cal} at the maximum flow rate for that day. Process units may include rapid mix, flocculation, sedimentation, filtration, clearwell, and even the transmission pipeline prior to the first customer. The steps to determine compliance are as follows:

1. Determine the peak hourly flowrate, Q .
2. Compute the hydraulic retention time, $HRT = V/Q$ for each segment of the treatment process following the addition of the disinfectant.
3. Calculate the T_{10} for each segment. Use the results of a tracer study or use the baffling factors presented in Table 6:
 - a. Find the baffling factor that best represents the baffling condition of each unit.
 - b. Compute T_{10} : $T_{10} = B_f \times HRT$
4. Measure the disinfectant residual, C , in mg/L at any number of locations throughout the treatment process. Also measure the water temperature in °C and the pH at each point.

5. Compute the actual CT_{cal} for each point where a residual was measured using the measured residual C and the T_{10} :

$$CT_{cal} = C \times T_{10}$$

6. Find the $CT_{99.9}$ for Giardia from Table 4 and the $CT_{99.99}$ for viruses from Table 5 for the corresponding measured values of temperature, pH and disinfectant residual.
7. Compute the inactivation ratios, $CT_{cal}/CT_{99.9}$ and $CT_{cal}/CT_{99.99}$ for Giardia and viruses, respectively.
8. Compute the log inactivation for each segment of the treatment process by multiplying the inactivation ratios from step 7 by 3 for Giardia and 4 for viruses, since $CT_{99.9}$ and $CT_{99.99}$ represent 3 and 4 log inactivation, respectively.
9. Sum the segmental log inactivation to determine the total log inactivation for the process.
10. Determine if the log inactivation is adequate:
 - a. For systems without filters, if the sum of the inactivation ratios is equal to or greater than one for both Giardia and viruses, then disinfection is adequate and in compliance with the SWTR.
 - b. For systems with filters, determine the required total inactivation from Table 7 for Giardia and Viruses. If the total process inactivation from step 9 is equal to or greater than the required inactivation for both Giardia and viruses, disinfection is adequate and in compliance with the SWTR.
11. The total percent inactivation can be calculated:

$$y = 100 - 100/10^x$$

Where:

y = percent inactivation.

x = log inactivation.

Secondary Disinfection

Secondary disinfection is the maintenance of a disinfectant residual in the distribution system. The residual protects against contamination and bacterial regrowth. Biological stability can be demonstrated by maintaining a disinfectant residual within the distribution system or by measuring the Heterotrophic Plate Count and maintaining counts below 500 organisms/mL. Chlorine dioxide residuals do not persist a long time and Ozone residuals only persist for a few minutes, thus these disinfectants are not suited for secondary disinfection. **Free chlorine and chloramines are most commonly used for secondary disinfection.**

Example Problem No. 11

A direct filtration water treatment plant uses ozone for primary disinfection. The ozone contactor has a hydraulic retention time (HRT) of 2.0 minutes at design flow with superior baffling characteristics. The minimum water temperature is 10 °C and the pH ranges between 6.8 and 7.5.

- A. (PM)The surface water treatment rule requires this plant to achieve what level of Giardia inactivation through disinfection:
 - a) 0.5 Log
 - b) 1.0 Log
 - c) 2.0 Log
 - d) 3.0 Log

B. (PM) The minimum ozone residual following the contactor in mg/L is most nearly:

- a) 1.02 b) 0.71 c) 0.57 d) 0.36

C. (AM) Of the following choices for secondary disinfectant, which is most appropriate to protect the distribution system:

- a) Chlorine b) Ozone c) UV d) none of the above

Softening

Hardness is a quality of water caused by multivalent metallic cations. Calcium, Ca^{+2} , and magnesium, Mg^{+2} , are the most common in drinking water. The concentration of Ca^{+2} and Mg^{+2} expressed in mg/L of CaCO_3 is equal to the total hardness. Water is classified according the following table:

Classification	mg/L as CaCO_3
Soft	<60
Moderately Hard	61-120
Hard	121-180
Very Hard	181-350
Saline, brackish	>350

Hardness can be classified as carbonate hardness and non-carbonate hardness. Carbonate hardness is hardness available to combine with the alkalinity in the water (HCO_3^-). Non-carbonate hardness is the hardness in excess of the alkalinity. Thus, if total hardness is less than or equal to alkalinity, then all hardness is carbonate. If total hardness is greater alkalinity, then the carbonate hardness is equal to alkalinity and non-carbonate hardness is equal to the difference between total hardness and alkalinity.

Softening is the removal of hardness or the removal of Ca^{+2} and Mg^{+2} from the water. Softening can be accomplished by Lime and Soda Ash softening, zeolite softening and ion exchange softening. In addition reverse osmosis and nanofiltration can achieve some degree of softening.

Lime softening

Lime softening is a precipitation process used to remove hardness and other contaminants from water. The process involves the addition of lime and soda ash to react with the soluble forms of Ca^{+2} and Mg^{+2} to form insoluble precipitates. The precipitates are then settled from the water. Finished water is then stabilized by a process called recarbonation. Recarbonation is the addition of carbon dioxide to react with excess lime and remaining precipitates to lower the pH and prevent the build up of hardness scale.

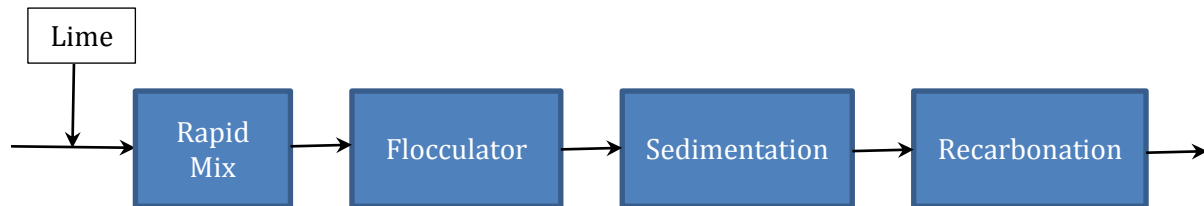


Figure 12 - Single Stage Lime Softening Flow Sheet

Single stage softening is used for selective calcium removal and carbonate hardness removal. Lime dosed to react with the carbon dioxide and calcium is used in the single stage process for selective calcium removal. For carbonate hardness removal, the lime dose is based on the carbon dioxide, calcium and carbonate magnesium hardness with excess lime added to ensure magnesium removal. The precipitation of magnesium carbonate hardness requires a pH above 10.6, thus excess lime addition may be practiced to increase the pH to a level sufficient for formation of magnesium hydroxide precipitants.

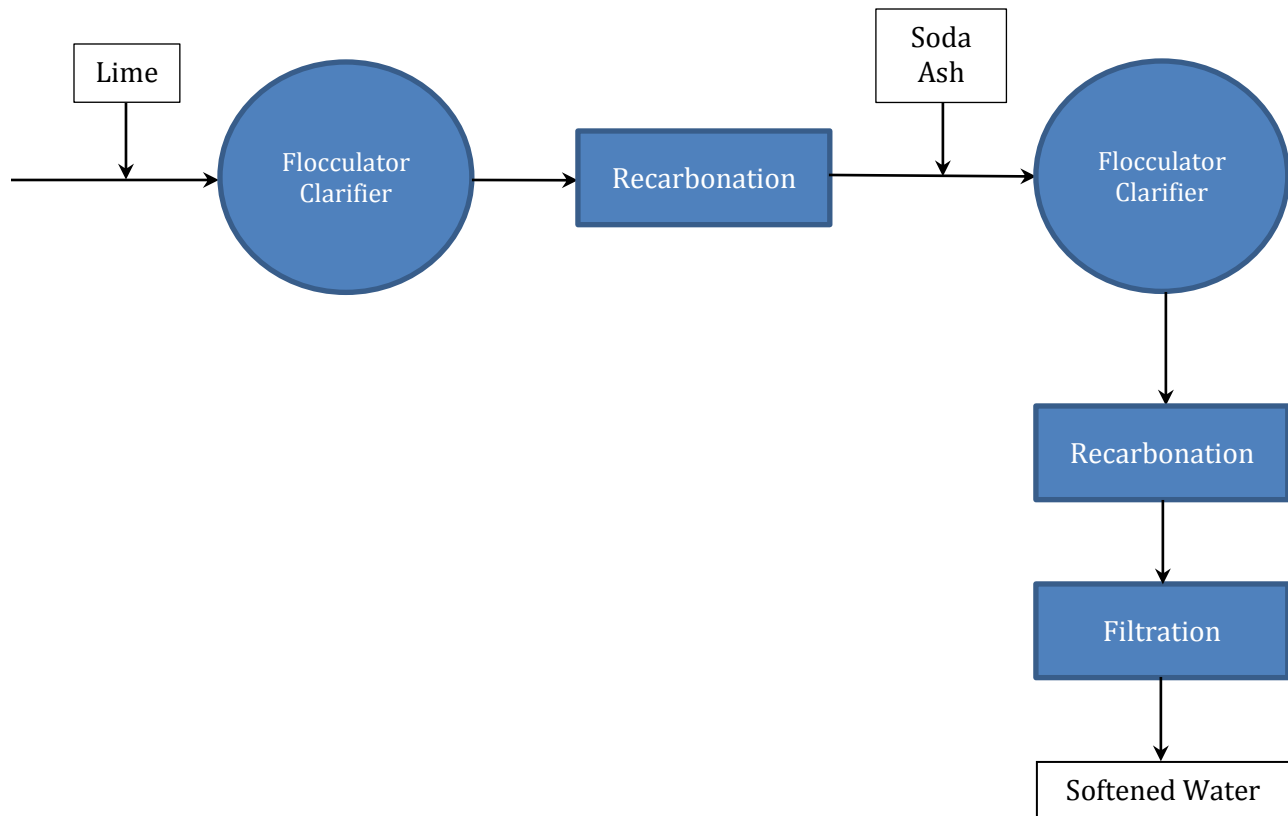


Figure 13 – Two Stage Lime-Soda Ash Softening Flow Sheet

The lime is responsible for converting the carbonate hardness in the first stage and the soda ash is used to convert non-carbonate hardness in a second stage. In the case of magnesium non-carbonate hardness, the lime precipitates the magnesium and leaves non-carbonate calcium hardness in its place that can then be precipitated by the soda ash.

Dosing

Dosing of Lime and Soda Ash depends upon the concentrations of calcium and magnesium hardness, alkalinity, and the concentration of carbon dioxide present in the water. Lime will react preferentially with carbon dioxide, thus it must first be reduced by pre-aeration or additional lime must be added to react with all the carbon dioxide. Dosing is determined as follows:

- One equivalent of Lime per each equivalent of CO₂.
- One equivalent of Lime per each equivalent of carbonate Ca⁺².
- Two equivalents of Lime per each equivalent of carbonate Mg⁺².
- One equivalent of Lime per each equivalent of non-carbonate Mg⁺².
- One equivalent of Soda Ash per each equivalent of non-carbonate hardness.

Recarbonation can be performed as a single stage process or in two stages. In the single stage process sufficient CO₂ is added to lower the pH to about 7. This converts the hydroxides to bicarbonates without precipitating any calcium. Two stage recarbonation allows for the precipitation of calcium in between stages. In the first stage sufficient CO₂ is added to convert the

Calcium hydroxide ($\text{Ca}(\text{OH})_2$) to Calcium carbonate (CaCO_3) which forms a precipitant that can be settled to remove the calcium. In the second stage any unsettled CaCO_3 is converted to calcium bicarbonate ($\text{Ca}(\text{HCO}_3)_2$). Single stage recarbonation dosing is determined based on the softened water analysis as follows:

- Two equivalents of CO_2 per equivalent of excess lime.
- One equivalent of CO_2 per equivalent of unsettled hardness.

Two stage recarbonation dosing is determined for each stage. The first stage is calculated based on the hydroxide alkalinity or

- One equivalent of CO_2 per equivalent of excess lime or hydroxide (OH) alkalinity.

The second stage recarbonation dose is determined based on the remaining unsettled hardness precipitants:

- One equivalent of CO_2 per equivalent of unsettled hardness.

Note that in the two stage process, the first stage converts the hydroxides to precipitants that are settled prior to the second stage. The hardness is reduced by settling prior to the second stage and thus is less than the hardness in the effluent from the first stage. The unsettled hardness in the influent to the second stage is dependent upon the efficiency of the settling basin used.

Ion Exchange

Ion exchange processes typically use a media of resin beads to adsorb hardness. The beads are activated by soaking in a brine solution of salt and water. The beads adsorb the sodium from the salt. When hard water is passed over the beads, the multivalent metallic cations trade places with the sodium ions. When the beads have adsorbed all the hardness it can, they can be regenerated by soaking in brine causing another ion exchange of sodium for hardness. Resin capacity is determined experimentally and given as hardness equivalents.

In water treatment facilities, the resin can be contained in pressure vessels or in open top concrete tanks. Pressure vessels are more common in small plants while concrete tanks are more economical for large plants. The process has four stages: treatment, backwashing, regeneration, and rinsing.

In the treatment stage, hard water is fed into the vessel at a hydraulic loading rate between 2 and 5 gpm/ft² depending upon the feed water hardness. The resin quantity required is dependent upon the flow rate, hardness, and frequency of regeneration. The depth of the resin in the vessel is typically between 2 and 5 feet. Pretreatment of the feed water is usually necessary to reduce suspended solids and provide turbidity less than 1 NTU. Iron and manganese typically must be removed from the influent if any dissolved oxygen is present to prevent fouling of the resin by oxides. Chlorine should not be present in the feed water. Organic material in the feed water can increase fouling and encourage biological growth in the resin.

The backwash is required to remove fouling materials from the resin especially the material that accumulates within the top layer of the resin during treatment. A fouled top layer increases the headloss across the resin bed and leads to channeled water flow through the bed and hardness leakage. The backwash cycle is typically 10 minutes long and expands the resin bed 50 to 75%. Sufficient head room must be provided in the vessel to accommodate the bed expansion.

The regeneration of the resin is accomplished with a brine solution. The concentration of salt in the brine is less important than the flow rate and contact time. Typically, about 10 lb NaCl per ft³ of resin is used for regeneration. The flow rate should not exceed 1 gpm/ft³ and the contact time should be at least 30 minutes.

Regeneration is followed by rinsing to remove excess Na⁺ ions from the resin. The rinse should be started as the regeneration is finishing at the same flow rate as the regeneration. This slow rinse should continue until 1 or 2 bed volumes of rinse water have been applied. The slow rinse is followed by a fast rinse with an increase in flow to about 1.5 gpm/ft³ that continues until the sodium concentration is reduced to less than 5 mg/L above the rinse water sodium concentration.

The volume of resin can be calculated as follows:

$$V = \frac{QHT100}{24EP}$$

Where:

V = Required resin volume, ft³.

Q = Flow rate, g/d.

H = Raw water hardness, kilograins/gal as CaCO₃.

T = Time between regeneration cycles, hours.

E = Resin exchange capacity, kilograins/ft³ as CaCO₃.

P = Average percent of time contactors are operating, %.

Effluent from ion exchange water softeners is usually less than 1 percent of the influent hardness. Hardness below 100 mg/L as CaCO₃ is typically considered desirable so effluent from the softener can be blended with unsoftened water to achieve a finished water with the desired level of hardness.

Example Problem No. 12

A water treatment plant treats a raw water with the following characteristics using a softening process.

pH = 7.5		
Carbon dioxide	CO ₂	5.7 mg/L
Calcium	Ca ⁺²	71.6 mg/L
Magnesium	Mg ⁺²	22.2 mg/L
Sodium	Na ⁺	4.7 mg/L
Bicarbonate	HCO ₃ ⁻	235 mg/L
Sulfate	SO ₄ ⁻	57.5 mg/L

Chloride Cl⁻ 19.4 mg/L

A. (PM) Assume that only selective calcium softening is required. The dose of lime in mg/L as CaCO₃ is most nearly:

- a) 77 b) 192 c) 270 d) 324

B. (PM) If calcium and magnesium are to be removed, an excess lime addition of 20 mg/L of Ca(OH)₂ is required. The total lime dose in mg/L as CaCO₃ is most nearly:

- a) 77 b) 192 c) 270 d) 324

C. (PM) Removal of the non-carbonate hardness requires the addition of soda ash with a dose in mg/L as CaCO₃ of most nearly:

- a) 12.9 b) 46 c) 77 d) 91

D. (PM) The effluent from the lime and soda ash softening process has a total hardness of 50 mg/L as CaCO₃ and includes the 20 mg/L of excess lime. Single stage recarbonation is planned for this water, the dose of carbon dioxide required in mg/L of CO₂ is most nearly:

- a) 12.9 b) 46 c) 77 d) 91

Advanced Treatment

Membranes

Membranes are special filtration process that uses manufactured membranes with tightly controlled pore sizes. The size of the pores determines the particle size excluded. Membranes can be manufactured in a range of pore sizes to preclude tiny particles such as dissolved solids in the case of RO membranes, viruses in the case of nanofiltration membranes, bacteria in the case of microfiltration membranes and visible particles in the case of ultrafiltration membranes.

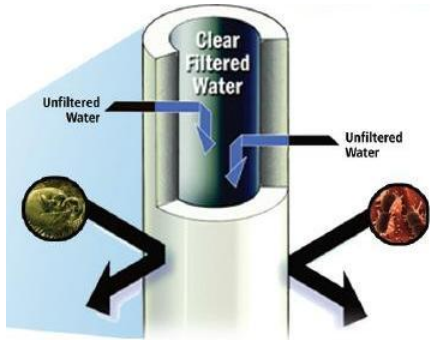


Figure 14 - Membrane Flow Diagram

Membranes are designed based on a hydraulic loading rate typically in GPM/FT² of membrane surface area. Hollow fiber membranes are most commonly used in water treatment. The membranes are bundled inside a hollow stainless steel cylinder with the hollow center of each fiber exposed at one end and sealed at the other.



Figure 15 - A Bundle of Fiber Membranes

Influent is to the steel cylinder where the pressure forces the water through the membrane pores to the center of the hollow fiber, where the permeate is collected at the end of the fiber. The cylinders are piped together in a module that operates together. The membranes require frequent cleaning by back pulsing or backwashing. Back-pulsing or backwashing is accomplished by reversing the flow through the membranes and collecting the backwash waste for separate processing.

Activated Carbon

Activated Carbon is used to remove natural and synthetic organic compounds, taste and odor causing compounds, and disinfection byproducts from water. Activated carbon uses adsorption to remove organic compounds from water. **Adsorption is the attraction and accumulation of one substance on the surface of another.** Organic compounds are attracted to the surface of activated carbon, making activated carbon effective at removing taste and odor causing compounds as well as disinfection by-product precursors. Organic solvents, pesticides and herbicides can be reduced to trace levels using activated carbon. The activated carbon most commonly used in water treatment is made from coal which is activated by heating to a very high temperature in a steam environment. The activated carbon can be pulverized into a powder producing Powdered Activated Carbon (PAC). Alternatively, it can be processed in granular form to produce Granular Activated Carbon (GAC). Analysis of the adsorptive capacity of activated carbon is based on isotherms determined experimentally. The equation for the isotherm is:

$$\frac{x}{m} = kC^{1/n}$$

Where:

x = the mass of compound adsorbed onto the carbon, lb.

m = the mass of activated carbon, lb.

C = the residual concentration of compound, mg/L.

k and n = isotherm constants determined experimentally for the specific compound and for the specific activated carbon.

For design values, a safety factor is included:

$$\left(\frac{x}{m}\right)_d = kC_0^{-1/n} * SF$$

Where:

$\left(\frac{x}{m}\right)_d$ = the design capacity of the GAC to retain the compound to be removed in lb of compound per lb of GAC.

C_0 = Influent Concentration, mg/L

SF = Safety factor for design, usually between 0.75 and 0.90.

k and n = isotherm constants.

