Environmental Math for Water and Wastewater

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Chapter One

1.0 MATHEMATICS

1.1 Addition

Adding 10 plus 10 and reaching a conclusion of 20 is a simple operation, but adding complex numbers like 13.333 and 0.0033 pose a larger challenge. To avoid arriving at incorrect answers when adding complex numbers, follow the basic rules below.

1. Decimals points and numbers should line up in columns. When this rule is followed correctly, the previous complex addition problem is easily performed.

\[
\begin{align*}
13.3330 & \\
+ & 0.0033 \\
13.3363 & 
\end{align*}
\]

2. Be sure you are adding apples and apples, and not apples and oranges. All numbers must represent the same types of units (i.e.; inches, pounds, feet, etc.). When adding the length of two pieces of pipe, if one is 32 inches and the other is 3 ½ feet, you must convert the measurements to common units. Either divide 32 inches by 12 inches per foot to convert to 2.667 feet or multiply 3 ½ feet by 12 inches per foot to convert to 42 inches before the adding the numbers. Converting 32 inches to feet with a fraction also can be done as shown below.

\[
\begin{align*}
32 \text{ in.} & \\
+ & 42 \text{ in.} \\
74 \text{ in.} & \\
+ & \frac{2}{3} \text{ft.} \\
& \frac{3.500 \text{ ft.}}{6.167 \text{ ft.}} \\
& \frac{3-\frac{1}{2} \text{ ft.}}{6-\frac{1}{2} \text{ ft.}}
\end{align*}
\]
3. Write down carryover numbers when adding columns of numbers. This will prevent another common error shown below. Numbers carryover from right to left in these operations.

\[
\begin{array}{c}
279 \\
+ 165 \\
\hline
334 \\
\end{array}
\]

which should be + 11 (carryover numbers)

\[
\begin{array}{c}
279 \\
+ 165 \\
\hline
444 \\
\end{array}
\]

1.2 Subtraction

Subtraction problems are the reverse operation of addition problems and the same general rules apply.

1. Keep all decimal points and numbers aligned in columns.

\[
\begin{array}{c}
4.457 \\
- 0.050 \\
\hline
4.407 \\
\end{array}
\]

2. Carryover numbers are not used in subtraction, but sometimes “-borrowing” numbers is required. Borrowing numbers

\[
\begin{array}{c}
216 \\
- 286 \\
\hline
88 \\
\end{array}
\]

**Step One** (the ones column) Borrow one unit (10) from the 7 in the tens column. You now subtract 6 from 14 to get 8 in the ones column.

**Step Two** (the tens column) You borrowed one unit from the seven which leaves six. You must now borrow one unit (100) from one hundreds column. You now subtract 8 from 16 to get 8 in the tens column.
After borrowing from the one hundreds column you are left with a 2 in that column. Finally, 2 minus 2 equals zero in that column. No entry is needed in the hundreds column. This leaves an answer of 88 for the subtraction problem.

Always check your answers. The best way to check your answer in a subtraction problem is to use addition. Add your answer to the number you subtracted and you should get the number you subtracted from. Below you see that 88 plus 286 equals 374, which is where you started.

\[
\begin{array}{c}
88 \\
+ 286 \\
\hline
374
\end{array}
\]

3. Be sure you are subtracting apples from apples and not apples from oranges. You must work in like units (units that are the same). This is called dimensional analysis and is discussed later in this chapter.

1.3 Multiplication

Multiplication is like a shortcut to adding numbers. For example, 5 x 4 is simply:

- \[4 + 4 + 4 + 4 + 4 = 20\]
- \[5 \times 4 = 20\]

Multiplication can always be checked by addition, but to save time, multiplication tables through 10 times 10 should be memorized.

Multiplication problems involving larger numbers can be solved by addition too, but could take too much time. Simple multiplication steps are preferred when multiplying larger numbers.

**Example 1.1** 12 x 39

\[
\begin{array}{c}
12 \\
x 39 \\
\hline
\end{array}
\]

\[1^{st} \text{ step - multiply the ones column}\]

- 9 x 2 = 18, write down the 8 and carry the 1 to the next column.

\[\text{8}\]

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12

2nd step - multiply the 9 in the ones column by the
x 39
1 in the tens column 1 x 9 = 9, then add the carryover
108 and write down 10 next to the ones column.