Powdered Activated Carbon (PAC)

PAC is used in water treatment primarily for taste and odor control. PAC is often used for removal of color and certain organic compounds that might interfere with coagulation and filtration in addition to removal of taste and odor causing compounds. One advantage of PAC is that it can be easily retrofitted to an existing plant. The addition of storage and feed facilities is sufficient to add the PAC to the treatment system with other chemicals. Contact time with the water is achieved in the mixing and sedimentation basins as the PAC is removed in the filters. Used PAC is removed from the water with sedimentation basin sludge and filter backwash wastewater. PAC can be stored dry in bags or silos and fed with a gravimetric or volumetric feeder into an educator for

delivery of the slurry to the treatment process. Alternatively, it can be unloaded into slurry tanks where it is mixed with water and fed from the slurry tank to the process by chemical metering pumps. Doses of PAC vary from about 1 to 5 mg/L for taste and odor control, and up to 20 or 30 mg/L for severe tastes and odors and other compound removal. Dosages can be determined from isotherm information and verified with bench tests and full scale experience.^{vi}

Doses calculated using isotherms can be determined as follows:

$$D = \frac{(C_0 - C)}{\left(\frac{x}{m}\right)_d}$$

Where:

D = PAC dose to achieve removal of compound, mg/L.

C_0 = Influent concentration of compound to be removed, mg/L.

C = Effluent concentration of compound to be removed, mg/L.

$\left(\frac{x}{m}\right)_d$ = Design removal capacity of the PAC for the compound, lb/lb.

Granular Activated Carbon (GAC)

GAC can be used in small quantities for taste and odor control and in large contactors for other organic compound removal. GAC requires the following system components:

- A contactor for the water to be treated for the length of time required to achieve the necessary removal of organic compounds.
- Reactivation or replacement of spent carbon.
- Transport of the activated carbon to the contactors.
- Transport of spent activated carbon from the contactors to reactivation or disposal facilities.
- Facilities to backwash the GAC beds in the contactors.^{vii}

The contactors contain the beds of GAC and are designed based on the Empty Bed Contact Time (EBCT) and the approach velocity or hydraulic loading rate, v_a .

$$EBCT = \frac{\text{contactor volume}}{\text{flow}} = \frac{V_c}{Q}$$

Where:

EBCT = Empty Bed Contact Time

V_c = Contactor volume

Q = Flow through contactor

$$v_a = \frac{\text{flow}}{\text{contactor area}} = \frac{Q}{A_c}$$

Where:

v_a = HLR or approach velocity.

Q = Flow through contactor.
A_s = Surface area of the GAC bed.

The adsorptive capacity of a GAC contactor is described as the number of Empty Bed Volumes (EBV) of water that can be treated before the GAC is exhausted. The design capacity of the GAC from the isotherm analysis can be used to estimate the EBV:

$$EBV = \left(\frac{x}{m}\right)_d \frac{\rho_B}{(C_0 - C)} \times 16,000$$

Where:

EBV = The number of empty bed volumes of water that can be treated.

$\left(\frac{x}{m}\right)_d$ = The design capacity of the GAC in lb/lb.

ρ_B = The bulk density (unit weight) of the GAC in lb/ft³.

C_0 = The influent compound concentration in mg/L.

C = The effluent compound concentration in mg/L, usually = 0.

16,000 = unit conversion factor.

To determine the total run time of a contactor, we can calculate the time to exhaustion of the GAC bed:

$$T_E = \left(\frac{x}{m}\right)_d \frac{\rho_B}{(C_0 - C)} \times EBCT \times 11.1$$

Where:

T_E = Time to exhaustion in days.

EBCT = Empty bed contact time in minutes.

11.1 = unit conversion factor.

Others as defined above.

Desalination

There are many processes that can be used for removal of ions (salt) from water including distillation, reverse osmosis, electrodialysis and ion exchange. Distillation is a process by which the brine (saline water) is heated to boiling, the steam collected and condensed. The vaporization of the water leaves the ions in the brine and thus the condensate is ion free. Distillation is energy intensive in comparison to other alternatives and generally impractical for large scale water treatment. Reverse osmosis, electrodialysis, and ion exchange are discussed below.

Reverse Osmosis

Reverse osmosis is the natural process of osmosis forced to operate in reverse. Osmosis is the natural tendency of water on two sides of an osmotic membrane to equalize the salinity between the two as shown in Figure 16. During osmosis, water flows through the membrane from the fresh water side to the saline (brine) side. The osmotic pressure is the pressure difference between the saline side and the fresh side of the membrane at which no fluid flows through the membrane.

Thus, reverse osmosis occurs when pressure in excess of the osmotic pressure is applied to the saline side to force fluid through the membrane to the fresh water side as shown in Figure 16.

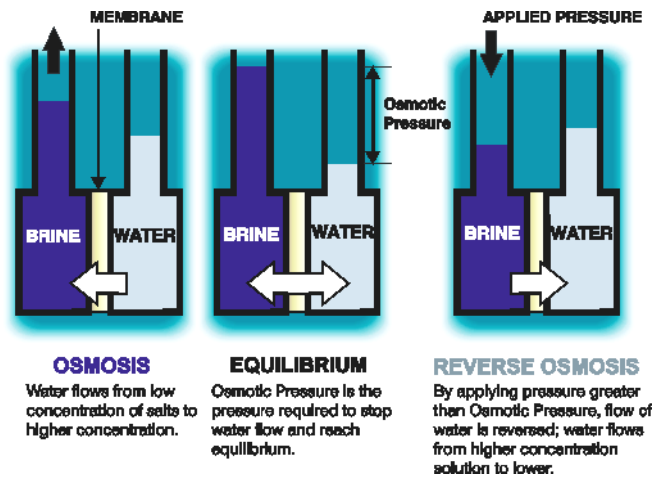


Figure 16 - Reverse Osmosis Illustrated

The effective size of the pores in a RO membrane is between 0.1 to 1.2 nm (0.0001 to 0.0012 μm). This pore size rejects most solute ions and molecules and is effective at excluding cysts, bacteria, viruses, natural organic matter (NOM), and disinfection by-products (DBPs). RO membranes systems are available in four different configurations: plate and frame, tubular, spiral wound, and hollow fiber. The spiral wound configuration is most commonly used in water treatment. Water to be treated is pumped into the RO unit at high pressure, exceeding the osmotic pressure. Water that passes through the membrane is called the permeate or product water and exits the membrane at near atmospheric pressure. The water containing the remaining ions is called the concentrate or reject water and leaves the RO unit at near influent pressure. Operating pressure for seawater desalination is between 800 and 1200 PSI, while pressures used for desalting brackish waters is between 300 and 600 PSI. The concentrate produced by desalting seawater is about 50 to 60% of the influent, while concentrate produced by desalting brackish water is about 10 to 25% of the influent.^{viii}

The average driving pressure is called the transmembrane pressure:

$$P_{tm} = \frac{P_{in} - P_{out}}{P_p}$$

Where:

P_{tm} = Transmembrane pressure, psi.

P_{in} = Inlet water pressure, psi.

P_{out} = Outlet water pressure, psi.

P_p = Permeate water pressure, psi.

A number of relationships have been developed to determine or estimate the osmotic pressure. When solute concentrations are low the EPA equation may be used:

$$\Delta\pi = C_S RT$$

Where:

$\Delta\pi$ = Osmotic pressure, psi.

C_S = concentration of solutes in solution, mol/ft³.

R = ideal gas constant, ft lb/mol K.

T = Absolute temperature, Kelvin = °C + 273.

Recovery is the term used to describe the quantity of permeate produced by an RO system as a function of the influent:

$$R = \frac{Q_P}{Q_f} 100 = \left(\frac{Q_P}{Q_P + Q_C} \right) 100$$

Where:

R = Recovery in %.

Q_P = Product water flow, gpm.

Q_f = Feed water flow (influent), gpm.

Q_C = Concentrate water flow, gpm.

Thus, the reject water is the difference between the feed water and product water. The concentrate factor describes the increase in concentration of solute in the concentration flow as a function of the recovery:

$$CF = \frac{1}{1 - R}$$

Where:

CF = concentration factor, decimal.

R = recovery, decimal.

The water flux through the membrane is described as a HLR in units of gallons per day per square foot of membrane surface area. The water flux can be estimated by:

$$J = k_W(\Delta P - \Delta\pi) = \frac{Q_P}{A}$$

Where:

J = Membrane flux, g/d/ft².

k_W = mass transfer coefficient for water, g/d/ft²/psi.

ΔP = pressure drop across the membrane (transmembrane pressure), psi.

$\Delta\pi$ = Osmotic pressure, psi.

Q_P = Product water flow, g/d.

A = Membrane surface area, ft².

Since membranes contain imperfections some solute will be transferred across the membrane. The solute flux is given by:

$$J_i = k_i \Delta C = \frac{Q_P C_P}{A}$$

Where:

J_i = Solute flux, lb/d/ft².

k_i = Solute mass transfer coefficient, ft/d.

ΔC = Concentration gradient, lb/ft³.

Q_P = Permeate flow rate, ft³/d.

C_P = Permeate stream solute concentration, lb/ft³.

A = Membrane surface area, ft².

The simplest model to estimate the permeate solute concentration is the Linear Solution Diffusion Model:

$$C_P = \frac{k_i C_f}{k_w (\Delta P - \Delta \pi) [(2 - 2R)/(2 - R)] + k_i}$$

Where variables are defined as above.

Electrodialysis

Electrodialysis (ED) is similar to RO in that it uses a selective membrane to separate salts (solutes) from water. However, electrodialysis is electrically driven instead of pressure driven. ED uses permselective or ion-selective membranes. Ion-selective membranes have the ability to discriminate between positive and negative ions. Cation-exchange membranes are permeable to cations but not anions, while anion-exchange membranes are permeable to anions but not cations. ED works by using one membrane of each type to separate a vessel into three compartments in series. The middle compartment between the two membranes is where the dialysate is produced. In the compartment bounded by the anion-exchange membrane, an electrical cathode is placed. In the compartment bounded by the cation-exchange membrane, an electrical anode is placed. When the anode and cathode are connected by a DC current, the cathode attracts anions and the anode attracts cations thus pulling both through the selective membranes from the center compartment.

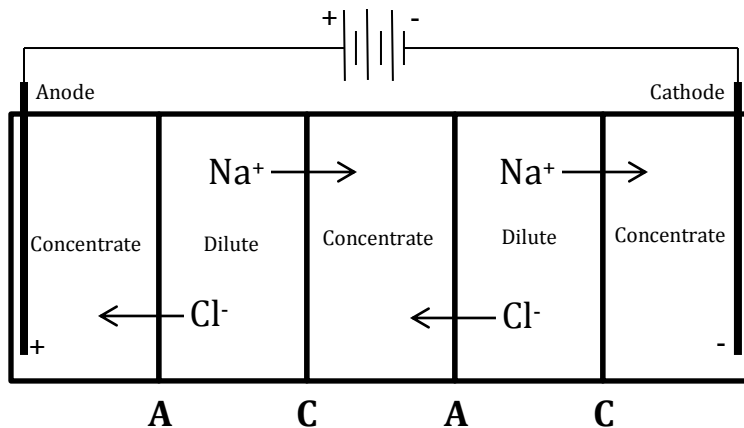


Figure 17 - Electrodialysis modules or stack

Electrodialysis Reversal (EDR) is a variation in which the arrangement of membranes is such that there are four compartments with the two in the middle separated by an anion-exchange membrane and the end compartments separated from the middle by cation-exchange membranes. This creates a concentrate and product in the center two compartments.

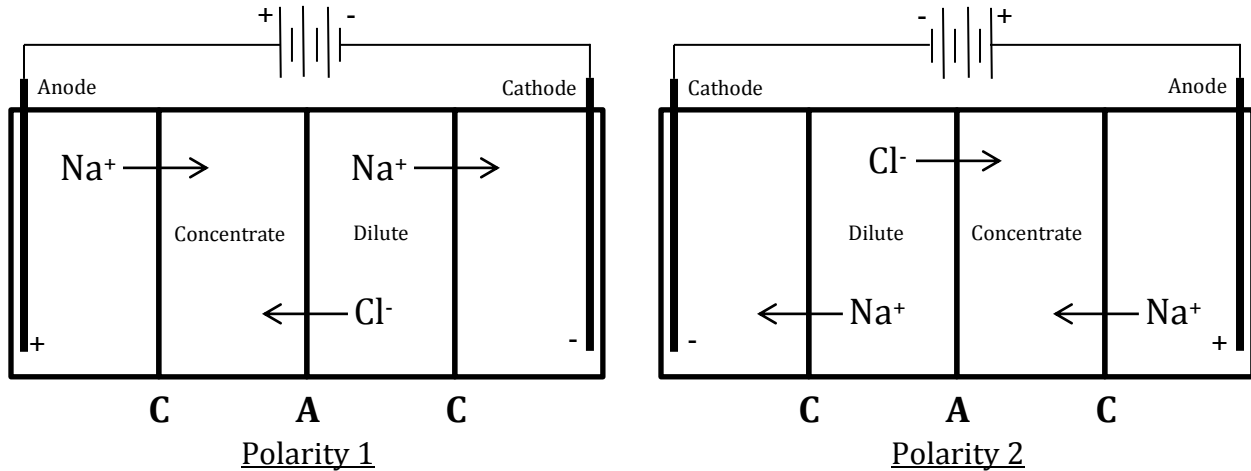
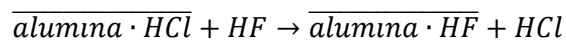


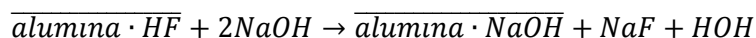
Figure 18 - Electrodialysis Reversal

Activated Alumina

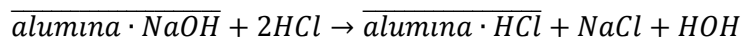
Packed beds of Activated Alumina can be used to remove fluoride, arsenic, selenium, silica, and humic materials from water.^{ix} Activated alumina is made by dehydrating aluminum hydroxide $Al(OH)_3$ to form a mixture of amorphous and gamma aluminum oxide ($\gamma-Al_2O_3$). The alumina particles are usually between 0.3 and 0.6 mm in diameter with a surface area of about 50 to 300 m^2/g . Alumina removes anions from water by exchanging the anion with hydroxides from the alumina. The process begins with neutral water washed alumina that is acidified with an acid wash to activate the alumina producing an alumina with acid molecules attached to the surface. Water containing fluoride, arsenic, selenium or other contaminant is fed to the bed of alumina. The anions displace the acid molecules. The displacement of hydrochloric acid (HCl) by fluoride (HF) is illustrated as:



The alumina is regenerated with a dilute solution of sodium hydroxide (NaOH). The sodium hydroxide displaces the fluoride producing sodium fluoride (NaOH) and water (HOH) as shown below:



To prepare the alumina for additional treatment it is washed in acid again to displace the sodium hydroxide as shown below:



Thus, the alumina is ready to perform additional removal. Unlike ion exchange resins the repetitive cycle of acidification and regeneration wears on alumina. Reactions with the acid and sodium hydroxide produce soluble forms $[Al(H_2O)_6^{3+}, Al(H_2O)_2(OH)_4^-]$ of aluminum thus slowly dissolving the media.

Corrosion Control

Controlling the corrosivity of water to maintain non-corrosive water is a strategy to protect the quality since some piping and plumbing systems contain materials that can be harmful to human health. For example, lead and copper finds its way from plumbing system materials into drinking water that is corrosive.

Corrosion control is often linked to the propensity for water to scale. Scaling is the deposition of calcium or magnesium on the walls of pipes, etc. Theoretically, a thin film of scale protects pipes, etc. from corrosion. The propensity to scale is dependent upon the hardness, alkalinity, total dissolved solids, temperature and pH of the water. The Langelier Saturation Index (LSI) or the Ryznar Stability Index (RSI) are two factors used to indicate the scaling potential of water. These indices are based on the calculated pH of saturation for calcium carbonate, pH_s . When the pH of the water is greater than pH_s , calcium carbonate scale is deposited.

$$LSI = pH - pH_s$$

$$RSI = 2pH_s - pH$$

Table 8 - Interpretation of Langelier Saturation Index

LSI Value	Indication
2.0	Scale forming but non-corrosive
0.5	Slightly scale forming and corrosive
0	Balanced but pitting corrosion possible
-0.5	Slightly corrosive but non-scale forming
-2.0	Highly corrosive

Table 9 - Interpretation of the Ryznar Stability Index

RSI Value	Indication
4.0 – 5.0	Heavy Scale
5.0 – 6.0	Light Scale
6.0 – 7.0	Little Scale or Corrosion
7.0 – 7.5	Corrosion Significant
7.5 – 9.0	Heavy Corrosion
≥ 9.0	Corrosion Intolerable

The pH_s is a function of the calcium hardness, total dissolved solids, water temperature and alkalinity. The pH_s is calculated as follows:

$$pH_s = (9.3 + A + B) - (C + D)$$

Where:

$$A = (\log(TDS) - 1)/10$$

$$B = (-13.12 \log(^{\circ}\text{C} + 273)) + 34.55$$

$$C = (\log(\text{Ca Hardness})) - 0.4$$

$$D = \log(\text{Alkalinity})$$

TDS=Total Dissolved Solids, mg/L

$^{\circ}\text{C}$ = Water Temperature, $^{\circ}\text{C}$

Ca Hardness, mg/L as CaCO_3

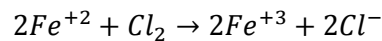
Alkalinity = total in mg/L as CaCO_3

Ultraviolet Light

Ultraviolet light (UV) is a powerful disinfectant and can be used to inactivate a wide variety of pathogens including cryptosporidium which is resistant to chlorine. UV can also be used with oxidants to oxidize organic carbon and reduce precursors to disinfection byproducts. Design of UV systems is based on the dose of the UV light at a wavelength of 254 nm in megajoules per square centimeter (MJ/cm^2).

Oxidation/Filtration

Oxidation/filtration is the use of an oxidant to oxidize contaminants to an insoluble form that can be filtered from the water. A chemical is oxidized when it loses electrons to another substance. The loss of electrons increases the oxidation state, the valence, of the substance while the other substance incurs a reduction in its oxidation state. This reaction is commonly referred to as an oxidation-reduction reaction. An example of oxidation of ferrous iron to ferric iron by chlorine is shown below:



In the reaction one electron is given up by each iron molecule, the two electrons are taken by the chlorine to produce chloride.

Packed Tower Aeration

Packed tower aeration is used to strip volatile compounds from water including odor causing compounds like hydrogen sulfide, as well as volatile organic compounds such as solvents. The unit sprays the contaminated water over packing in a vertical tower the water flows over and through the packing to the bottom of the tower. Just above the bottom, air is blow into and upward through the tower. The packing increases the surface area of the water exposed to the air allowing the stripping of various volatile compounds.

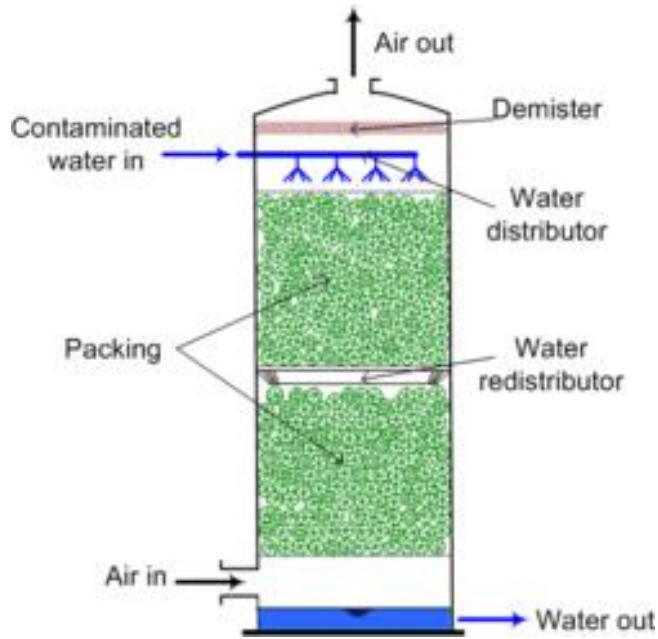


Figure 19 - Packed Tower Aerator

Enhanced Coagulation

The addition of higher doses of coagulation to remove a particular contaminant or class of contaminants, such as total organic carbon (TOC). Typical coagulation is typically optimized for turbidity removal. Enhanced coagulation is optimized for the removal of the target contaminant or class of contaminants.

If an excess of alum is added so that the dosed water pH is less than 5.0, then the metal ions (Al^{3+}) directly neutralize the negatively charged organic compounds and colloids in the raw water. This allows the organic molecules to contribute to floc formation and is often referred to as *enhanced coagulation*. This is often done to boost the removal of disinfection by-product (DBP) precursors. Obviously, coagulating at such a low pH requires attention to potential corrosion problems, as well as the need for post-treatment pH adjustment /alkalinity adjustment to ensure that the treated water is not corrosive.

ⁱ Water Quality and Treatment: a handbook of community water supplies. American Water Works Association, 4th Ed. McGraw Hill, Inc. 1990, p. 20-22.

ⁱⁱ Water Supply and Pollution Control. Viessman, Jr., Warren; Hammer, Mark J.; 6th Ed., Addison Wesley Longman, Inc., 1998, p. 173

ⁱⁱⁱ Water Quality and Treatment: a handbook of community water supplies. American Water Works Association, 4th Ed. McGraw Hill, Inc., 1990, p. 352, 353.

^{iv} Water Quality and Treatment: a handbook of community water supplies. American Water Works Association, 4th Ed. McGraw Hill, Inc., 1990, p 614.

^v Water Quality and Treatment: a handbook of community water supplies. American Water Works Association, 4th Ed. McGraw Hill, Inc., 1990, p 614.

^{vi} Handbook of Public Water Systems, HDR Engineering, Inc., 2nd Ed., John Wiley & Sons, 2001, p. 564.

vii Ibid.

viii Water and Wastewater Calculations Manual. Lin, Shun Dar; Lee, C.C.; 2nd ed., McGraw Hill Companies, Inc., 2007, p. 448, 449.

ix Water Quality and Treatment: a handbook of community water supplies. American Water Works Association, 4th Ed. McGraw Hill, Inc., 1990, p. 567.

Water Chemistry

Definitions

Atomic Weight: weight of an element relative to Hydrogen. Hydrogen = 1.

Anions: ions with a negative charge.

Cations: ions with a positive valence.

Equivalent Weight: molecular weight of a substance divided by the electrical charge (valence) of the element of the substance. Combining weight of an ion, radical or compound.

$$\text{equivalent weight} = \frac{\text{atomic weight}}{\text{valence}}$$

$$\text{meq} = \text{mg} / \text{l} \times \frac{\text{valence}}{\text{atomic weight}} = \frac{\text{mg} / \text{l}}{\text{equivalent weight}}$$

Ions: atoms or groups of atoms with a positive or negative charge.

mole: molecular weight expressed in grams.

Multivalent: having a valence of 2 or greater.

Radicals: groups of atoms that act together as a unit in a large number of molecules, e.g. Hydroxyl (OH⁻).

Valence: combining power of element based on Hydrogen atom. Hydrogen Atom = 1, 2⁺ can replace 2 hydrogen atoms, 2⁻ can combine with 2 hydrogen atoms.

Mass and Concentration relationships

A concentration of a substance is the mass of the substance per unit volume of water.

Concentrations are generally described in units of mg/L which is equivalent to parts per million for low concentrations. High concentrations may be expressed as a mass percentage of the total mass that is the substance. For example, thickened sludge is usually expressed in terms of the percentage of solids in the sludge; 3 to 5% solids is common in thickened sludge. This means that 3 to 5 percent of the total mass of the sludge is solids while the remaining mass (95-97 percent) is water.

We can determine the mass of a substance entering a unit process, given the concentration. For example if 100 million gallons (MG) of water flows into a unit process with a concentration of a substance equal to 200 mg/L, then the total mass of the substance entering the unit process is given by:

$$\text{Mass of solids} = 100 \text{ MG} * 200 \text{ mg/L} = 20,000 \text{ MG*mg/L}$$

If we remember that mg/l is equivalent to parts per million and the unit weight of water is 8.34 lb/G then:

$$\text{Weight of solids} = 100 \text{ MG} * 200 \text{ ppM} * 8.34 \text{ lb/G} = 166,800 \text{ lb.}$$

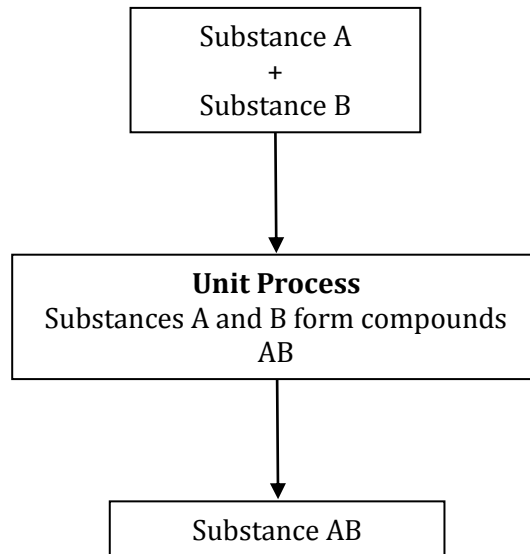
We can use this expression to determine mass flows. For example a unit process has an influent flow of 5 million gallons per day (MGD) with a concentration of 35 mg/L of substance A, the mass flow into the unit process is:

$$\text{Mass flow} = 5 \text{ MGD} * 35 \text{ mg/L} * 8.34 \text{ lb/G} = 1,459.5 \text{ lb/D.}$$

These concepts are useful when performing mass balances around individual unit processes or treatment trains composed of several unit processes.

Mass Balance

A Mass balance is based on the principal of conservation of mass which says that the mass of a substance entering a process is equal to the mass of the substance converted in the process plus the mass exiting the process. For example in the diagram below a mass of substance A and substance B is added to a unit process resulting in a discharge from the process of a compound, substance AB. The mass of substance A that enters the unit process must equal the mass of substance A in the compound AB. The same is true with substance B, so that the total mass of substance A plus substance B is equal to the mass of substance AB.



The diagram below represents a hypothetical unit process. If 10 million gallons per day (MGD) of water with a concentration of 200 mg/L of substance A enters the process from the top, and 9 MGD of water with a 100 mg/L concentration of substance A in the effluent to the right of the unit

process, the concentration of substance A in the effluent below the unit process is determined as follows:

Balance flows:

$$10 \text{ MGD} = 9 \text{ MGD} + B \text{ MGD}$$

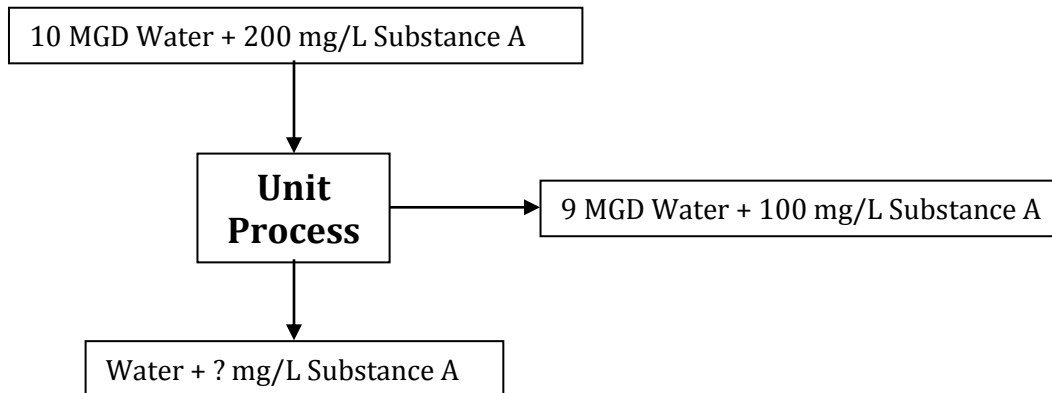
$$B = 10 - 9 = 1 \text{ MGD}$$

Balance mass:

$$10 \text{ MGD} \left(200 \frac{\text{mg}}{\text{L}}\right) = 9 \text{ MGD} \left(100 \frac{\text{mg}}{\text{L}}\right) + 1 \text{ MGD} \left(A \frac{\text{mg}}{\text{L}}\right)$$

$$A = \frac{2000 \text{ MGD} \left(\frac{\text{mg}}{\text{L}}\right) - 900 \text{ MGD} \left(\frac{\text{mg}}{\text{L}}\right)}{1 \text{ MGD}} = \frac{1100 \text{ mg}}{1 \text{ L}} = 1100 \frac{\text{mg}}{\text{L}}$$

The concentration exiting the flow at the bottom is 1100 mg/L.



Chemical Feed

Chemicals for water treatment come in gases, liquids and solids. Gases used for water treatment include chlorine, carbon dioxide, and ozone. Liquids include alum solutions, ferric solutions, polymers, acids, and bases. Solids include lime, alum, powdered activated carbon, potassium permanganate and other chemicals.

Some gases are dissolved in water by bubbling them through diffusers, with the water sometimes under pressure to enhance the efficiency. Gases such as chlorine, sulfur dioxide and others can be dissolved in water using ejectors to create a concentrated solution that can be fed to the process water. Vacuum ejectors have a venturi that a stream of water is passed through. The venturi creates a vacuum that draws the gas into the water. The gas flow can be regulated by a rotometer.

Liquids are fed using positive displacement metering pumps. These pumps include, diaphragm, piston, rotary, and peristaltic pumps. The positive displacement nature of these pumps allow them to dispense precise volumes of liquids to the process water.

Solids are generally fed with volumetric or gravimetric dry feeders. These feeders usually feed to a mixing basin where the solid chemicals are dissolved or mixed in a suspension or slurry before being fed to the process water. Some solids are dissolved in water in day tanks and fed to the process as liquids.

Facilities to feed chemicals are generally designed to provide a certain feed rate. Design considerations include minimum and maximum doses, daily consumption, storage quantities and the feed rate. Feed rate, R_F , is generally computed as follows:

$$R_F = \frac{DQ8.34}{P}$$

Where:

R_F = Chemical feed rate in lb/day of active chemical.

D = Dose of chemical required, mg/L.

Q = Process water flow rate, MGD.

P = Potency, or the Decimal fraction of the chemical that is active.

Equipment is selected to provide a variety of feed rates between minimum doses and minimum process flow rates to maximum doses and maximum process flow rates. Often, to achieve the wide variation in feed rate required multiple feed units are provided.

Daily consumption is used to size day tanks. Day tanks are used to provide one day of storage for the actual feeder. Feeders draw from a day tank. Every day, operators refill the day tanks. The average daily consumption also is used to determine costs for chemicals, since chemicals represent a major cost of operating a water treatment plant. The day tanks are filled from larger storage tanks. These storage facilities are designed to store sufficient chemicals to prevent running out between deliveries. Knowledge of local availability of chemicals is important when sizing storage facilities. The delivery method is also an important consideration in the design of storage facilities. Means for unloading tanker trucks, rail cars, etc. are required.

For example, many dry chemicals like lime can be unloaded from trucks or rail cars with forced air. The powdered dry chemicals can be vacuumed from the delivery vehicle into silos.

Calcium Carbonate Equivalents

Since calcium carbonate is the source of alkalinity and hardness in drinking water or because its molecular weight is an even 100, it is often used as the base for describing quantities and concentrations of chemicals in water and used in water treatment. Table 1 provides the name, chemical formula, molecular weight, equivalent weight and the CaCO_3 conversion factor for the chemicals most commonly encountered in water treatment.

For Example, CaCO_3 has a molecular weight of 100 grams per mole and an equivalent weight of 50 grams per mole. Thus one mole, 40 grams, of Ca^{+2} with an equivalent weight of 20 grams per mole imparts a hardness equivalent to 2.5 moles, 250 grams, of CaCO_3 since $50/20=2.50$ (ratio of equivalent weights). Thus the factor for Ca^{+2} is 2.50.

Table 1 - Water Chemistry CaCO₃ Equivalents

Chemical	Formula	Molecular Weight	Equivalent Weight	Factor
Cations				
Aluminum	Al ⁺³	27.0	9.0	5.56
Ammonium	NH ₄ ⁺	18.0	18.0	2.78
Calcium	Ca ⁺²	40.1	20.0	2.50
Cupric copper	Cu ⁺²	63.6	31.8	1.57
Cuprous copper	Cu ⁺³	63.6	21.2	2.36
Ferric iron	Fe ⁺³	55.8	18.6	2.69
Ferrous iron	Fe ⁺²	55.8	27.9	1.79
Hydrogen	H ⁺	1.0	1.0	50.0
Manganese	Mn ⁺²	54.9	27.5	1.82
Magnesium	Mg ⁺²	24.3	12.2	4.10
Potassium	K ⁺	39.1	39.1	1.28
Sodium	Na ⁺	23.0	23.0	2.18
Anions				
Bicarbonate	HCO ₃ ⁻	61.0	61.0	0.82
Carbonate	CO ₃ ⁻²	60.0	30.0	1.67
Chloride	Cl ⁻	35.5	35.5	1.41
Fluoride	F ⁻	19.0	19.0	2.66
Hydroxide	OH ⁻	17.0	17.0	2.94
Nitrate	NO ₃ ⁻	62.0	62.0	0.81
Nitrite	NO ₂ ⁻	46.0	46.0	1.09
Phosphate (tribasic)	PO ₄ ⁻³	95.0	31.7	1.58
Phosphate (dibasic)	HPO ₄ ⁻²	96.0	48.0	1.04
Phosphate (monobasic)	H ₂ PO ₄ ⁻	97.0	97.0	0.52
Sulfate	SO ₄ ⁻²	96.1	48.0	1.04
Sulfite	SO ₃ ⁻²	80.1	40.0	1.25
Compounds				
Aluminum hydroxide	Al(OH) ₃	78.0	26.0	1.92
Aluminum Sulfate	Al ₂ (SO ₄) ₃	342.1	57.0	0.88
Alumina	Al ₂ O ₃	102	17	1.94
Sodium aluminate	Na ₂ Al ₂ O ₄	164.0	27.3	1.83
Calcium bicarbonate	Ca(HCO ₃) ₂	162.1	81.1	0.62
Calcium carbonate	CaCO ₃	100.1	50.1	1.00
Calcium chloride	CaCl ₂	111.0	55.5	0.90
Calcium hydroxide (pure)	Ca(OH) ₂	74.1	37.1	1.35
Calcium hydroxide (90%)	Ca(OH) ₂	-	41.1	1.22
Calcium oxide (Lime)	CaO	56.1	28.0	1.79
Calcium sulfate (anhydrous)	CaSO ₄	136.2	68.1	0.74
Calcium sulfate (gypsum)	CaSO ₄ ·2H ₂ O	172.2	86.1	0.58
Calcium phosphate	Ca ₃ (PO ₄) ₂	310.3	51.7	0.97
Disodium phosphate	Na ₂ HPO ₄ ·12H ₂ O	358.2	119.4	0.42
Disodium phosphate (anhydrous)	Na ₂ HPO ₄	142.0	47.3	1.06

Chemical	Formula	Molecular Weight	Equivalent Weight	Factor
Ferric chloride	FeCl ₃	162.2	54.1	0.92
Ferric oxide	Fe ₂ O ₃	159.6	26.6	1.88
Iron oxide (magnetic)	Fe ₃ O ₄	321.4	-	-
Ferric sulfate	Fe ₂ (SO ₄) ₃	399.9	133.3	0.38
Ferrous sulfate (copperas)	FeSO ₄ ·7H ₂ O	278.0	139.0	0.36
Hydrogen Peroxide	H ₂ O ₂	34.0	17.0	2.94
Magnesium oxide	MgO	40.3	20.2	2.48
Magnesium bicarbonate	Mg(HCO ₃) ₂	146.3	73.2	0.68
Magnesium carbonate	MgCO ₃	84.3	42.2	1.19
Magnesium chloride	MgCl ₂	95.2	47.6	1.05
Magnesium hydroxide	Mg(OH) ₂	58.3	29.2	1.71
Magnesium phosphate	Mg ₃ (PO ₄) ₂	263.0	43.8	1.14
Magnesium sulfate	MgSO ₄	120.4	60.2	0.83
Monosodium phosphate	NaH ₂ PO ₄ ·H ₂ O	138.1	46.0	1.09
Monosodium phosphate (anhydrous)	NaH ₂ PO ₄	120.1	40.0	1.25
Metaphosphate	NaPO ₃	102.0	34.0	1.47
Potassium permanganate	KMnO ₄	158.0	19.8	2.53
Silica	SiO ₂	60.1	30.0	1.67
Sodium bicarbonate	NaHCO ₃	84.0	84.0	0.60
Sodium carbonate (Soda Ash)	Na ₂ CO ₃	106.0	53.0	0.94
Sodium chloride	NaCl	58.5	58.5	0.85
Sodium hydroxide	NaOH	40.0	40.0	1.25
Sodium hypochlorite	NaOCl	74.4	37.2	1.34
Sodium nitrate	NaNO ₃	85.0	85.0	0.59
Sodium sulfate	Na ₂ SO ₄	142.0	71.0	0.70
Sodium sulfite	Na ₂ SO ₃	126.1	63.0	0.79
Tetrasodium EDTA	(CH ₂) ₂ N ₂ (CH ₂ OONa) ₄	380.2	95.1	0.53
Trisodium phosphate	Na ₃ PO ₄ ·12H ₂ O	380.2	126.7	0.40
Trisodium phosphate (anhydrous)	Na ₃ PO ₄	164.0	54.7	0.91
Trisodium NTA	(CH ₂) ₃ N(COONa) ₃	257.1	85.7	0.58
Gases				
Ammonia	NH ₃	17	17	2.94
Carbon dioxide	CO ₂	44	22	2.27
Chlorine	Cl ₂	70.9	35.5	1.41
Chlorine dioxide	ClO ₂	67.5	13.5	1.48
Hydrogen	H ₂	2.0	1	50.00
Hydrogen sulfide	H ₂ S	34	17	2.94
Oxygen	O ₂	32	8	6.25
Ozone	O ₃	48	8	6.25
Acids				
Carbonic	H ₂ CO ₃	62.0	31.0	1.61
Hydrochloric	HCl	36.5	36.5	1.37
Nitric	HNO ₃	63.0	63.0	0.79

Chemical	Formula	Molecular Weight	Equivalent Weight	Factor
Phosphoric	H ₃ PO ₄	98.0	32.7	1.53
Sulfuric	H ₂ SO ₄	98.1	49.1	1.02

Hydrogen Ion Concentration and pH

Water, H₂O, dissociates into hydrogen and hydroxide ions: H⁺ and OH⁻, at the rate of 10⁻⁷ mole hydrogen atoms per liter of water. We define the dissociation constant for water, K_w as:

$$K_w = [H^+] \cdot [OH^-] = 1 \times 10^{-14} \text{ moles}^2/\text{liter}^2$$

If we take the logarithm of the dissociation constant, we get:

$$\log K_w = \log [H^+] \cdot [OH^-] = -14$$

Thus when water is neutral, i.e. it has equal hydrogen and hydroxide ions the logarithm of the concentration of Hydrogen ions is equal to:

$$\log [H^+] = \log [OH^-] = -7$$

Thus, we define pH as:

$$pH = \log \frac{1}{[H^+]}$$

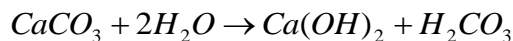
and thus when water is neutral the pH is 7 and when Hydrogen ions dominate, the pH is less than 7 and when hydroxide ions dominate, the pH is greater than 7. We call a solution with a predominance of hydrogen ions acidic, and a solution with a predominance of hydroxide ions basic.

Compounds dissolve in water through dissociation into ions, similar to the dissociation of water into hydrogen and hydroxide ions. Addition of an acid such as hydrochloric acid, HCl, results in the dissociation of the acid into hydrogen ions and chlorine ions increasing the number of hydrogen ions in the water and thus lowering the pH. Addition of a base such as sodium hydroxide, NaOH, results in the dissociation of the base into sodium and hydroxide ions increasing the total number of hydroxide ions in the water and thus increasing the pH of the water.

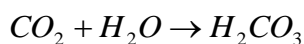
The concentration of dissociated Hydrogen ions in solution in water is expressed in terms of pH, which is the base ten logarithm of the inverse of the concentration of hydrogen ions in solution in the water.

Alkalinity

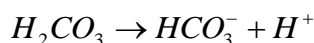
Alkalinity is the introduction of a strong base and a weak acid into the water typically through weathering of limestone rock as follows:



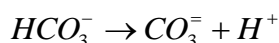
Limestone rock, $CaCO_3$, reacts with water to form calcium hydroxide, $Ca(OH)_2$, and Carbonic Acid, H_2CO_3 . In addition, carbon dioxide, CO_2 , from the atmosphere combines with water to form carbonic acid.



Carbonic acid dissociates into the bicarbonate ion, HCO_3^- , and a hydrogen ion.