12

3rd step - multiply the 3 in the tens column by the
x 39
2 in the ones column 3 x 2 = 6, then write down 6
108 in the tens column.

6

12

4th step - multiply the 3 in the tens column by the
x 39
1 in the tens column 3 x 1 = 3, then write down 3
108 in the hundreds column. Then add a zero to the ones
360 column to keep numbers lines up.

12

5th step - add the numbers in the columns
x 39
108
+ 360
468

Add 108 + 360 = 468
12 x 30 = 468

There are several rules to remember in multiplication problems.

1. The number of decimal places in the answer is equal to the sum of decimal
   places in the numbers multiplied. Remember to keep number in columns.

12.002
x 1.03

3 decimal places
2 decimal places
36006
00000
12002
12.36206
5 decimal places
2. Units do not have to be apples and apples. They can be apples and oranges. That is why it is important to specify the units that go with the numbers and include them in the answer.

A ten pound weight on the end of a 5 foot lever would produce:

\[ 10 \text{ lbs.} \times 5 \text{ ft.} = 50 \text{ ft.-lbs.} \]

Four men working three hours each would work:

\[ 4 \text{ men} \times 3 \text{ hours} = 12 \text{ man-hours of labor} \]

3. Multiplication operations can be indicated by several different symbols. The most common is the multiplication sign (x) or times sign. Multiplication can also be indicated by parentheses ( ) or by brackets [ ] or simply with a dot (·). The previous example of four men working could be indicated several ways, including:

\[ 4 \text{ men} \times 3 \text{ men} = 12 \text{ man-hours} \]
\[ (4 \text{ men})(3 \text{ hours}) = 12 \text{ man-hours} \]
\[ [4\text{men}][3 \text{ hours}] = 12 \text{ man-hours} \]
\[ 4 \text{ men} \cdot 3 \text{ hours} = 12 \text{ man-hours} \]
\[ (4 \text{ men})\cdot(3 \text{ hours}) = 12 \text{ man-hours} \]

When solving a problem that uses parentheses or brackets, **ALWAYS** complete the operations inside the parentheses or brackets before performing other operations.

**Example 1.2**

\[ (10-3) \ (7 + 2) \ (3 + 2) \]
\[ = (7) \ (9) \ (6) \]
\[ = 7 \times 9 \times 6 \]
\[ = 378 \]
Example 1.3  

\[
[12-(3+2)(3-1)] [8+(6-2)] \\
= [12-(5)(2)] [8+4] \\
= [12-10][12] \\
= 24 
\]

**Other basic math rules.**

1. Do operations inside any brackets [ ] or parenthesis( ) first.
2. Do multiplication and division operations before addition and subtraction.
3. Do addition and subtraction operations next.
4. Do special operations (like square root, etc.) last.

1.4 Division

Division is a way to determine how many times one number is contained within another. It is done using a series of subtractions. For example, when we say divide 10 by 2, we are also saying, how many times can we subtract 2 from 10 to reach 0 or at least a number less than 2.

1. By subtraction, 10 divided by 2 is:

\[
\begin{align*}
10 -2 &= 8 & \text{(one time)} \\
8 -2 &= 6 & \text{(two times)} \\
6 -2 &= 4 & \text{(three times)} \\
4 -2 &= 2 & \text{(four times)} \\
2 -2 &= 0 & \text{(five times)} \\
\end{align*}
\]

2. By Division:

\[
\begin{array}{c}
5 \\
\hline \\
2 \leftarrow 10 \\
\end{array}
\]

How many times does 2 go into 10. The answer is 5. Multiply 5 x 2 to check your answer. 5 x 2 = 10
Division problems also can be written in other ways, including:

\[ 10 \div 2 = 5 \text{ or } 10 / 2 = 5 \text{ or } \frac{10}{2} \]

(Note: It is always easier to divide by a whole number.)