The bicarbonate ion can further dissociate into the carbonate ion, CO_3^{2-} , and a hydrogen ion.



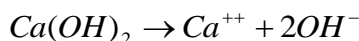
Addition of an acid to water with alkalinity in this form causes the bicarbonate ion to combine with the free hydrogen ion to form carbonic acid thus maintaining the balance of hydrogen ions and hydroxide ions. Addition of a strong base to the water converts bicarbonate ions to carbonate ions, thus releasing additional hydrogen ions and maintaining the balance. Since a balance of hydrogen ions and hydroxide ions is maintained in both processes, there is little or no effect on the pH of the water with the addition of acids and bases. Therefore, alkalinity provides a buffering capacity to the water against the addition of acids and bases.

Alkalinity is the concentration of hydroxyl, carbonate and bicarbonate ions present in the water that provides the water with the ability to buffer additions of acids and bases to the water without significant changes in the pH. Below pH of 10, hydroxyl ions do not contribute to alkalinity, and below pH 8.5, no significant carbonate ion exists. Therefore, in most drinking water, alkalinity is the concentration of bicarbonate ions. Alkalinity is usually expressed in terms of an equivalent mass or concentration of $CaCO_3$.

Alkalinity is measured in the laboratory usually by titrating a water sample with an acid until the pH of the sample is 4.2. At pH = 4.2, all alkalinity has been consumed by the acid, thus the quantity of acid expressed as equivalents of $CaCO_3$ required to bring the pH to 4.2 is equal to alkalinity of the sample.

Hardness

Hardness is a quality of water caused by multivalent metallic cations. Calcium, Ca^{++} , and magnesium, Mg^{++} , are the most common. In weathering of limestone rock, as shown above, the dissolved calcium carbonate forms calcium hydroxide and carbonic acid. The calcium hydroxide dissociates into calcium and hydroxide ions:



The hydroxide ions balance hydrogen ions released from the dissociation of carbonic acid and maintains a near neutral pH. Thus the calcium remains in solution giving the water hardness.

Hardness is typically expressed in terms of an equivalent mass of calcium carbonate. See Table 1 for molecular weights, equivalent weights and factors.

Hardness is often expressed in grains. The conversion to equivalents as CaCO_3 is 1 grain per gallon is equal to 17.1 mg/L as CaCO_3 .

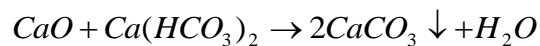
Hardness is not harmful to health but effects the way water is used. Hardness interferes with the ability of soap to form suds or lather. Hardness causes the soaps to form a precipitant that is recognized as soap scum. Hardness can also cause the formation of scale on pipes, plumbing fixtures and other bathroom and kitchen surfaces. The scale is precipitant forms of the hardness: calcium carbonate (CaCO_3), magnesium hydroxide ($\text{Mg}(\text{OH})_2$), and calcium sulfate (CaSO_4) are most common.

Table 2 Classification of Water for Softness/Hardness

Classification	mg/l as CaCO_3
Soft	<60
Moderately Hard	61-120
Hard	121-180
Very Hard	181-350
Saline, brackish	>350

Precipitation Reactions

Precipitation reactions are reactions that result insoluble forms of substances previously dissolved in the water. The insoluble precipitates of undesirable substances. For example, calcium oxide (lime) is used to remove hardness:



In the reaction above, the calcium oxide combines with calcium bicarbonate to form calcium carbonate and water. Calcium carbonate is non-soluble and precipitates readily.

Precipitation is the addition of a chemical that reacts with a substance in the water to form a non-soluble substance that can be settled or filtered from the water.

Colloids and Coagulation

Colloids do not settle out of solution and range in size from 1 to 500 millimicrons (nanometers). Colloids are classified as hydrophobic (water hating) and hydrophilic (water loving). Hydrophilic colloids are stable because of their attraction to water, e.g. soap, soluble starch, blood serum. Hydrophobic colloids depend on their electric charge to maintain stability. The natural force of attraction between colloidal particles is offset by repulsive forces developed by positive ions adsorbed onto their surfaces in solution. The magnitude of this repulsive force is called the *Zeta Potential*.

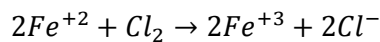
Chemical coagulation destabilizes colloidal particles. Hydrophobic particles are destabilized by salts of aluminum and iron. These salts form metal ions in water which compress the diffuse

double layer surrounding individual particles. Slow mixing, called *flocculation*, allows particles to contact each other and stick together. Organic polymers can be used to provide bridging between particles by attaching themselves to the adsorbant surfaces of the particles, thus creating larger flocculated masses that will then settle out.

Coagulation is process including the addition of a chemical to destabilize colloids causing them to settle. Flocculation is the process of slow mixing to allow particles to stick together to form larger particles that settle more easily. Metal salts and polymers are commonly used coagulants. Commonly used metal salts include alum (aluminum sulfate, Al_2SO_4), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), and ferrous sulfate ($FeSO_4 \cdot 7H_2O$).

Oxidation

A chemical is oxidized when it loses electrons to another substance. The loss of electrons increases the oxidation state, the valence, of the substance while the other substance incurs a reduction in its oxidation state. This reaction is commonly referred to as an oxidation-reduction reaction. An example of oxidation of ferrous iron to ferric iron by chlorine is shown below:



In the reaction one electron is given up by each iron molecule, the two electrons are taken by the chlorine to produce chloride.

Table 3 - Properties of Water at Atmospheric Pressure (US customary units)

Temperature	Density	Absolute viscosity	Kinematic viscosity	Surface tension	Vapor pressure head	Bulk modulus
°F	LB/FT ³	LB·s/FT ²	FT ² /s	LB/FT	FT	LB/in ²
32	62.42	3.746 X 10 ⁻⁵	1.931 X 10 ⁻⁵	0.518 X 10 ⁻²	0.20	293 X 10 ³
40	62.43	3.229 X 10 ⁻⁵	1.664 X 10 ⁻⁵	0.514 X 10 ⁻²	0.28	294 X 10 ³
50	62.41	2.735 X 10 ⁻⁵	1.410 X 10 ⁻⁵	0.509 X 10 ⁻²	0.41	305 X 10 ³
60	62.37	2.359 X 10 ⁻⁵	1.217 X 10 ⁻⁵	0.504 X 10 ⁻²	0.59	311 X 10 ³
70	62.30	2.050 X 10 ⁻⁵	1.059 X 10 ⁻⁵	0.500 X 10 ⁻²	0.84	320 X 10 ³
80	62.22	1.799 X 10 ⁻⁵	0.930 X 10 ⁻⁵	0.492 X 10 ⁻²	1.17	322 X 10 ³
90	62.11	1.595 X 10 ⁻⁵	0.826 X 10 ⁻⁵	0.486 X 10 ⁻²	1.62	323 X 10 ³
100	62.00	1.424 X 10 ⁻⁵	0.739 X 10 ⁻⁵	0.480 X 10 ⁻²	2.21	327 X 10 ³
110	61.86	1.284 X 10 ⁻⁵	0.667 X 10 ⁻⁵	0.473 X 10 ⁻²	2.97	331 X 10 ³
120	61.71	1.168 X 10 ⁻⁵	0.609 X 10 ⁻⁵	0.465 X 10 ⁻²	3.96	333 X 10 ³
130	61.55	1.069 X 10 ⁻⁵	0.558 X 10 ⁻⁵	0.460 X 10 ⁻²	5.21	334 X 10 ³
140	61.38	0.981 X 10 ⁻⁵	0.514 X 10 ⁻⁵	0.454 X 10 ⁻²	6.78	330 X 10 ³
150	61.20	0.905 X 10 ⁻⁵	0.476 X 10 ⁻⁵	0.447 X 10 ⁻²	8.76	328 X 10 ³
160	61.00	0.838 X 10 ⁻⁵	0.442 X 10 ⁻⁵	0.441 X 10 ⁻²	11.21	326 X 10 ³
170	60.80	0.780 X 10 ⁻⁵	0.413 X 10 ⁻⁵	0.433 X 10 ⁻²	14.20	322 X 10 ³
180	60.58	0.726 X 10 ⁻⁵	0.385 X 10 ⁻⁵	0.426 X 10 ⁻²	17.87	313 X 10 ³
190	60.36	0.678 X 10 ⁻⁵	0.362 X 10 ⁻⁵	0.419 X 10 ⁻²	22.29	313 X 10 ³
200	60.12	0.637 X 10 ⁻⁵	0.341 X 10 ⁻⁵	0.412 X 10 ⁻²	27.61	308 X 10 ³
212	59.83	0.593 X 10 ⁻⁵	0.319 X 10 ⁻⁵	0.404 X 10 ⁻²	35.38	300 X 10 ³

Water Treatment

Formula Sheet

Maximum Contaminant Level Goal

$$DWEL = \frac{[NOAEL \text{ in } mg/(kg \cdot day)](70 \text{ kg})}{(UF)(2 \text{ L/day})}$$

Where:

NOAEL = No observed adverse effect level.

70 kg = Assumed weight of an adult.

2 L/day = Assumed daily water consumption of an adult.

UF = Uncertainty factor (usually 10, 100, or 1000).

$$MCLG = DWEL(\text{Percentage contribution from drinking water})$$

Average Demand

$$\text{Annual average day demand} = \frac{\text{Total demand for one year}}{365 \text{ days in one year}}$$

Hydraulic Loading Rates

Hydraulic Retention Time (HRT)

$$HRT = \frac{\text{Volume}}{\text{Flow}} = \frac{V}{Q}$$

Hydraulic Surface Loading Rate (HLR)

$$HLR = \frac{\text{Flow}}{\text{Surface Area}} = \frac{Q}{A_s}$$

Weir Loading Loading Rate (WLR)

$$WLR = \frac{\text{Flow}}{\text{Weir Length}} = \frac{Q}{L_w}$$

Sedimentation

Stoke's Law

$$V_c = \frac{g(\rho_s - \rho)d^2}{18\mu}$$

where:

V_c = particle settling velocity, terminal velocity, (FT/s)

d = diameter of the particle, (FT)

g = acceleration due to gravity, (FT/s²)

ρ_s = mass density of particle, (slug/FT³)

ρ = mass density of fluid, (slug/FT³)

μ = dynamic viscosity of fluid (LB-s/FT²)

Taste and Odor Control

Threshold Odor Number

$$\text{TON} = \frac{V_{\text{sample}} + V_{\text{dilute}}}{V_{\text{sample}}}$$

Rapid Mix

Mixing Equation

$$G = \sqrt{\frac{P}{\mu V}}$$

Where:

G = velocity gradient (s⁻¹)

P = power requirement (FT-LB/s)

μ = dynamic viscosity of liquid (LB-s/FT²)

V = volume mixed (FT³)

Turbine/Propeller Mixers

$$P = k\rho n^3 D^5 \quad \text{Turbulent Mixing } N_R > 10,000$$

where:

P = power (FT-LB/s)

k = constant

μ = dynamic viscosity (LB-s/FT²)

ρ = mass density (slug/FT³)

D = diameter of impeller (FT)

n = speed of revolution (rev/s)

N_R = Reynold's Number

$$N_R = \frac{D^2 n \rho}{\mu}$$

Flocculation

Paddle Wheel Mixers

$$P = F_D V_p = \frac{C_D A_p \rho v_p^3}{2}$$

where:

P = power (LB-FT/s)

F_D = drag force (LB)

C_D = drag coefficient for paddle

A_p = cross-sectional area of paddles (FT²)

ρ = mass density of fluid (slug/FT³)

v_t = tip speed of paddles (FT/s)

v_p = relative velocity of paddles with respect to fluid (FT/s).

$$v_p = 0.6 \text{ to } 0.75 v_t$$

Turbine/Propeller Mixers

$$P = k\mu n^2 D^3 \quad \text{Laminar Mixing } N_R < 10$$

where:

P = power (FT-LB/s)

k = constant

μ = dynamic viscosity (LB-s/FT²)

ρ = mass density of fluid (slug/ft³)

D = diameter of impeller (FT)

n = speed of revolution (rev/s)

N_R = Reynold's Number

$$N_R = \frac{D^2 n \rho}{\mu}$$

Disinfection

CT

$$CT = C \times T$$

Where:

CT = a measure of the effectiveness of a disinfection process, mg/L-min.

C = disinfectant concentration in mg/L.

T = disinfectant contact time in minutes.

Demand

$$\text{Demand} = \text{Dose} - \text{Residual}$$

Contact Time

$$T_{10} = HRT \times B_f = \frac{V}{Q} \times B_f$$

Percent Inactivation

$$y = 100 - 100/10^x$$

Where:

y = percent inactivation.

x = log inactivation.

Ion Exchange Softening

$$V = \frac{QHT100}{24EP}$$

Where:

V = Required resin volume, ft³.

Q = Flow rate, g/d.

H = Raw water hardness, kilograins/gal as CaCO₃.

T = Time between regeneration cycles, hours.

E = Resin exchange capacity, kilograins/ft³ as CaCO₃.

P = Average percent of time contactors are operating, %.

Activated Carbon

Carbon Adsorption Capacity

$$\frac{x}{m} = kC^{1/n}$$

Where:

x = the mass of compound adsorbed onto the carbon, lb.

m = the mass of activated carbon, lb.

C = the residual concentration of compound, mg/L.

k and n = isotherm constants determined experimentally for the specific compound and for the specific activated carbon.

$$\left(\frac{x}{m}\right)_d = kC_0^{-1/n} * SF$$

Where:

$\left(\frac{x}{m}\right)_d$ = the design capacity of the GAC to retain the compound to be removed in lb of compound per lb of GAC.

C_0 = Influent Concentration, mg/L

SF = Safety factor for design, usually between 0.75 and 0.90.

k and n = isotherm constants.

Powdered Activated Carbon Dose

$$D = \frac{(C_0 - C)}{\left(\frac{x}{m}\right)_d}$$

Where:

D = PAC dose to achieve removal of compound, mg/L.

C_0 = Influent concentration of compound to be removed, mg/L.

C = Effluent concentration of compound to be removed, mg/L.

$\left(\frac{x}{m}\right)_d$ = Design removal capacity of the PAC for the compound,

lb/lb.

GAC Empty Bed Contact Time

$$EBCT = \frac{\text{contactor volume}}{\text{flow}} = \frac{V_c}{Q}$$

Where:

EBCT = Empty Bed Contact Time

V_c = Contactor volume

Q = Flow through contactor

GAC Hydraulic Loading Rate (Approach Velocity)

$$v_a = \frac{\text{flow}}{\text{contactor area}} = \frac{Q}{A_s}$$

Where:

v_a = HLR or approach velocity.

Q = Flow through contactor.

A_s = Surface area of the GAC bed.

GAC Capacity

$$EBV = \left(\frac{x}{m}\right)_d \frac{\rho_B}{(C_0 - C)} \times 16,000$$

Where:

EBV = The number of empty bed volumes of water that can be treated.

$\left(\frac{x}{m}\right)_d$ = The design capacity of the GAC in lb/lb.

ρ_B = The bulk density (unit weight) of the GAC in lb/ft³.

C_0 = The influent compound concentration in mg/L.

C = The effluent compound concentration in mg/L, usually = 0.
16,000 = unit conversion factor.

GAC Run time

$$T_E = \left(\frac{x}{m}\right)_d \frac{\rho_B}{(C_0 - C)} \times EBCT \times 11.1$$

Where:

T_E = Time to exhaustion in days.

EBCT = Empty bed contact time in minutes.

11.1 = unit conversion factor.

Others as defined above.

Reverse Osmosis

Transmembrane Pressure

$$P_{tm} = \frac{P_{in} - P_{out}}{P_p}$$

Where:

P_{tm} = Transmembrane pressure, psi.

P_{in} = Inlet water pressure, psi.

P_{out} = Outlet water pressure, psi.

P_p = Permeate water pressure, psi.

Osmotic Pressure

$$\Delta\pi = C_sRT$$

Where:

$\Delta\pi$ = Osmotic pressure, psi.

C_s = concentration of solutes in solution, mol/ft³.

R = ideal gas constant, ft lb/mol K.

T = Absolute temperature, Kelvin = °C + 273.

Recovery

$$R = \frac{Q_p}{Q_f} 100 = \left(\frac{Q_p}{Q_p + Q_c} \right) 100$$

Where:

R = Recovery in %.

Q_p = Product water flow, gpm.

Q_f = Feed water flow (influent), gpm.

Q_c = Concentrate water flow, gpm.

Concentration Factor

$$CF = \left[\frac{1}{1 - R} \right]$$

Where:

CF = concentration factor, decimal.

R = recovery, decimal.

Flux (Hydraulic Loading Rate)

$$J = k_w(\Delta P - \Delta\pi) = \frac{Q_p}{A}$$

Where:

J = Membrane flux, g/d/ft².

k_w = mass transfer coefficient for water, g/d/ft²/psi.

ΔP = pressure drop across the membrane (transmembrane pressure), psi.

$\Delta\pi$ = Osmotic pressure, psi.

Q_p = Product water flow, g/d.

A = Membrane surface area, ft².

Solute Flux

$$J_i = k_i\Delta C = \frac{Q_p C_p}{A}$$

Where:

J_i = Solute flux, lb/d/ft².

k_i = Solute mass transfer coefficient, ft/d.

ΔC = Concentration gradient, lb/ft³.

Q_p = Permeate flow rate, ft³/d.

C_p = Permeate stream solute concentration, lb/ft³.

A = Membrane surface area, ft².

Permeate Solute Concentration

$$C_p = \frac{k_i C_f}{k_w(\Delta P - \Delta\pi)[(2 - 2R)/(2 - R)] + k_i}$$

Corrosion Control

Langelier Saturation Index

$$LSI = pH - pH_s$$

Ryznar Stability Index

$$RSI = 2pH_s - pH$$

pH Saturation

$$pH_s = (9.3 + A + B) - (C + D)$$

Where:

$A = (\log(TDS) - 1)/10$, TDS=Total Dissolved Solids, mg/L

$B = (-13.12 \log(°C + 273)) + 34.55$, °C = Water Temperature, °C

$C = (\log(Ca \text{ Hardness})) - 0.4$, Ca Hardness, mg/L as CaCO₃

$D = \log(Alkalinity)$, Alkalinity = total in mg/L as CaCO₃

|

Water Treatment

Workshop Problems

(AM) indicates problems that could be breadth problems in the morning session of the Civil PE exam or depth problems in Water Resources and Environmental.

(PM) indicates problems that could be depth problems in the Water Resources and Environmental afternoon session of the Civil PE exam.

1) (AM) The following data is for the Frio River in Texas during the year 1952. A community near the gauging station needs a water supply reservoir to balance seasonal demand and supply. Assume no loss in evaporation. For the design year data shown, the total storage required in acre-feet is most nearly:

- a) 3,000 b) 3,150 c) 3,300 d) 3,450

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Daily River Flow (cfs)	20	20	23	32	43	27	12	4	2	2	7	20
Average Daily Water Demand (MGD)	5	5	6	6	7	9	11	11	10	10	9	7

2) (AM) A community with an average daily demand of 165 gallons per capita per day (gpcd) requires an expansion of the existing surface water treatment plant to meet future demands. Historical records show that the maximum day demand is 2.2 times the average demand and the peak hour demand is 4.0 times the average demand. The existing treatment plant can treat up to 3.0 million gallons per day (MGD). The projected population of the community in the design year for the plant expansion is 20,000 people. The additional treatment capacity, in MGD, needed in the plant expansion is most nearly:

- a) 7.3 b) 0.3 c) 3.3 d) 4.3

3) (AM) Determine the capacity of a water treatment plant required to serve a community of 5,000 people if the average consumption is 175 gallons per capita per day. It has also been determined that the maximum day demand is 2.15 times the average.