1.5 Fractions

Fractions represent division or parts of a whole. The number on the bottom of the fraction represents the total number of equal parts into which an object is divided. This number is called the denominator. The number on top of the fraction, called the numerator, indicates how many of those equal parts are being represented.

\[
\frac{1}{2} + \frac{1}{2} = \frac{2}{2} = 1
\]

\[
\frac{4}{6} + \frac{2}{6} = \frac{6}{6} = 1
\]
1.5.1 Improper Fractions

Improper fractions have a larger numerator than denominator. Therefore, they represent a number larger than one. Improper fractions can be converted to whole numbers or mixed numbers by performing the division operation indicated by the fraction. Divide the numerator by the denominator as shown in Example 1.4

Example 1.4

\[
\frac{12}{8} = 1 + \frac{4}{8} = 1 \frac{1}{2}
\]

1.5.2 Reducing Fractions

To reduce a fraction to its lowest terms divide the numerator and denominator by the largest number that equally divides into both. See Example 1.5.

Example 1.5

\[
\frac{10}{30} = \frac{10 \div 10}{30 \div 10} = \frac{1}{3}
\]

Note: Dividing or multiplying both the numerator and denominator by the same number do not change the value of the fraction. It is the equivalent of dividing or multiplying by 1 (one).

With complex fractions it may not be easy to determine the largest number that equally divides into both the numerator and denominator. In this case, determine a number (or a factor) that will divide evenly into both. Continue this process until it can no longer be performed by a number larger than one.
Example 1.6

\[
\begin{align*}
256 \div 2 &= 128 \div 2 = 64 \div 8 = 8 \\
288 \div 2 &= 144 \div 2 = 72 \div 8 = 9
\end{align*}
\]

1.5.3 Adding and Subtracting Fractions

Before fractions can be added or subtracted the denominators must be the same. When the denominators are the same, simply add or subtract the numerators.

Example 1.7

\[
\frac{2}{8} + \frac{3}{8} = \frac{2+3}{8} = \frac{5}{8}
\]

If the denominators are not the same, they must be manipulated so that they are the same before addition or subtraction can take place. To change denominators so that they are equal, fractions must be multiplied by a fraction representing 1 (one), for example 3/3 or 8/8 or x/x, determined by the desired result.

Example 1.8

To add 2/5 and 3/10, fifths must be converted to tenths so that the denominators are the same. Multiply 2/5 by 2/2.

\[
\frac{2}{5} + \frac{3}{10} = \frac{2 \times 2}{5 \times 2} + \frac{3}{10} = \frac{4}{10} + \frac{3}{10} = \frac{7}{10}
\]

In many cases, one denominator cannot be changed to match another by multiplication. For example, when adding 1/3 and 1/4, the 1/3 cannot be changed to an even fourth. In this case, both numbers must both be changed to the Least Common Denominator (LCD). The least common denominator is the lowest number that is evenly divisible by both denominators, in this case 12. To convert to the LCD each denominator must be multiplied by a fraction representing 1 (one).
Example 1.9

To add 1/3 and 1/4, both must be converted to 12ths.

\[
\frac{1}{3} \times 4 + \frac{1}{4} \times 3 = \frac{4}{12} + \frac{3}{12} = \frac{7}{12}
\]

1.5.4 Multiplying Fractions

To multiply fractions, multiply all numerators together to arrive at a new numerator and multiply all denominators together to arrive at a new denominator.

Example 1.10

\[
\frac{1}{4} \times \frac{3}{7} \times \frac{5}{3} = \frac{(1 \times 3 \times 5)}{(4 \times 7 \times 3)} = \frac{15}{84} = \frac{5}{28}
\]

1.5.5 Dividing Fractions

To divide two fractions, invert the numerator and denominator of the divisor and multiply.

Example 1.11

\[
\frac{1}{3} \div \frac{1}{2} = \frac{1 \times 2}{3 \times 1} = \frac{2}{3}
\]

1.6 Percentages

Expressing a number as a percentage is just another way of writing a fraction or a decimal. Think of percentages as parts per 100. In fraction form, the denominator of a percentage is always 100. To change a fraction to a percent, multiply by 100.
Example 1.12

\[
\frac{1}{2} \times \frac{100}{1} = \frac{100}{2} = 50\%
\]

To change a percent to a fraction, multiply by \( \frac{1}{100} \).

Example 1.13

\[
\frac{40\%}{100\%} \times \frac{1}{100\%} = \frac{40\%}{100\%} = \frac{4}{10} = \frac{2}{5}
\]

Note: The percent signs cancel out.

To change a percentage to a decimal fraction, move the decimal point two places to the left and remove the % sign.

Example 1.14

\[
28.5\% = 0.285 \\
0.01\% = 0.0001 \\
100\% = 1.00
\]

1.7 Decimals

Decimals are numerical representations of fractions that have 10, 100, 1,000 or some other multiple of 10 as a denominator.

Example 1.15

\[
\frac{3}{10} = 0.3 = \text{three tenths} \\
\frac{13}{100} = 0.13 = \text{thirteen hundredths}
\]
1.7.1 Changing a fraction to a decimal

To change a fraction to decimal, divide the numerator by the denominator.

Example 1.16
\[
\frac{3}{4} = 3 \div 4 = 0.75
\]

1.7.2 Changing a decimal to a fraction

To change a decimal to a fraction, multiply the decimal by a fraction that represents 1 (one) and has a multiple of 10 in the numerator and denominator, 10/10, 100/100, etc.

Example 1.17
\[
0.0625 \times \frac{10,000}{10,000} = \frac{625}{10,000} = \frac{125}{2,000} = \frac{1}{16}
\]

1.8 Ratios and Proportions

A ratio is the comparison of two numbers of like units. For example, 1 foot compared to 4 feet (1/4 feet) or 3 pipe lengths compared to 7 pipe lengths (3/7 pipes lengths).

A proportion is made of two equivalent ratios. For example, 4/8 is equal to 1/2.

To solve proportions when one number is unknown, use cross multiplication. Multiply the numerator of one ratio by the denominator of the other ratio. This sum should be equal to ratio by the numerator of the second ratio.
Example 1.18

\[
\frac{A}{B} = \frac{C}{D}
\]

Then, \(A \times D = B \times C\).

When one ratio is known and either the numerator or denominator of a second ratio is known, this cross multiplication technique can be used to find the unknown number.

Example 1.19

\[
\frac{X}{6} = \frac{1}{3}
\]

\((X)(3) = (1)(6)\)  \hspace{1cm} (After you cross multiply.)

\[X = \frac{6}{3}\]

\[X = 2\]

Proportions come in handy in numerous water calculations. See Example 1.20 below.

Example 1.20

If two (2) pounds of salt are added to eleven (11) gallons of water to make a solution of a specified strength, how many pounds of salt must be added to 121 gallons to make a solution of the same concentration? (Remember to cross multiply.)

\[
\begin{align*}
\frac{2 \text{ lbs}}{11 \text{ gal}} \times \frac{x \text{ lbs}}{121 \text{ gal}} &= \frac{2 \text{ lbs}}{11 \text{ gal}} \times \frac{121 \text{ gal}}{11 \text{ gal}} \\
\frac{2 \text{ lbs}}{11 \text{ gal}} &= \frac{x \text{ lbs}}{11 \text{ gal}} \\
\frac{2 \times 11}{11 \times 11} &= \frac{x}{11}
\end{align*}
\]

Note that gallons cancelled each other.
\[
\frac{242 \text{ lbs}}{11} = x \text{ lbs}
\]
\[
22 \text{ lbs} = x
\]

Therefore, 22 pounds of salt must be added to 121 gallons of water to reach the same concentration as when 2 pounds of salt is added to 11 gallons.

### 1.8.1 Inverse Proportions

Sometimes proportions are the opposite (or inverse) of what you think it should be. These are called inverse proportions since they are proportions, but the answer is less than we started with. An example of an inverse proportion follows.

**Example 1.21**

One man can do a job in 6 hours. How many hours will it take two men to do the same job?