4) (AM) A community with an average daily demand of 175 gallons per capita per day (gpcd) requires a new elevated storage tank. Historical records show that the maximum day demand is 2.0 times the average demand and the peak hour demand is 4.5 times the average demand. The design population for the water system is 20,000 persons. The community has the ability to treat 7.0 million gallons per day. The total distribution system storage, in million gallons (MG), needed during the peak hour is most nearly:

- a) 9.0 b) 0.5 c) 1.0 d) 32

5) (PM) A water treatment plant uses liquid sodium hypochlorite for disinfection. The delivered concentration is about 12 percent as Cl_2 . If a dose of 2.0 mg/L is required to treat 2.5 MGD, the feed rate is most nearly:

- a) 45 lb/day b) 350 lb/day c) 139 lb/day d) 175 lb/day

6) (PM)A water treatment plant uses liquid sodium hypochlorite (unit weight = 10 lb. per gal.) for disinfection. The delivered concentration is about 12 percent as Cl_2 . If a dose of 2.0 mg/L is required to treat 2.5 MGD, the day tank volume required is most nearly:

- a) 350 gallons b) 3,475 gallons c) 35 gallons d) 175 gallons

7) (PM)A water treatment plant uses liquid sodium hypochlorite (unit weight = 10 lb. per gal.) for disinfection. The delivered concentration is about 12 percent as Cl_2 . If a dose of 2.0 mg/L is required to treat 2.5 MGD, the feed pump capacity is most nearly:

- a) 1.45 gph b) 834 gph c) 35 gph d) 8.34 gph

8) (PM)A water treatment plant uses liquid sodium hypochlorite (unit weight = 10 lb. per gal.) for disinfection. The delivered concentration is about 12 percent as Cl_2 . A dose of 2.0 mg/L is required to treat 2.5 MGD. If deliveries of sodium hypochlorite can only be made once per month, the storage tank volume needed is most nearly:

- a) 35 gallons b) 350 gallons c) 834 gallons d) 1100 gallons

9) (PM) You are designing rapid mix facilities for a water treatment plant with a capacity of 10 MGD. The desired velocity gradient, G , is 1000 s^{-1} and the desired hydraulic detention time is 10 seconds. The water temperature is 20°C . The power required for mixing in horsepower is most nearly:

- a) 6 b) 7 c) 8 d) 9

10) (PM) A Marine Impeller (3 blade, pitch of 2) is used in a rapid mix basin having liquid dimensions of $5'-0'' \times 5'-0'' \times 10'-0''$ deep. Assume a design velocity gradient of 700 s^{-1} , impeller diameter will be 50% of basin width, water temp is 10°C and baffles will be present. Assume $K=1.00$ for impeller, dynamic viscosity of water, $\mu = 2.735 \times 10^{-5} \text{ lb}\cdot\text{s}/\text{ft}^2$, and the density of water, $\rho = 1.94 \text{ slug}/\text{ft}^3$. The impeller speed required is most nearly:

- a) 200 rpm b) 150 rpm c) 100 rpm d) 300 rpm

11) (AM) A 10 MGD water treatment plant requires a flocculation basin to follow rapid mix facilities. The flocculation basin will include horizontal shaft paddle mixers with flat paddles. The design criteria for flocculation is a G value of 50 s^{-1} , a hydraulic detention time of 20 minutes, and a paddle tip speed of $2.5 \text{ ft}/\text{s}$. The flocculator volume required in cubic feet is most nearly:

- a) 16,000 b) 17,400 c) 18,600 d) 19,000

12) (PM) 10 MGD water treatment plant requires a flocculation basin to follow rapid mix facilities. The flocculation basin will include horizontal shaft paddle mixers with flat paddles. The design criteria for flocculation is a G value of 50 s^{-1} , a hydraulic detention time of 20 minutes, and a paddle tip speed of 2.5 ft/s. Assuming a flocculator volume of 20,000 cubic feet and a dynamic viscosity of water of 2.05×10^{-5} , the Power required in lb-ft/s is most nearly:

- a) 1200 b) 1100 c) 900 d) 800

13) (PM) Assuming the mixing power required for flocculation is 1000 lb-ft/s, the ratio of the relative velocity of the paddles to the fluid is equal to 0.7 times the paddle tip speed, and the paddle drag coefficient is 1.8, the required paddle area in square feet is most nearly: (Use 1.936 slug/ft^3 for the density of water and 2.5 ft/s for the paddle tip speed.)

- a) 50 b) 70 c) 90 d) 110

14) (PM) A water treatment plant has a flocculation basin with dimensions 30' - 9" wide by 61' - 6" long by 20' - 0" deep. Assume two paddle wheels on a single shaft spanning the length of the basin. Assume design $G = 35 \text{ s}^{-1}$, each wheel will be 40% of basin width and 35% of basin length. Assume a water temperature of 10°C , dynamic viscosity of water, $\mu = 2.735 \times 10^{-5} \text{ lb}\cdot\text{s/ft}^2$, the density of water, $\rho = 1.94 \text{ slug/ft}^3$, paddle tip speed = 3 ft./s, and $V_p = 0.6$ times tip speed, and $C_D = 1.8$. The required rotational speed is most nearly:

- a) 5 rpm b) 10 rpm c) 3 rpm d) 8 rpm

15) (PM) The paddle area required for the previous problem is most nearly:

- a) 125 ft² b) 150 ft² c) 135 ft² d) 175 ft²

16) (AM) The overflow rate in gpd/ft² for a sedimentation basin with length of 120 feet, a width of 40 feet and depth of 15 feet for a water treatment plant that treats 4 MGD is most nearly:

- a) 1200 b) 800 c) 500 d) 1000

17) (AM) Design sedimentation tanks for a coagulation water treatment plant with an average flow of 12 MGD and a maximum day flow that is 2.0 times the average day. Assume an overflow rate of 400 gpd/ft², a length to width ratio of 5:1, a maximum length of 250 feet, a sidewater depth of 16 feet, and a weir loading rate of 12,000 gpd/ft. The total surface area required in square feet at average flow is most nearly:

- a) 50,000 b) 20,000 c) 40,000 d) 30,000

18) (AM) The number of basins required above for the average flow is most nearly:

- a) 2 b) 3 c) 4 d) 5

19) (AM) If the width of each basin above is 45 ft the length is most nearly:
a) 200 ft b) 225 ft c) 250 ft d) 275 ft

20) (AM) Assuming an overall surface area of 30,375 ft², the overall detention time for the problem above at average flow is most nearly:
a) 2.4 hours b) 3.6 hours c) 5.8 hours d) 7.3 hours

21) (AM) Assuming 3 basins, the weir length required per basin at average flow is most nearly:
a) 110 feet b) 335 feet c) 225 feet d) 440 feet

22) (AM) The number of 45 ft by 225 ft basins required for peak capacity is most nearly:
a) 4 b) 5 c) 6 d) 7

23) (AM) A rapid sand filter is 10 ft wide and 15 ft long. If the flow through the filter is 450,000 gpd, what is the filter loading rate in gallons per minute per square foot?

24) (AM) A 2.0 feet deep filter bed is composed of 1.2 ft. of uniform sand and 0.8 ft. of uniform anthracite. Assume a maximum filtration rate of 2.5 gpm/ft.², porosity of 0.40, temperature is 10°C. The anthracite has an average size of 1.6 mm, shape factor of 0.73 and the sand has an average size of 0.5 mm and shape factor of 0.82. Assume a backwash rate of 20 gpm/ft.². Sand has a specific gravity of 2.60, anthracite 1.60. The design capacity in gpd of a filter bed that is 12 feet square is most nearly:

- a) 144,000 b) 510,000 c) 480,000 d) 530,000

25) (PM) A sufficient number of beds must be provided so that the design filtration rate is not exceeded when one bed is out of service for backwashing. If the design filtration rate is 2.5 gpm/ft.², the number of 10 foot by 10 foot filter beds at a water treatment plant designed to treat 3.8 MGD is most nearly:

- a) 12 b) 11 c) 10 d) 13

26) (PM) Assuming that during backwash the 2.0 foot deep filter bed is expanded 75 percent and six inches of freeboard is required over the expanded filter bed, the height of the wash troughs over the unexpanded filter bed is most nearly:

- a) 3.5 ft b) 2.0 ft c) 1.5 ft d) 4.0 ft

27) (PM) Tracer studies performed on a conventional water treatment plant showed that at a rate of 5 MGD, the contact time, T_{10} , is 25 min. What residual chlorine concentration must be maintained to satisfy the surface water treatment rule for disinfection of Giardia (See Table) on a day when the flow is 5 MGD, the water temperature is 10°C and the pH is 7.0. Note that the chlorine dosage must not exceed 1.8 mg/l to keep excessive disinfection byproducts from forming.

CT values (mg/l·min) for inactivation of Giardia cysts by free chlorine at 10°C						
Chlorine Concentration (mg/l)	PH=7.0					
	Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0
≤0.4	18	33	33	70	82	105
0.6	19	38	56	75	94	113
0.8	20	40	59	79	99	119
1.0	21	41	62	82	103	123
1.2	21	42	64	85	106	127
1.4	22	44	65	87	109	131
1.6	22	45	67	89	112	134
1.8	23	46	68	91	114	137
2.0	23	46	70	93	116	139
2.2	24	47	71	95	118	142
2.4	24	48	72	96	120	144
2.6	24	49	73	97	122	146
2.8	25	49	74	99	123	148
3.0	25	50	75	100	125	150

28) (PM) Chlorine is more effective as disinfectant when the water:

- a) pH is increasing and temperature is decreasing
- b) pH is decreasing and temperature is increasing
- c) pH is increasing and temperature is increasing
- d) pH is decreasing and temperature is decreasing

- 29) (PM) If the water from the treatment plant is found to require a chlorine dose of 5 mg/L and the plant treats 7.0 MGD, the required addition of hypochlorite (70% available chlorine) is most nearly:
- a) 420 lb/d b) 480 lb/d c) 530 lb/d d) 580 lb/d

- 30) (PM) When a free chlorine residual is maintained in a treated water high in organic carbon:
- a) Disinfection is more effective
 b) Trihalomethanes are formed
 c) chloroform is produced
 d) b and c
 e) a and b

- 31) (PM) A conventional water treatment plant uses coagulation, flocculation, sedimentation and filtration (in that order) to treat water. Disinfection is provided by chlorinating the raw water prior to coagulation with free chlorine. The raw water chlorine demand is about 8.0 mg/L. The residual chlorine concentration measured following filtration is 1.2 mg/L. The following table provides the design information for each of the treatment units. If the design flow of the water treatment plant is 5 MGD, the CT value in mg/L·min provided is most nearly:
- a) 550 b) 475 c) 400 d) 325

Unit	Volume (ft ³)	Baffling Factor
Coagulation	250	0.5
Flocculation	20,000	0.7
Sedimentation	150,000	0.7
Filtration	15,000	0.5

32) (PM) A water analysis shows 24 mg/L of calcium ion (Ca^{++}). The calcium ion concentration in terms of calcium carbonate (CaCO_3) is most nearly:

- a) 24 mg/L b) 48 mg/L c) 60 mg/L d) 96 mg/L

33) (PM) Determine the pH of a solution with a concentration of hydrogen ions of 2.09×10^{-8} moles/liter. Determine the concentration of hydroxide ions in the solution.

34) (PM) Water contaminated with the equivalent of 50 pounds of sulfuric acid requires neutralization. The amount in pounds of pure sodium hydroxide required to neutralize the acid is most nearly:

- a) 25 b) 100 c) 45 d) 60

35) A water analysis yields the following results:

Calcium	Ca^{++}	29 mg/L	Sulfate	SO_4^{--}	22.0 mg/L
Magnesium	Mg^{++}	16.4 mg/L	Bicarbonate	HCO_3^-	210 mg/L
Sodium	Na^+	23.0 mg/L	Chloride	Cl^-	12.0 mg/L
Potassium	K^+	17.5 mg/L	pH		7.6

(PM) The alkalinity of the water in mg/L of CaCO_3 is most nearly:

- a) 170 b) 190 c) 210 d) 230

36) Using the following water analysis:

Calcium	Ca ⁺⁺	29 mg/L	Sulfate	SO ₄ ⁻	22.0 mg/L
Magnesium	Mg ⁺⁺	16.4 mg/L	Bicarbonate	HCO ₃ ⁻	210 mg/L
Sodium	Na ⁺	23.0 mg/L	Chloride	Cl ⁻	12.0 mg/L
Potassium	K ⁺	17.5 mg/L	pH		7.6

(PM)The hardness of the water expressed in mg/L of CaCO₃ is most nearly:

- a) 110 b) 140 c) 170 d) 200

37) (PM)Total hardness is the sum of carbonate hardness and non-carbonate hardness and is equal to calcium hardness + magnesium hardness + other multi-valent metallic cations. When alkalinity is less than total hardness, the carbonate hardness is equal to alkalinity. When alkalinity is greater than total hardness, the carbonate hardness is equal to total hardness. Given water with the following analysis determine the alkalinity, total hardness, carbonate hardness and non-carbonate hardness of the water. Express your results in terms of mg/l of CaCO₃.

Calcium	Ca ⁺⁺	80 mg/l	Sulfate	SO ₄ ⁻	64 mg/l
Magnesium	Mg ⁺⁺	30 mg/l	Bicarbonate	HCO ₃ ⁻	336 mg/l
Sodium	Na ⁺	19 mg/l	Carbon dioxide	CO ₂	15 mg/l
Chloride	Cl ⁻	18 mg/l	pH		7.80

38) (PM) A raw water with an analysis as shown is treated using a two stage Lime-Soda-ash softening process. Excess Lime and soda-ash is added to achieve a residual hardness to the practical limit of 30 mg/L of CaCO_3 and 10 mg/L Mg(OH)_2 as CaCO_3 . Assume an excess lime addition of 35 mg/L.

Water Analysis:

		mg/L
Calcium	Ca^{++}	80
Magnesium	Mg^{++}	30
Sodium	Na^+	19
Chloride	Cl^-	18
Sulfate	SO_4^-	64
Bicarbonate	HCO_3^-	336
Carbon dioxide	CO_2	15

Which of the following lists some of the possible combinations that may exist in the raw water?

- Ca_2HCO_3 , NaHCO_3 , Mg_4SO_4 , MgCl
- $\text{Ca(HCO}_3)_2$, $\text{Mg(HCO}_3)_2$, NaCl , MgSO_4
- $\text{Mg(HCO}_3)_2$, NaCl , CaCl , Ca_4SO_4
- CaSO_4 , Na_2SO_4 , CaCO_3 , NaCa

The amount of Lime (CaO) required is most nearly:

- a) 1888 lb/MG b) 1955 lb/MG c) 1977 lb/MG d) 2310 lb/MG

The amount of soda ash required is most nearly:

- a) 225 lb/MG b) 500 lb/MG c) 355 lb/MG d) 430 lb/MG

The total amount of carbon dioxide needed for both stages of recarbonation is most nearly:

- a) 380 lb/MG b) 250 lb/MG c) 425 lb/MG d) 320 lb/MG

39) (PM) A water system treats water from a reservoir. The treatment system uses conventional technology including coagulation, flocculation, sedimentation, filtration, and disinfection. Under the enhanced surface water treatment rule, the water treatment system must always produce water with a turbidity less than:

- a) 1.5 NTU b) 1.0 NTU c) 0.5 NTU d) 0.3 NTU

40) A water analysis of inorganic constituents yields the following results:

Antimony	1 ppb	Cyanide	300 ppb
Arsenic	8.0 ppb	Flouride	0.2 ppm
Asbestos	0.5 MFL	Mercury	0.5 ppb
Barium	1.0 ppm	Nitrate	12 ppm
Beryllium	1.2 ppb	Nitrite	0.1 ppm
Cadmium	3.2 ppb	Selenium	15 ppb
Chromium	600 ppb	Thallium	1 ppb

(PM) Which chemicals violate the MCL's of the primary drinking water standards?

(PM) Which chemicals violate the Public Health Goals of the primary drinking water standards?

41) (PM) A water analysis of secondary constituents yields the following results:

Aluminum	0.05 mg/L	Manganese	105 ppb
Chloride	120 mg/L	Odor	0 Odor #
Color	2 Color Units	pH	6.2
Copper	0.8 mg/L	Silver	10 ppb
Flouride	0.5 mg/L	Sulfate	50 mg/L
Foaming agents	0.05 mg/L	TDS	230 mg/L
Iron	1.2 mg/L	Zinc	0.5 mg/L

The water is not in compliance with the Secondary MCL's for the following constituents:

- a) Chloride, Iron and Manganese
- b) Flouride, Sulfate and TDS
- c) Iron, Manganese and pH
- d) Iron, Sulfate and pH

42) (PM) Given the following water analysis, which contaminants do not meet the MCLs set under the Safe Drinking Water Act.

Barium	2.3 mg/l
Cadmium	3 µg/l
Chromium	150 µg/l
Cyanide	21 µg/l
Flouride	2.1 mg/l
Nitrate	5.0 mg/l
Nitrite	0.5 mg/l
Selenium	25 µg/l
Thallium	1 µg/l
Combined Radium	4.4 pCi/l

43) (PM) Convert the following water analysis results into equivalents as CaCO_3 and draw a bar diagram to display your results.

pH = 7.5

Carbon dioxide	CO_2	5.7 mg/L
Calcium	Ca^{+2}	71.6 mg/L
Magnesium	Mg^{+2}	22.2 mg/L
Sodium	Na^+	4.7 mg/L
Bicarbonate	HCO_3^-	235 mg/L
Sulfate	SO_4^-	57.5 mg/L
Chloride	Cl^-	19.4 mg/L

44) (PM) Using the water analysis above and assuming an excess lime addition of 20 mg/L as CaCO_3 , the feed rate in tons per day (tpd) of pure lime (CaO) in a lime and soda ash softening process to treat 30 MGD is most nearly:

- a) 177 b) 316 c) 22 d) 40

45) (PM) Using the information from the previous problem, the dose of pure soda ash in mg/L Na_2CO_3 required to remove the non-carbonate hardness is most nearly:

- a) 22 b) 40 c) 77 d) 82

46) (PM) A single stage lime softening process uses 50 mg/L as CaCO₃ of excess lime and reduces the hardness to 40 mg/L as CaCO₃. The dose of pure carbon dioxide in mg/L of CO₂ required to stabilize the water through recarbonation is most nearly:

- a) 22 mg/L b) 62 mg/L c) 90 mg/L d) 140 mg/L

47) (PM) A water treatment plant softens water with the lime and soda ash softening process. The process includes an excess lime addition of 60 mg/L CaCO₃ beyond the stoichiometric requirements. Given the following water analysis, the dose of lime as pure Ca(OH)₂ and soda ash as pure Na₂CO₃ is most nearly:

22.7	0.0	161	197	234	247
CO ₂	Ca ⁺²	Mg ⁺	Na ⁺	K ⁺	
	HCO ₃ ⁻		SO ₄ ⁺²	Cl ⁻	
0.0	205		240	247	

- a) 256 mg/L Ca(OH)₂ and 0 mg/L Na₂CO₃
 b) 189 mg/L Ca(OH)₂ and 52 mg/L Na₂CO₃
 c) 234 mg/L Ca(OH)₂ and 0 mg/L Na₂CO₃
 d) 316 mg/L Ca(OH)₂ and 189 mg/L Na₂CO₃

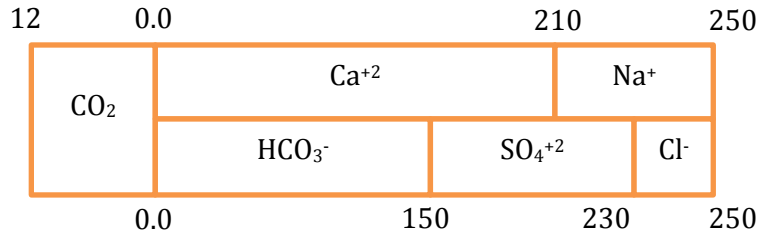
48) (PM) A 5 MGD water treatment plant uses lime softening to remove calcium hardness from water. The bar diagram below provides the water analysis to be treated. Assume 50 mg/L of excess lime as CaCO_3 is needed in addition to the stoichiometric requirements. The feed rate in lb/d of hydrated lime (90% Ca(OH)_2) is most nearly:

a) 10,300

b) 7,260

c) 2,230

d) 223



Water Treatment

Problem Solutions

Example Problems

- 1) The Drinking Water Equivalent Level (DWEL) of a contaminant is based on the reference dose or the No Observed Adverse Effect Level (NOAEL) of exposure to the contaminant and the size of the person and the daily quantity of water consumed.

$$DWEL = \frac{[NOAEL \text{ in } mg/(kg \cdot day)](70 \text{ kg})}{(UF)(2 \text{ L/day})}$$

Where:

NOAEL = No observed adverse effect level.

70 kg = Assumed weight of an adult.

2 L/day = Assumed daily water consumption of an adult.

UF = Uncertainty factor (usually 10, 100, or 1000).

The problem confirms the assumption of a 70 kg adult that drinks 2 L/d and gives an uncertainty factor of 100, thus the DWEL is:

$$DWEL = \frac{[300 \text{ mg}/(kg \cdot day)](70 \text{ kg})}{(100)(2 \text{ L/day})} = 105 \text{ mg/L}$$

Since exposure to the contaminant may come from other sources besides drinking water, the MCLG must take into account the portion of the overall exposure to the contaminant from drinking water, which is given as 20%, so:

$$MCLG = DWEL(20\%) = 105(0.20) = 21 \text{ mg/L}$$

The correct answer is b) 21 mg/L.

- 2) A community of 20,000 people uses an average of 3,360 acre-feet of water per year. The maximum recorded daily consumption was 6 million gallons and the maximum hour consumption was 7,000 gallons per minute.

A. The average demand for water per person is calculated as follows:

$$\text{Annual average day demand} = \frac{\text{Total demand for one year}}{365 \text{ days in one year}}$$

We're given that 20,000 people use 3,360 acre-feet of water per year.

$$3,360 \text{ acre} \cdot \text{feet} * \frac{43560 \text{ ft}^2}{1 \text{ acre}} * \frac{7.48 \text{ g}}{\text{ft}^3} = 1,094,784,768 \text{ gallons}$$

$$\text{Annual average day demand} = \frac{1,094,784,768 \text{ g}}{365 \text{ d}} = 2,999,410 \text{ g/d}$$

And:

$$\frac{2,999,410 \text{ g/d}}{20,000 \text{ persons}} = 149.97 \frac{\text{g}}{\text{person} \cdot \text{day}} \approx 150 \text{ gpcd}$$

The correct answer is c) 150 gpcd.

- B. The total water treatment capacity needed in 2040 is equal to the maximum daily demand in 2040, so calculate the maximum daily demand for the 2040 design population as follows:

In the current year the daily demand computed in A is 3.0 MGD and the maximum day demand is given as 6.0 MGD, so the maximum day demand factor is:

$$\frac{6.0 \text{ MGD}}{3.0 \text{ MGD}} = 2.0$$

The average day demand in 2040 can be computed from the average demand per person from A. above and given a projected population of 50,000:

$$50,000 \text{ persons} * 150 \text{ gpcd} = 7,500,000 \text{ gpd} = 7.5 \text{ MGD}$$

To compute the maximum day demand use the maximum day demand factor times the average demand:

$$2.0 * 7.5 \text{ MGD} = 15.0 \text{ MGD}$$

The total water treatment capacity needed in 2040 is the correct answer: d) 15 MGD.

- C. To calculate the maximum hour demand in 2040 we need to first compute the current maximum hour demand factor using current data given, which includes a maximum hour demand of 7,000 GPM:

$$\frac{7,000 \text{ G}}{\text{M}} * \frac{60 \text{ M}}{\text{Hr}} * \frac{24 \text{ Hr}}{\text{D}} = 10,080,000 \frac{\text{G}}{\text{D}} = 10.1 \text{ MGD}$$

The Factor is:

$$\frac{10.1 \text{ MGD}}{3.0 \text{ MGD}} = 3.36$$

Using the 2040 average demand computed in B above, the maximum hour demand in 2040 is:

$$7.5 \text{ MGD} * 3.36 = 25.2 \text{ MGD}$$

This is the rate at which water is projected to be used during the maximum hour of the day, so the volume used during maximum hour is:

$$\frac{25.2 \text{ MG}}{D} * \frac{D}{24 \text{ Hr}} = 1.05 \frac{\text{MG}}{\text{Hr}}$$

Since maximum hour is only one hour the correct answer is a) 1.0 MG.

3) Elevated storage is designed to maintain water pressure in a distribution system when pumping is off or not available.

- A. To maintain a static water pressure the height of the tank must be set to maintain a pressure greater than the minimum at the highest ground elevation and not greater than the maximum at the lowest ground elevation. To find this elevation, we need add the minimum pressure to the highest ground elevation and the maximum pressure to the lowest ground elevation. Recall from hydraulics that:

$$H = \frac{P}{\gamma} = \frac{P}{\rho g}$$

So:

$$H = \frac{40 \text{ PSI}}{62.4 \text{ LB/FT}^3} * \frac{12^2 \text{ IN}^2}{\text{FT}^2} = 92.3 \text{ FT}$$

And:

$$H = \frac{90}{62.4} * 144 = 208 \text{ FT}$$

Compute the heights:

$$900 + 92.3 = 992.3 \text{ FT}$$

$$800 + 208 = 1008 \text{ FT}$$

The range for the top of the operating level of the tank, the overflow elevation, is between 992.3 FT and 1008 FT above MSL. The correct answer is c) 1000 FT MSL.

- B. The equalizing volume is stored between the lower elevation of the operating range and the upper elevation of the operating range. The lowest operating level in the tank must provide at least 35 PSI static pressure, so the height is the highest ground elevation plus the 35 PSI:

$$H = \frac{35 \text{ PSI}}{62.4 \text{ LB/FT}^3} * \frac{12^2 \text{ IN}^2}{\text{FT}^2} = 80.8 \text{ FT}$$

$$900 + 80.8 = 980.8$$

Now compute the height difference between the overflow (elevation when tank is full) and the minimum operating level:

$$1000 - 980.8 = 19.2 \text{ FT}$$

This is the operating range of the tank within which the required equalizing volume must be stored, since area times height is the volume of a cylinder, the area can be computed:

$$\text{Area} = \frac{0.5 \text{ MG}}{19.2 \text{ FT}} * \frac{1,000,000 \text{ G}}{\text{MG}} * \frac{\text{FT}^3}{7.48 \text{ G}} = 3,481.5 \text{ FT}^2$$

And then the diameter is:

$$\text{Diameter} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(3,481.5)}{\pi}} = 66.6 \text{ FT}$$

So the correct answer is b) 67 FT.

4) The hydraulic loading of a treatment unit depends upon the flow, the volume of the unit, the surface area of the unit and the length of the weirs:

A. The hydraulic retention time (HRT) is computed:

$$\text{HRT} = \frac{V}{Q} = \frac{100 \times 40 \times 20}{2.5 \text{ MGD}} = \frac{80,000 \text{ FT}^3}{2,500,000 \frac{\text{G}}{\text{D}}} \times \frac{7.48 \text{ G}}{\text{FT}^3} \times \frac{24 \text{ hours}}{\text{D}} = 5.74 \text{ hours}$$

The correct answer is a) 5.7 hours.

B. The hydraulic surface loading rate (HLR) is computed:

$$\text{HLR} = \frac{Q}{A_s} = \frac{2.5 \text{ MGD}}{100 \text{ FT} \times 40 \text{ FT}} = \frac{2,500,000 \text{ GPD}}{4,000 \text{ FT}^2} = 625 \text{ GPD/FT}^2$$

The correct answer is b) 625 GPD/FT².

C. The weir loading rate (WLR) is computed:

$$\text{WLR} = \frac{Q}{L_w} = \frac{2,500,000 \text{ GPD}}{80 \text{ FT}} = 31,250 \text{ GPD/FT}$$

The correct answer is b) 31,000 GPD/FT.

5) The size and number of sedimentation basins is controlled by the HLR, while the HRT dictates the volume and thus if HLR provides the surface area, then HRT provides the minimum depth.

A. The maximum size of the each basin is based on the maximum length given of 300 FT and the length to width ratio thus dictates a maximum width of:

$$\frac{300}{5} = 60 \text{ FT}$$

So the largest possible basin has a surface area of:

$$300 \times 60 = 18,000 \text{ FT}^2$$

The total surface required is given by the HLR:

$$HLR = \frac{Q}{A_s} \Rightarrow A_s = \frac{Q}{HLR} = \frac{25,000,000 \text{ GPD}}{800 \text{ GPD/FT}^2} = 31,250 \text{ FT}^2$$

Thus the number of basins required is:

$$\frac{31,250 \text{ FT}^2}{18,000 \text{ FT}^2} = 1.736$$

So the correct answer is c) 2.

- B. Determine the total area required, divide by the number of basins and then compute the length based on the length to width ratio and the area:

$$A_s = \frac{Q}{HLR} = \frac{35,000,000}{800} = 43,750 \text{ FT}^2$$

Since there are three basins:

$$A_s = \frac{43,750}{3} = 14,583 \text{ FT}^2$$

$$A_s = W \times L = \frac{L}{5} \times L = \frac{L^2}{5} \Rightarrow L = \sqrt{5A_s} = \sqrt{5(14,583)} = 270 \text{ FT}$$

The correct answer is b) 270 FT.

- C. Determine the volume required and divide by the surface area:

$$HRT = \frac{V}{Q} \Rightarrow V = Q \times HRT = \frac{25,000,000 \text{ G}}{D} \times 4.0 \text{ hours} \times \frac{D}{24 \text{ hours}} \times \frac{\text{FT}^3}{7.48 \text{ G}} = 557,041 \text{ FT}^3$$

$$\text{Depth} = \frac{557,041 \text{ FT}^3}{46 \text{ FT} \times 230 \text{ FT} \times 3} = 17.55 \text{ FT}$$

The correct answer is c) 18 FT.

- 6) Use the TON equation for calculation of the threshold odor number:

$$TON = \frac{V_{\text{Sample}} + V_{\text{Dilute}}}{V_{\text{Sample}}} = \frac{200 + 550}{200} = \frac{750}{200} = 3.75$$

The correct answer is d) 3.75.

- 7) Use HRT to find the basin volume and use the mixing equation to find the power required for mixing. Use the power required for mixing in the turbine mixer equation to find the mixer speed.

A. Volume is a function of HRT:

$$HRT = \frac{V}{Q} \Rightarrow V = Q \times HRT = \frac{5,000,000 \text{ G}}{D} \times 10 \text{ s} \times \frac{\text{hour}}{3600 \text{ s}} \times \frac{D}{24 \text{ hours}} \times \frac{FT^3}{7.48 \text{ G}} = 77.4 \text{ FT}^3$$

The correct answer is b) 77 FT³.

B. First compute the power required for mixing:

$$G = \sqrt{\frac{P}{\mu V}} \Rightarrow P = G^2 \mu V = 1000^2 (2.05 \times 10^{-5}) 77 = 1,578.5 \frac{LB \cdot FT}{s}$$

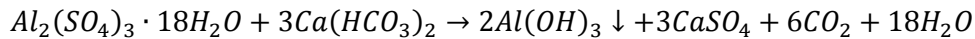
Then use the mixer equation to determine speed:

$$P = k \rho n^3 D^5 \Rightarrow n = \sqrt[3]{\frac{P}{k \rho D^5}} = \sqrt[3]{\frac{1,578.5}{1.25(1.936)(2.0)^5}} = 2.73 \text{ s}^{-1}$$

$$\frac{2.73 \text{ rev}}{s} \times \frac{60 \text{ s}}{M} = 164 \text{ RPM}$$

The correct answer is c) 164 RPM

8) To find the alkalinity required we can review the equation of the reaction between alum and alkalinity:



From the equation we see that one mole of alum reacts with 3 moles of Calcium bicarbonate, which represents the alkalinity. The molecular weight of alum is 342.1 and the molecular weight of Calcium bicarbonate is 162.1. Since there are 3 moles of Calcium bicarbonate, the total molecular weight is 486.3, so the ration of the alkalinity to alum is:

$$\frac{486.3}{342.1} = 1.42$$

To find the alkalinity needed to complete the reaction multiply the ratio by the quantity of alum:

$$65 \frac{mg}{L} \times 1.42 = 92.3 \text{ mg/L}$$

So, 92.3 mg/L of alkalinity as Calcium bicarbonate is required. Now convert to units as Calcium Carbonate. The equivalent weight of Calcium bicarbonate is 81.1 and the equivalent weight of Calcium Carbonate is 50.1, so:

$$\frac{50.1}{81.1} \times 92.3 = 57.0 \frac{mg}{L} \text{ as } CaCO_3$$

Alternatively, Use the factor to convert the alum to equivalents as calcium carbonate (0.88):

$$65 \times 0.88 = 57.2 \frac{mg}{L} \text{ as } CaCO_3$$

The correct answer is b) 57.

- 9) Use HRT to calculate the volume of the flocculation basin, the mixing equation to determine the power required for mixing and the paddle wheel flocculator equation to compute the surface area of the paddles.

A. Compute HRT:

$$HRT = \frac{V}{Q} = \frac{25 \text{ FT} \times 62 \text{ FT} \times 12 \text{ FT}}{10,000,000 \text{ GPD}} \times \frac{7.48 \text{ G}}{\text{FT}^3} \times \frac{1440 \text{ Min.}}{D} = 20.0 \text{ min.}$$

The correct answer is c) 20 min.

B. Use mixing equation:

$$G = \sqrt{\frac{P}{\mu V}} \Rightarrow P = G^2 \mu V = 80^2 (2.05 \times 10^{-5}) (25 \times 62 \times 12) = 2,440 \frac{\text{LB} \cdot \text{FT}}{\text{s}}$$

The correct answer is a) 2,440.

C. From the paddle wheel equation:

$$P = \frac{C_D A_P \rho v_p^3}{2} \Rightarrow A_P = \frac{2P}{C_D \rho v_p^3} = \frac{2(2,440)}{1.8(1.936)(0.7 * 2.0)^3} = 510 \text{ FT}^2$$

The correct answer is b) 510 FT².

- 10) The filtration system is designed based on hydraulic loading rates.

A. The capacity of the plant is the capacity of each filter multiplied by the total number of filters in the plant. The capacity of each filter is limited by its run time. Since each filter must be removed from service daily for backwashing and the backwash process takes about an hour, only 23 hours can be productive. Based on the HLR, one filter can produce:

$$HLR = \frac{Q}{A_S} \Rightarrow Q = HLR * A_S = 3 \frac{\text{GPM}}{\text{FT}^2} * (11 \text{ FT} * 22 \text{ FT}) = 726 \text{ GPM}$$

So the total volume produced by one filter in 23 hours is:

$$\frac{726 \text{ G}}{\text{M}} \times \frac{60 \text{ M}}{\text{Hr}} \times 23 \text{ Hr} \times \frac{\text{MG}}{1,000,000 \text{ G}} = 1.002 \text{ MG}$$

So the total plant capacity is:

$$1.002 \text{ MGD} \times 6 \text{ filters} = 6.0 \text{ MGD}$$

The correct answer is c) 6.0 MGD

- B. Compute the total surface area of the filters and calculate the overall backwash volume using the HLR and length of backwash:

$$A_s = 6 \text{ filters} \times 11 \text{ FT} \times 22 \text{ FT} = 1,452 \text{ FT}^2$$

$$HLR = \frac{Q}{A_s} \Rightarrow Q = HLR \times A_s = 18 \times 1452 = 26,136 \text{ GPM}$$

$$V = \frac{26,136 \text{ G}}{M} \times 20 \text{ M} \times \frac{MG}{1,000,000 \text{ G}} = 0.523 \text{ MG}$$

The correct answer is d) 0.52 MG.

- C. Use the HLR of the backwash for one filter to determine the required pump capacity:

$$HLR = \frac{Q}{A_s} \Rightarrow Q = HLR \times A_s = 18 \times (11 \times 22) = 4,356 \text{ GPM}$$

The correct answer is b) 4,356 GPM

11) A direct filtration plant does not have sedimentation facilities preceding the filters. Direct filtration achieves at least a 2.0 Log removal for Giardia and a 1.0 Log removal of viruses.

- A. The surface water treatment rule requires a minimum of a 3.0 Log removal/inactivation of Giardia. Since direct filtration achieves a 2.0 Log removal, the remainder must be achieved through inactivation. Thus: $3.0 - 2.0 = 1.0$, and a 1.0 Log inactivation is required. The correct answer is b) 1.0 Log.
- B. To determine the ozone required, the CT for Giardia and the CT for viruses must be determined. The largest CT will control the design. From the tables, to achieve a 3.0 Log inactivation of Giardia: $CT = 1.43 \text{ mg/L}\cdot\text{min}$. To achieve a 3.0 Log inactivation of viruses: $CT = 0.8 \text{ mg/L}\cdot\text{min}$. The required inactivation of Giardia is 1.0 Log and the required inactivation of viruses is 3.0 Log, thus:

$$CT_{Giardia} = \frac{1.0 \text{ Log inactivation}}{3.0 \text{ Log inactivation}} \times 1.43 = 0.48$$

Since $0.8 > 0.48$, the CT for inactivation of viruses controls the design.

The ozone contactor has superior baffling characteristics, thus the baffling factor is 0.70. Compute the contact time, T_{10} :

$$T_{10} = HRT \times B_f = 2.0 \times 0.70 = 1.4 \text{ min.}$$

Compute the minimum ozone residual based on the CT for viruses:

$$CT = C \times T_{10} \Rightarrow C = \frac{CT}{T_{10}} = \frac{0.8}{1.4} = 0.57$$

The correct answer is c) 0.57 mg/L.

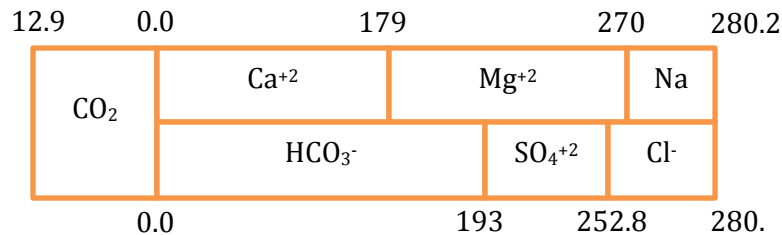
- C. Chlorine is the only disinfectant in the list that provides stable long-lasting residual to protect the distribution system. Ozone residuals only last for a few minutes and Ultraviolet Light (UV) does not create a residual at all.

The correct answer is a) Chlorine.

12) Construction of an ion bar chart can be helpful in solving lime softening problems:

		Concentration		Factor	=	CaCO ₃ equivalents
Carbon dioxide	CO ₂	5.7 mg/L	X	2.27	=	12.9
Calcium	Ca ⁺²	71.6 mg/L	X	2.50	=	179
Magnesium	Mg ⁺²	22.2 mg/L	X	4.10	=	91
Sodium	Na ⁺	4.7 mg/L	X	2.18	=	10.2
Bicarbonate	HCO ₃ ⁻	235 mg/L	X	0.82	=	193
Sulfate	SO ₄ ⁻	57.5 mg/L	X	1.04	=	59.8
Chloride	Cl ⁻	19.4 mg/L	X	1.41	=	27.4

Now draw the bar chart with cations on top starting with calcium and magnesium, the anions on the bottom starting with bicarbonate then sulfate and the gas to the left of zero:



The value of the CaCO₃ equivalents increases as you add ions to the right of zero. The cations should balance with the anions.

- A. The dose for selective calcium softening is equal to the quantity needed to react with carbon dioxide CO₂ and with the carbonate hardness from calcium. The CO₂ quantity is 12.9 mg/L as CaCO₃ and since the calcium concentration is less than the bicarbonate concentration, all the calcium is considered carbonate hardness, which is 179 mg/L as CaCO₃. Since both quantities are expressed as CaCO₃, they can be summed to determine the dose:

$$12.9 + 179 = 191.9$$

The correct answer is b) 192.

- B. The total lime dose is the sum of doses required to react with CO₂, Ca⁺², Mg⁺² carbonate hardness and Mg⁺² non-carbonate hardness, and the excess lime.

For CO ₂ :	12.9 mg/L as CaCO ₃
For Ca ⁺² :	179 mg/L as CaCO ₃
For Mg ⁺² carbonate hardness:	2 x (193 - 179) = 28 mg/L as CaCO ₃
For Mg ⁺² non-carbonate hardness:	270 - 193 = 77 mg/L as CaCO ₃
For the excess lime:	20 x 1.35 = 27 mg/L as CaCO ₃

The total is 323.9 mg/L as CaCO₃. The correct answer is d) 324.

C. The soda ash dose is the same as the non-carbonate hardness:

$$270 - 193 = 77$$

The correct answer is c) 77.

D. To convert the excess lime to a soluble form requires two equivalents of CO₂ and to solubilize the remaining hardness requires one equivalent of CO₂.

The excess lime is 20 mg/L x 1.35 = 27 mg/L as CaCO₃ x 2 = 54 mg/L as CaCO₃.

The remaining hardness is given as 50 mg/L as CaCO₃, thus the total dose of CO₂ is 54 + 50 = 104 mg/L as CaCO₃. The problem asks for the concentration in terms of CO₂, so convert:

$$\frac{104}{2.27} = 45.8$$

The correct answer is b) 46.

Workshop Problems

1) Storage required to meet seasonal demands is based on the total volume of the water supply deficit throughout the year. To solve this problem determine the difference between the stream flow and the water demand and then calculate the volume of water in the deficit months. First Calculate the average daily stream flow in MGD:

$$\text{MGD} = \text{cfs} \times 3600\text{sec/hr} \times 24\text{hr/day} \times 7.4805\text{gal/cf} \div 1,000,000\text{gal/MG}$$

Determine the deficit by subtracting the demand from the river flow, negative values represent the deficit. Determine the volume of the deficit in each month by multiplying the deficit by the number of days in the month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Daily River Flow (cfs)	20	20	23	32	43	27	12	4	2	2	7	20
Average Daily Water Demand (MGD)	5	5	6	6	7	9	11	11	10	10	9	7
Avg. Daily River Flow (MGD)	12.9	12.9	14.9	20.7	27.8	17.5	7.8	2.6	1.3	1.3	4.5	12.9
Difference between flow and demand (MGD)	7.9	7.9	8.9	14.7	20.8	8.5	-3.2	-8.4	-8.7	-8.7	-4.5	5.9

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Deficit Volume (MG)							99.2	260	261	270	135	

Sum the total of the deficit volumes and convert the total to acre-feet:

$$\text{Acre-feet} = \text{MG} \times 1,000,000 \text{ gal/MG} \div 7.4805 \text{ gal/cf} \div 43560 \text{ sf/acre}$$

Therefore:

$$99.2 + 260 + 261 + 270 + 135 = 1,025.2 \text{ MG}$$

$$1,025.2 \text{ MG} \times 1,000,000 \div 7.4805 \div 43560 = 3,146 \text{ acre-feet}$$

The correct answer is b) 3,150 acre-feet.

- 2) The treatment capacity of a water treatment plant should be based on the maximum day demand. The maximum day demand is determined by multiplying the average day demand by the maximum day factor given as 2.2. The average day demand is determined by multiplying the design year population by the average demand per capita given as 165 gallons per capita per day. Therefore:

$$\text{Average demand } 20,000 \times 165 = 3,300,000 \text{ gallons per day}$$

$$\text{Maximum day demand} = 2.2 \times 3,300,000 = 7,260,000 \text{ gallons per day} = 7.26 \text{ MGD}$$

Since the existing plant can treat up to 3.0 MGD, the expansion capacity needed is the difference between the maximum day demand and the existing capacity:

$$\text{Expansion needed} = 7.26 \text{ MGD} - 3.0 \text{ MGD} = 4.26 \text{ MGD}$$

The correct answer is d) 4.3 MGD.

- 3) Calculate the average daily demand.

$$5,000 \times 175 = 875,000 \text{ gallons per day.}$$

Calculate the maximum day demand.

$$875,000 \times 2.15 = 1,881,250 \text{ gallons per day.}$$

Since treatment facilities are designed with a capacity equal to the maximum day demand the treatment plant capacity is 1.88 MGD.

- 4) The distribution storage needed during peak hour is the difference between the volume of the demand during the peak hour and the volume of supply during the peak hour. The peak hour demand is calculated by determining the average daily demand and multiplying the peak hour factor given as 4.5. The average daily demand is calculated as in problem 2.

Average daily demand = $20,000 \times 175 = 3,500,000$ gpd = 3.50 MGD

Peak Hour demand = 3.50 MGD $\times 4.5 = 15.75$ MGD

The volume of the demand is calculated by converted MGD or gpd to gallons per hour:

Peak Hour demand volume = $15,750,000$ gpd $\div 24 = 656,250$ gallons

Since treatment capacity given is 7.0 MGD, the peak hour supply is calculated similarly:

Peak Hour supply = $7,000,000 \div 24 = 291,667$ gallons

The difference is the storage required for peak hour:

Peak hour storage required = $656,250 - 291,667 = 364,583$ gallons = 0.365 MG

Therefore the correct answer is b) 0.5 MG. Note that additional storage is actually required because it is likely that the hour preceding and the hour following peak hour will also exceed the supply, as will other hours of the day.

5) Use the feed rate formula to solve:

$$R_F = \frac{DQ8.34}{P}$$

$$R_F = \frac{2.0(2.5)8.34}{0.12} = 347.5 \text{ lb/day}$$

The correct answer is b) 350 lb/day.

6) Use the feed rate formula to solve:

$$R_F = \frac{DQ8.34}{P}$$

$$R_F = \frac{2.0(2.5)8.34}{0.12} = 347.5 \text{ lb/day}$$

Since the unit weight of sodium hypochlorite is 10 lb/gal, the volume needed for each day is:

$$V = \frac{R_F}{10} = \frac{347.5}{10} = 34.75 \text{ gallons}$$

The correct answer is c) 34 gallons.

7) Use the feed rate formula to solve:

$$R_F = \frac{DQ8.34}{P}$$

$$R_F = \frac{2.0(2.5)8.34}{0.12} = 347.5 \text{ lb/day}$$

Since the unit weight of sodium hypochlorite is 10 lb/gal, the volume needed for each day is:

$$V = \frac{R_F}{10} = \frac{347.5}{10} = 34.75 \text{ gallons}$$

Thus, the feed pump must feed at a rate equal to:

$$\frac{34.75}{24} = 1.45 \text{ gph}$$

The correct answer is a) 1.45 gph.

8) Use the feed rate formula to solve:

$$R_F = \frac{DQ8.34}{P}$$

$$R_F = \frac{2.0(2.5)8.34}{0.12} = 347.5 \text{ lb/day}$$

Since the unit weight of sodium hypochlorite is 10 lb/gal, the volume needed for each day is:

$$V = \frac{R_F}{10} = \frac{347.5}{10} = 34.75 \text{ gallons}$$

Thus, the volume needed for a month is 30 days:

$$34.75 * 30 = 1042.5 \text{ gallons}$$

The correct answer is d) 1100 gallons.

9) The mixing equation:

$$G = \sqrt{\frac{P}{\mu V}}$$

requires the values for the dynamic viscosity of water and the volume of the tank. From a table we determine the viscosity of water at 20°C is 2.05 X 10⁻⁵ lb-s/ft². The volume of the tank we determine from the hydraulic detention time:

$$\theta = \frac{V}{Q} \Rightarrow V = \theta \cdot Q = 10s \cdot \frac{10 \times 10^6 \text{ GPD}}{24 \text{ hr}} \cdot \frac{1 \text{ hr}}{3600s} \cdot \frac{1 \text{ ft}^3}{7.4805 \text{ gallons}} = 155 \text{ ft}^3$$

Then using the mixing equation we find power, P:

$$1000 = \sqrt{\frac{P}{(2.05 \times 10^{-5}) \cdot 155}} \Rightarrow 1000^2 = \frac{P}{(2.05 \times 10^{-5}) \cdot 155} \Rightarrow P = 1000^2 (2.05 \times 10^{-5}) \cdot 155$$

$$P = 3177.5 \text{ lb} \cdot \text{ft} / \text{s}$$

$$P = 3177.5 \text{ lb} \cdot \text{ft} / \text{s} \div 550$$

$$P = 5.78 \text{ Hp}$$

The correct answer is a) 6 horsepower.

10) Rapid Mix facilities are designed based on the mixing equation:

$$G = \sqrt{\frac{P}{\mu V}}$$

Where the velocity gradient, G is given as 700 s^{-1} and the dynamic viscosity, μ is given as $2.735 \times 10^{-5} \text{ lb} \cdot \text{s} / \text{ft}^2$. The basin volume, V can be calculated from the dimensions given:

$$V = 5 \times 5 \times 10 = 250 \text{ ft}^3$$

And the Power, P is calculated from the mixing formula:

$$700 = \sqrt{\frac{P}{(2.735 \times 10^{-5}) \cdot 250}}$$

$$700^2 = \left(\sqrt{\frac{P}{(2.735 \times 10^{-5}) \cdot 250}} \right)^2$$

$$490,000 = \frac{P}{0.006838}$$

$$P = 3,350 \text{ lb} \cdot \text{ft} / \text{s}$$

We can use the Power calculated in the mixing formula in the power formula for propellers and turbines:

$$P = K n^3 D_i^5 \rho$$

Where K is given as 1.00, n is the rotational speed, D_i is the impeller diameter and ρ is the density of water given as $1.94 \text{ slug} / \text{ft}^3$. Thus:

$$3350 = 1.00n^3(2.5)^5 1.94$$

$$3350 = 189n^3$$

$$n^3 = 17.7$$

$$n = 2.61 \text{ rot/s}$$

The solution needs to be in revolutions per minute so multiply by 60 and:

$$N = 2.61 \times 60 = 156 \text{ rpm}$$

The correct answer is b) 150 rpm.

11) Find the volume required using the specified hydraulic detention time:

$$\theta = \frac{V}{Q}$$

$$V = Q\theta$$

$$V = \frac{10 \times 10^6 \text{ MGD}}{1440 \text{ min/d}} (20) = 138,889 \text{ gallons}$$

$$V = \frac{138889 \text{ gal}}{7.4805 \text{ gal / ft}^3} = 18,567 \text{ ft}^3$$

The correct answer is c) 18,600 cubic feet.

12) Use the mixing formula and solve for P:

$$G = \sqrt{\frac{P}{\mu V}}$$

$$P = G^2 \mu V = 50^2 (2.05 \times 10^{-5}) 20,000$$

$$P = 1025 \text{ lb} \cdot \text{ft/s}$$

The correct answer is b) 1100 lb-ft/s.

13) Determine the relative velocity of the paddle with respect to the fluid based on factor given and tip speed:

$$v_p = 0.7(2.5) = 1.75 \text{ ft/s}$$

Use the paddle-wheel flocculator formula to determine the required paddle area:

$$P = \frac{C_D A_p \rho v_p^3}{2}$$

$$1000 = \frac{1.8 A_p (1.936)(1.75)^3}{2}$$

$$A_p = \frac{2(1000)}{1.8(1.936)(1.75)^3} = 107 \text{ ft}^2$$

The correct answer is d) 110 square feet.

14) A flocculator design is similar to the rapid mix design in that we use the mixing equation. To determine the rotational speed of the paddle wheel we merely need to know the diameter of the wheel and the tip speed. The diameter of wheel can be obtained from the problem statement that the shaft spans the length of the basin and the paddle wheel is 40% of the basin width. Thus the diameter of the wheel is:

$$D = 0.40 \times 30.75 = 12.3 \text{ ft}$$

The rotational speed is given by the tip speed divided by the circumference of the wheel, C:

$$C = \pi D = 3.141493 \times 12.3 = 38.64 \text{ ft}$$

$$\text{Rotational speed} = 3 \div 38.64 = 0.0776 \text{ rev/s}$$

Convert the rotational speed to revolutions per minute (rpm) by multiplying by 60 seconds in a minute:

$$\text{Rotational Speed} = 0.0776 \times 60 = 4.66 \text{ rpm}$$

The correct answer is a) 5 rpm.

15) To determine the paddle wheel area we use the paddle wheel power formula with the power required calculated by the mixing formula:

Paddle Wheel formula:
$$P = \frac{C_D A_p \rho V_p^3}{2}$$

Mixing Formula
$$G = \sqrt{\frac{P}{\mu V}}$$

The basin volume is given by the dimensions:

$$V = 30.75 \times 61.5 \times 20.0 = 37,822.5 \text{ ft}^3$$

And:

$$35 = \sqrt{\frac{P}{(2.735 \times 10^{-5})37822.5}}$$

$$35^2 = \frac{P}{1.03444}$$

$$P = 1225 * 1.0344 = 1267 \text{ lb} \cdot \text{ft} / \text{s}$$

Now we can calculate the required paddle area, A using the Paddle Wheel formula:

$$1267 = \frac{(1.8)A(1.94)(0.6 * 3)^3}{2}$$

$$2534 = 20.365A$$

$$A = 124 \text{ ft}^2$$

The correct answer is a) 125 ft².

16) The design overflow rate is the design flow divided by the surface area of the sedimentation basin. The surface is calculated:

$$A = L \times W = 120 \times 40 = 4,800 \text{ sf}$$

and thus the design overflow rate is calculated:

$$DOR = \frac{Q}{A} = \frac{4,000,000}{4,800} = 833.33 \text{ gpd} / \text{sf}$$

and the correct answer is b) 800 gpd/sf.

17) The surface area required is based on the overflow rate or surface loading rate given as 400 gpd/ft²:

$$\text{Overflow Rate} = 400 = \frac{Q}{A_s} = \frac{12,000,000}{A_s}$$

$$A_s = \frac{12,000,000}{400} = 30,000 \text{ ft}^2$$

The correct answer is d) 30,000 ft².

18) The number of basins required is based on the maximum length of the basin and the length to width ratio. Try a single tank, let w = the width and $5w$ = the length:

$$A = 5w \times w = 5w^2 = 30,000$$

$$w^2 = 30,000 \div 5 = 6,000$$

$$w = 77.5 \text{ ft}$$

and

$$5w = 387.5 \text{ ft}$$

Which is too long so for a second try assume the maximum length is 250 feet and thus the width is $250 \div 5 = 50 \text{ ft}$ and so the area of one tank is:

$$A = 250 \times 50 = 12,500 \text{ ft}^2$$

How many are required:

$$A = 30,000$$

$$\# \text{ Required} = 30,000 \div 12,500 = 2.4$$

So a minimum of three basins are required for average flow. The correct answer is b) 3 basins.

19) If the width of each basin is 45 ft, then the length is simply 5 times the width or 225 ft, so the correct answer is b) 225 ft.

20) The detention time is given by the volume of the basins divided by the flow rate:

$$\theta = \frac{V}{Q} = \frac{30,375 \times 16 \times 7.48}{12,000,000} = 0.303 \text{ days}$$

$$\theta = 0.303 \times 24 = 7.3 \text{ hours}$$

The correct answer is d) 7.3 hours.

21) The weir length required is given by the weir loading rate defined:

$$\text{Weir Loading Rate} = \frac{Q}{L_w} = 12,000 \frac{\text{gpd}}{\text{ft}}$$

Thus:

$$12,000 = \frac{12,000,000}{L_w}$$

$$L_w = \frac{12,000,000}{12,000} = 1,000 \text{ ft}$$

The total length required is 1,000 ft, so each basin requires $1,000 \div 3 = 333 \text{ ft}$ of weir. The correct answer is b) 335 ft.

22) The number of basins required for peak capacity is proportional to the peak flow to average flow ratio which is given as 2.0. Since 3 basins are required for average flow, $2 \times 3 = 6$ basins are required for peak flow. The correct answer is c) 6 basins.

23) Convert gallons per day to gallons per minute:

$$\frac{450000 \text{ gpd}}{1440 \text{ min/d}} = 312.5 \text{ gpm}$$

Then express the filter loading mathematically as:

$$\begin{aligned} \text{Filter Loading Rate} &= \frac{\text{gpm flow}}{\text{ft}^2 \text{ filter area}} \\ &= \frac{312.5}{10 \times 15} = \frac{312.5}{150} = 2.08 \text{ gpm/ft}^2 \end{aligned}$$

24) The filter area is $12 \times 12 = 144$ sq. feet. The specified filtration rate is 2.5 gpm/ft^2 . Thus $2.5 \times 144 = 360$ gpm. Answers are in gpd so multiply by 1,440 minutes in a day which gives 518,400 gpd. Thus the design capacity is most nearly b) 510,000 gpd.

25) Each 10 feet square filter bed will filter about $10 \times 10 \times 2.5 = 250$ gpm.

$$250 \text{ gpm} \times 1440 \text{ min/day} = 360,000 \text{ gpd} = 0.36 \text{ MGD}$$

$$3.8 \text{ MGD} \div 0.36 = 10.6$$

So 11 beds are needed to treat 3.8 MGD, thus 12 total beds meet the design criteria. The correct answer is a) 12.

26) The filter bed will expand in height 75% of its normal height during backwash for cleaning. Thus the expanded height of the filter bed is: $2.0 \times 1.75 = 3.50$. The height of the wash troughs over the bed is set six inches above the expanded bed depth. Therefore, $3.5 - 2.0 + 0.5 = 2.0$ ft above the filter bed. The correct answer is b) 2.0 ft.

27) The surface water treatment rule requires that a 3.0 log removal/inactivation of Giardia cysts be achieved. A credit of 2.5 log removal is given for conventional treatment including flocculation, sedimentation, and filtration. Therefore, the disinfection system must achieve a 0.5 log inactivation. Using a maximum chlorine dose of 1.8 mg/l, find $CT = 23$ in the column under 0.5 log inactivation. From this calculate the minimum residual concentration required:

$$\begin{aligned} CT &= \text{concentration (mg/l)} \times \text{contact time (min)} \\ \text{concentration} &= \frac{CT}{\text{contact time}} = \frac{23}{25} = 0.92 \text{ mg/l} \end{aligned}$$

28) The correct answer is b), The effectiveness of chlorine as a disinfectant is enhanced when the pH of the water is decreasing and the temperature of the water is increasing.

29) The chlorine required is calculated from the flow and dose:

$$\text{Chlorine Required} = 7.0 \times 5.0 \times 8.34 = 291.9 \text{ lb/d}$$

The hypochlorite required is based on the available chlorine (70%) thus:

$$\text{Hypochlorite Required} = 291.9 \div 0.7 = 417 \text{ lb/d}$$

The correct answer is a) 420 lb/d.

30) Chlorine and organic carbon react to form disinfection byproducts called trihalomethanes. Chloroform is one species of trihalomethane that is formed from free chlorine and organic matter. Organic carbon reduces the efficiency of chlorine as a disinfectant because of the demand placed on the water by the organic carbon. Therefore, the correct answer is d) b and c, Trihalomethanes form and chloroform is produced.

31) CT is the product of the chlorine residual and contact time which can be used to determine the efficiency of the disinfection process. Contact time can be calculated using baffling factors to reduce the theoretical hydraulic retention time in each unit to calculate the contact time in the unit. To solve the problem calculate the contact time in each unit and sum the contact times to determine the total time then multiply by the chlorine residual.

$$Q = 5 \frac{MG}{D} \frac{1D}{24hr} \frac{1hr}{60min} \frac{1,000,000gal}{MG} \frac{1ft^3}{7.48gal} = 464.2 \text{ ft}^3/\text{min}$$

$$\theta = \frac{V}{Q} = \frac{250}{464.2} = 0.54 \text{ min}$$

Unit	Volume (ft ³)	Baffling Factor	Theoretical Retention Time (min)	Calculated Contact Time (min)
Coagulation	250	0.5	0.54	0.27
Flocculation	20,000	0.7	43.1	30.2
Sedimentation	150,000	0.7	323	226
Filtration	15,000	0.5	32.3	16.1
Total				272

$$CT = 272 \times 1.2 = 326 \text{ mg/L}\cdot\text{min.}$$

The correct answer is d) 325 mg/L·min.

32) The molecular weight of Calcium is 40. Since calcium has a valence of 2+, its equivalent weight is 20. The molecular weight of CaCO₃ is 100 and its equivalent weight is 50. Therefore each mg/L of Calcium in the water is equivalent to 50/20 of CaCO₃. Thus:

$$24 \text{ mg/L Ca}^{++} = 24 \times 2.5 = 60 \text{ mg/L as CaCO}_3$$

The correct answer is c) 60 mg/L as CaCO₃.

33) Solution: Calculate the pH.

$$pH = \log \frac{1}{[H^+]} = \log \frac{1}{2.09 \times 10^{-8}}$$

$$pH = 7.68$$

Calculate the concentration of hydroxide ions.

The product of the concentration of hydrogen ions and the concentration of hydroxide ions is equal to K_w , the dissociation constant for water. $K_w = 1 \times 10^{-14}$ moles²/liter². Therefore:

$$[H^+] \cdot [OH^-] = 1 \times 10^{-14}$$

$$2.09 \times 10^{-8} \cdot [OH^-] = 1 \times 10^{-14}$$

$$[OH^-] = 4.78 \times 10^{-7}$$

The solution is $pH = 7.68$ and the concentration of hydroxide ions is 4.78×10^{-7} moles/liter.

34) Sulfuric acid, H_2SO_4 , dissociates into $2H^+$ and SO_4^{2-} . Sodium hydroxide, $NaOH$, dissociates into Na^+ and OH^- . Therefore, it takes two moles of sodium hydroxide to neutralize one mole of sulfuric acid. The molecular weight of sulfuric acid is 98.1 and the molecular weight of sodium hydroxide is 40. Therefore, it takes 2×40 lb of $NaOH$ to neutralize 1×98.1 lb of H_2SO_4 . Thus:

$$\text{Lb NaOH required} = 80/98.1 \times 50 = 40.8 \text{ lb of NaOH}$$

The correct answer is c) 45 lb of sodium hydroxide are required to neutralize 50 lb of sulfuric acid.

35) Alkalinity is the measure of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ion in the water. When the alkalinity is all carbonate ion, additional alkalinity may be contributed by hydroxide (OH^-) ions. However, at pH below 8.5 all alkalinity is converted to bicarbonate. Thus the analysis shows the pH as 7.6 and the concentration of bicarbonate as 210 mg/L. The equivalent weight of the bicarbonate ion is 61 and the equivalent weight of $CaCO_3$ is 50. Thus:

$$210 \text{ mg/L } HCO_3^- = 50/61 \times 210 = 172 \text{ mg/L Alkalinity as } CaCO_3$$

The correct answer is a) 170 mg/L Alkalinity as $CaCO_3$.

36) The quality of Hardness is contributed by multivalent metallic cations, usually calcium (Ca^{++}) and Magnesium (Mg^{++}). These are the only multivalent metallic cations shown in the analysis, thus hardness is a measure of the calcium and magnesium in the water. The equivalent weight of calcium is 20, magnesium is 12.2 and calcium carbonate is 50. Thus:

$$29 \text{ mg/L } Ca^{++} = 29 \times 50/20 = 72.5 \text{ mg/L } Ca^{++} \text{ as } CaCO_3$$

$$16.4 \text{ mg/L } Mg^{++} = 16.4 \times 50/12.2 = 67.2 \text{ mg/L } Mg^{++} \text{ as } CaCO_3$$

$$\text{Total Hardness} = 72.5 + 67.2 = 139.7 \text{ mg/L Hardness as } CaCO_3$$

The correct answer is b) 140 mg/L Hardness as $CaCO_3$.

37) Since the pH is less than 8.5, alkalinity is contributed to by Bicarbonate, HCO_3^- . Bicarbonate has an equivalent weight of 61.0 and CaCO_3 has an equivalent weight of 50.0 grams/mole. Therefore the equivalent of Bicarbonate alkalinity in CaCO_3 is:

$$336 \times 50/61 = 275 \text{ mg/l as } \text{CaCO}_3$$

Hardness is imparted by Calcium, Ca^{++} and Magnesium, Mg^{++} . Calcium has an equivalent weight of 20.0 and Magnesium has an equivalent weight of 12.2 grams/mole. Therefore:

$$80 \times 50/20 = 200 \text{ mg/l as } \text{CaCO}_3$$

$$30 \times 50/12.2 = 123 \text{ mg/l as } \text{CaCO}_3$$

Thus the total hardness is the sum of the Calcium hardness and the Magnesium hardness:

$$200 + 123 = 323 \text{ mg/l as } \text{CaCO}_3$$

What is the carbonate hardness expressed as CaCO_3 ?

Since alkalinity is less than total hardness, the carbonate hardness is 275 mg/L as CaCO_3 .

38) In answer a) Ca_2HCO_3 is not a possible compound because the valence of calcium is 2+ and the valence of the bicarbonate ion is 1-. NaHCO_3 is a theoretically valid compound, but Mg_4SO_4 and MgCl are not because of incompatible valences. Answer b) offers compatible valences in all compounds listed. Answer c) offers compatible valences in all compounds except CaCl and Ca_4SO_4 . Answer d) offers compatible valences in all compounds except NaCa which is composed of both positive ions and thus not valid. The correct answer is b). Other possible compounds include CaSO_4 and NaHCO_3 .

The lime, CaO reacts with calcium, magnesium, and carbon dioxide in the water. Determine the total alkalinity and total hardness. The total alkalinity is given by the HCO_3^- which is:

$$336 \text{ mg/L } \text{HCO}_3^- = 50/61 \times 336 = 275 \text{ mg/L Alkalinity as } \text{CaCO}_3$$

The hardness is given by the Calcium and Magnesium as follows:

$$80 \text{ mg/L } \text{Ca}^{++} = 50/20 \times 80 = 200 \text{ mg/L Hardness as } \text{CaCO}_3$$

$$30 \text{ mg/L } \text{Mg}^{++} = 50/12.2 \times 30 = 123 \text{ mg/L Hardness as } \text{CaCO}_3$$

$$\text{Total Hardness} = 200 + 123 = 323 \text{ mg/L as } \text{CaCO}_3$$

Thus, since the total alkalinity is greater than the calcium hardness, we can assume the calcium hardness is all carbonate. Since the total hardness is greater than the total alkalinity, some magnesium hardness is carbonate and some is non-carbonate. The carbonate fraction is equal to $275 - 200 = 75 \text{ mg/L as } \text{CaCO}_3$. Thus the remaining magnesium hardness is noncarbonated, $123 - 75 = 48 \text{ mg/L as } \text{CaCO}_3$. Since one mole of lime is required per mole of calcium hardness and per mole of noncarbonate magnesium hardness, 323 mg/L of lime as CaCO_3 is needed. In addition, one

extra mole of lime is required for the carbonate magnesium hardness, so 75 mg/L of lime as CaCO_3 is required. The CO_2 in the water is equivalent to:

$$15 \text{ mg/L CO}_2 = 50/22 \times 15 = 34 \text{ mg/L as CaCO}_3$$

Thus the total lime needed to meet stoichiometric requirements is:

$$323 \text{ mg/L} + 75 \text{ mg/L} + 34 \text{ mg/L} = 432 \text{ mg/L as CaCO}_3$$

35 mg/L excess lime is needed to ensure the pH is raised sufficiently to make the reactions go forward and the equivalent weight of lime is 28, thus:

$$\text{Lime Dosage} = 28/50 \times 432 + 35 \text{ mg/L excess} = 276.92 \text{ mg/L}$$

To calculate the lime dosage in lb/MG use 8.34:

$$\text{Lime} = 276.92 \times 8.34 = 2,309 \text{ lb/MG}$$

The correct answer is d) 2,310 lb/MG.

Soda ash is required to eliminate the calcium noncarbonate hardness that remains after the magnesium noncarbonate hardness is removed. The noncarbonate hardness is the total hardness minus the total alkalinity = $323 - 275 = 48 \text{ mg/L as CaCO}_3$. One mole of Soda Ash (Na_2CO_3) is required per mole of noncarbonate hardness. The equivalent weight of soda ash is 53, thus:

$$48 \times 53/50 = 51 \text{ mg/L of soda ash are required.}$$

$$\text{Soda Ash} = 51 \times 8.34 = 425.3 \text{ lb/MG of soda ash is required.}$$

The correct answer is d) 430 lb/MG.

The lime softening process produces CaCO_3 which settles and Mg(OH)_2 which also settles. However not all the calcium carbonate and magnesium hydroxide settles out. The problem statement indicates that 30 mg/L of CaCO_3 remains and 10 mg/L of Mg(OH)_2 as CaCO_3 remains. Since the equivalent weight of CaCO_3 is 50, then $30/50 = 0.6 \text{ meq/l}$ of Ca^{++} remains and $10/50 = 0.2 \text{ meq/l}$ of Mg^{++} remains and 0.2 meq/l of OH^- ion remains. In addition, the excess lime must be neutralized and it is equivalent to: $35 \times 50/28 = 62.5 \text{ mg/L as CaCO}_3$. Recarbonation is required to reduce the pH by neutralizing the excess lime, calcium carbonate and hydroxide in the water. One mole of CO_2 is required to neutralize each mole of lime, calcium carbonate and hydroxide ion. Thus,

$$\text{CO}_2 \text{ required} = 30 + 10 + 62.5 = 102.5 \text{ mg/L as CaCO}_3$$

And since the equivalent weight of CO_2 is 22:

$$\text{CO}_2 \text{ required} = 102.5 \times 22/50 = 45.1 \text{ mg/L CO}_2$$

$$\text{And: } 45.1 \times 8.34 = 376 \text{ lb/MG.}$$

The correct answer is a) 380 lb/MG.

39) The enhanced surface water treatment rule, effective January 1, 2002 requires that systems servicing more than 10,000 people and effective January 14, 2005, systems servicing less than 10,000 people must produce water with less than 0.3 NTU in 95% of all filtered water samples taken each month and never exceed 1.0 NTU. Therefore the correct answer is b) 1.0 NTU.

40) The chemical rule specifies Maximum Contaminant Levels (MCLs) for various radioactive, inorganic, synthetic organic, and volatile organic contaminants. The MCLs are enforceable under the The Chemical Rule. The rule also specifies Maximum Contaminant Level Goals (MCLGs) for each contaminant. The MCLGs are not enforceable under the rule, The MCLs for each of the inorganic contaminants is listed below:

Antimony	6 ppb
Arsenic	50 ppb
Asbestos	7 MFL
Barium	2 ppm
Beryllium	4 ppb
Cadmium	5 ppb
Chromium	100 ppb
Cyanide	200 ppb
Flouride	4 ppm
Mercury	2 ppb
Nitrate	10 ppm
Nitrite	1 ppm
Selenium	50 ppb
Thallium	2 ppb

By comparing the analysis given in the problem with the table above, we find that Chromium, Cyanide and Nitrate are the contaminants that exceed the MCL. Therefore, the correct answer is c) Chromium, Cyanide and Nitrate.

41) Secondary water quality standards govern aesthetic constituents rather than contaminants that cause health problems. The Secondary MCLs are as follows:

Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 Color Units
Copper	1.0 mg/L
Corrosivity	non-corrosive
Flouride	2.0 mg/L
Foaming agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 Odor #
pH	6.5 to 8.5
Silver	0.1 mg/L

Sulfate	250 mg/L
TDS	500 mg/L
Zinc	5 mg/L

By comparing the analysis given in the problem with the above table, we find that iron, manganese and pH do not meet the Secondary MCLs. Note that the MCL for pH is an acceptable range between 6.5 and 8.5, and that a pH higher than 8.5 or lower than 6.5 is not in compliance. The correct answer is c) Iron, manganese, and pH.

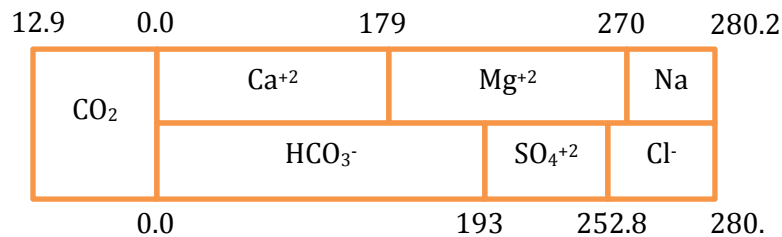
42) Solution: Units of mg/l are equal to ppm. To convert $\mu\text{g/l}$ to mg/l multiply by 0.001. Therefore Barium and Chromium are the only constituents that do not meet the MCLs set by the safe drinking water act. Chromium concentration is 0.15 mg/l which exceeds the MCL of 0.1.

43) Find the calcium carbonate equivalents for each substance:

Use the conversion factors from Appendix 22.C of the Lindberg review manual.

	Concentration		Factor	=	CaCO ₃ equivalents
Carbon dioxide	CO ₂ 5.7 mg/L	X	2.27	=	12.9
Calcium	Ca ⁺² 71.6 mg/L	X	2.50	=	179
Magnesium	Mg ⁺² 22.2 mg/L	X	4.10	=	91
Sodium	Na ⁺ 4.7 mg/L	X	2.18	=	10.2
Bicarbonate	HCO ₃ ⁻ 235 mg/L	X	0.82	=	193
Sulfate	SO ₄ ⁻ 57.5 mg/L	X	1.04	=	59.8
Chloride	Cl ⁻ 19.4 mg/L	X	1.41	=	27.4

Now draw the bar chart with cations on top starting with calcium and magnesium, the anions on the bottom starting with bicarbonate then sulfate and the gas to the left of zero:



The value of the CaCO₃ equivalents increases as you add ions to the right of zero. The cations should balance with the anions. This is sometimes referred to as an ion bar chart.

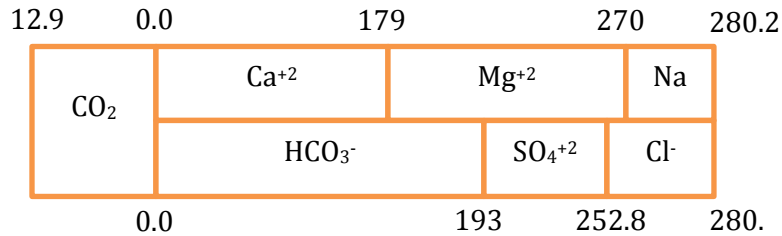
44) The recipe for lime and soda ash softening is as follows:

- 1 equivalent of lime per equivalent of carbon dioxide.
- 1 equivalent of lime per equivalent of calcium hardness.
- 2 equivalents of lime per equivalent of magnesium carbonate hardness.

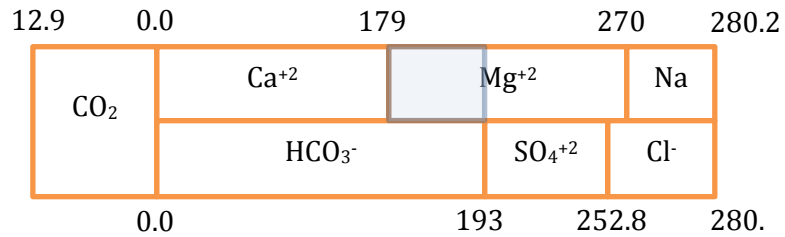
1 equivalent of lime per equivalent of magnesium non-carbonate hardness.

1 equivalent of soda ash (sodium carbonate) per equivalent of non-carbonate hardness.

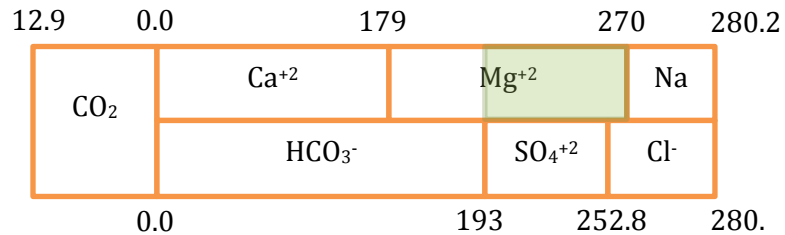
The problem asks for the lime dose and the hardness equivalents are shown in solution to previous problem:



The shaded area in this diagram shows the magnesium carbonate hardness:



The shaded area in this diagram shows the magnesium non-carbonate hardness:



Thus the factors from the recipe can be determined from the bar diagram and the lime dose calculated in accordance with the recipe.

Carbon dioxide is 12.9 mg/L thus lime required : $12.9 \times 1 = 12.9$

Calcium is 179 mg/L as CaCO_3 thus lime required: $179 \times 1 = 179$

Magnesium carbonate hardness is $193-179=14$ thus lime required: $14 \times 2 = 28$

Magnesium non-carbonate hardness is $270-193=77$ thus lime required: $77 \times 1 = 77$

Excess Lime: 20

Total Lime Dose: 316.9 mg/L
as CaCO_3

Convert dose to Lime (use factor for Calcium Oxide from table): $\frac{316.9}{1.79} = 177 \text{ mg/L CaO}$

The feed rate is determined from the feed rate equation:

$$F_R = \frac{Q * D * 8.34}{P} = \frac{30 * 177 * 8.34}{1.0} = 44,285 \text{ lb/d}$$

Thus:

$$\frac{44,285 \text{ lb}}{2000 \text{ lb/Ton}} = 22.1 \text{ Tons}$$

The correct answer is c) 22 tpd.

45) The recipe for lime and soda ash softening is as follows:

1 equivalent of lime per equivalent of carbon dioxide.

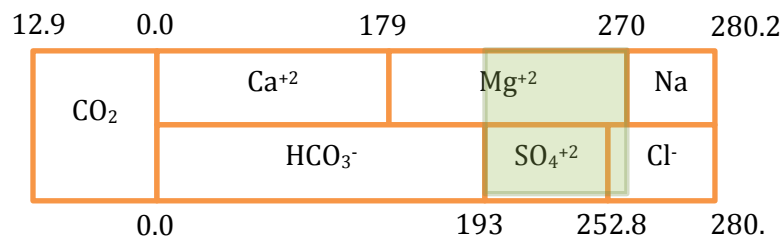
1 equivalent of lime per equivalent of carbonate calcium hardness.

2 equivalents of lime per equivalent of magnesium carbonate hardness.

1 equivalent of lime per equivalent of magnesium non-carbonate hardness.

1 equivalent of soda ash (sodium carbonate) per equivalent of non-carbonate hardness.

The problem asks for the soda ash dose and the hardness equivalents are shown in the following bar diagram. The shaded area in this diagram shows the non-carbonate hardness:



Thus the non-carbonate hardness is $270 - 193 = 77 \text{ mg/L as CaCO}_3$, so the soda ash dose is also $77 \text{ mg/L as CaCO}_3$. Convert to units of soda ash using the factor from the table:

$$\frac{77}{0.94} = 81.9 \text{ mg/L Na}_2\text{CO}_3$$

The correct answer is d) 82 mg/L

46) The dose of carbon dioxide required for recarbonation to remove the excess lime and convert the remaining hardness to carbonate forms is two equivalents per excess lime equivalent and one equivalent per hardness equivalent, thus:

$$2 \times 50 + 40 = 140$$

So, the dose is 140 mg/L of CO₂ as CaCO₃, convert dose to units of CO₂ using the factor from Appendix 22.C:

$$\frac{140}{2.27} = 61.7$$

The correct answer is b) 62 mg/L.

47) The recipe for lime and soda ash softening is as follows:

1 equivalent of lime per equivalent of carbon dioxide.

1 equivalent of lime per equivalent of carbonate calcium hardness.

2 equivalents of lime per equivalent of magnesium carbonate hardness.

1 equivalent of lime per equivalent of magnesium non-carbonate hardness.

1 equivalent of soda ash (sodium carbonate) per equivalent of non-carbonate hardness.

The lime dose is equal to:

$$\begin{array}{rccccccccc} \text{Carbon dioxide} & + & \text{Calcium} & + & \text{carbonate magnesium} & + & \text{excess lime} & = & \text{Lime dose} \\ 22.7 & + & 161 & + & 2 * (197 - 161) & + & 60 & = & 315.7 \text{ mg/L as CaCO}_3 \end{array}$$

Since there is no non-carbonate hardness, no soda ash is required, so the lime dose is calculated using the factor from Table 1 in the Water Chemistry notes:

$$\frac{315.7}{1.35} = 233.9$$

The correct answer is c) 234 mg/L Ca(OH)₂ and 0 mg/L Na₂CO₃.

48) The recipe for lime and soda ash softening is as follows:

1 equivalent of lime per equivalent of carbon dioxide.

1 equivalent of lime per equivalent of carbonate calcium hardness.

2 equivalents of lime per equivalent of magnesium carbonate hardness.

1 equivalent of lime per equivalent of magnesium non-carbonate hardness.

1 equivalent of soda ash (sodium carbonate) per equivalent of non-carbonate hardness.

There is no magnesium, so the lime dose is dependent upon the carbon dioxide, calcium hardness and excess lime:

$$\begin{array}{rcccccc} \text{Carbon dioxide} & + & \text{carbonate calcium hardness} & + & \text{excess lime} & = & \text{lime dose} \\ 12 & + & 150 & + & 50 & = & 212 \text{ mg/L as CaCO}_3 \end{array}$$

Convert the lime dose to 90% hydrated lime using the factor from Table 1 in the Water Chemistry notes:

$$\frac{212}{1.22} = 174 \text{ mg/L } 90\% \text{ Ca(OH)}_2$$

Use the feed rate equation to calculate the feed rate:

$$\frac{Q * D * 8.34}{P} = \frac{5 * 174 * 8.34}{1} = 7,256$$

The correct answer is b) 7,260 lb/d.