This is an inverse proportion because it makes sense that two men can do the job in less time than one man. Now set up the proportion, but follow a different rule to solve for the answer. When you have an inverse proportion, you **multiply across** rather than cross multiple. Watch the example below to see the correct operation.

\[
\frac{1 \text{ man}}{2 \text{ men}} = \frac{6 \text{ hrs}}{x \text{ hrs}}
\]

\[
(1)(6) = (2)(x)
\]

\[
6 = 2x
\]

\[
\frac{6}{2} = x = 3 \text{ hrs}
\]

Now check your answer. Does it make sense that two men could do the same job in half the time it takes one man to do the job? Yes, this makes sense and the answer is correct. Two men can do the same job in 3 hours that it takes one man to do the same job in 6 hours.
1.9 Analyzing Units

By analyzing units in an equation or mathematical calculation (called unit analysis or dimensional analysis), you can determine if the problem is set up correctly. To check a math problem setup, work only with the units of measure and not with the numbers. To analyze math setups you need to know three things.

1. **How to convert a horizontal fraction to a vertical fraction.**

   **Example 1.22**

   \[
   \frac{\text{cu.ft.}}{\text{min}} = \frac{\text{cu.ft}}{\text{min}}
   \]

2. **How to divide by a fraction (remember to invert and multiple as shown).**

   **Example 1.23**

   \[
   \frac{\text{gal}}{\text{min}} \div \frac{\text{gal}}{\text{cu.ft.}} = \frac{\text{gal}}{\text{min}} \times \frac{\text{cu.ft.}}{\text{gal}}
   \]

3. **How to cancel units.**

   **Example 1.24**

   \[
   \frac{\text{gal}}{\text{min}} \times \frac{\text{cu.ft.}}{\text{gal}} = \frac{\text{cu.ft.}}{\text{min}}
   \]

**Example 1.25**

The flow rate in a water line is 1.7 cfs. What is the flow rate in gallons per minute (gpm)? Use unit analysis to determine if the math problem setup is correct.
The first step is set up the problem using only units.

\[
\left( \frac{cu. ft}{sec} \right) \left( \frac{gal}{cu. ft.} \right) \left( \frac{sec}{min.} \right)
\]

The second step is to cancel the fractions.

\[
\left( \frac{cu. ft}{sec} \right) \left( \frac{gal}{cu. ft.} \right) \left( \frac{sec}{min.} \right) = \frac{gal}{min.}
\]

After canceling units we find that the final answer of this setup will be expressed in gal/min (gpm), which is what we are looking for.

**1.10 Powers and Scientific Notation**

Two common methods of expressing a number—powers notation and scientific notation—will be discussed in this chapter.

**1.10.1 Powers Notation**

The most basic form of powers notation is merely a short-hand method of writing multiplication. For example, \(4 \times 4\) can be written as \(4^2\).

This is referred to as \(4\) to the second power, or 4 squared. The small 2 is the exponent, or power. It tells you how many 4’s are to be multiplied together. In expanded form, \(4^2 = (4)(4)\)

The expression of 4 to the third power (usually called 4 cubed) is written as \(4^3\). In expanded form, this notation is \(4^3 = (4)(4)(4)\).
The examples that follow further illustrate the concept of powers notation.

**Example 1.26**

How is the term $2^3$ written in expanded form? The power (or exponent) of 3 means that the number is multiplied by itself three times.

$$2^3 = (2)(2)(2)$$

**Example 1.27**

How is the term $ft^2$ written in expanded form? The power or exponent of 2 means that the term is multiplied by itself two times.

$$ft^2 = (ft)(ft)$$

**Example 1.28**

How is the term $10^5$ written in expanded form? The exponent of 5 indicates that 10 is multiplied by itself five times.

$$10^5 = (10)(10)(10)(10)(10)$$

**Example 1.29**

How is the term $\left(\frac{2}{3}\right)^2$ written in expanded form? When parentheses are used, the exponent refers to the entire term within the parentheses. Therefore, in this problem, $\left(\frac{2}{3}\right)^2$ means:

$$\left(\frac{2}{3}\right)^2 = \left(\frac{2}{3}\right)\left(\frac{2}{3}\right) = \frac{4}{9}$$
Sometimes a negative exponent is used with a number or term. A number with a negative exponent can be rearranged and expressed using a positive exponent as follows:

**Example 1.30**

\[ 12^{-3} = \frac{1}{12^3} = \frac{1}{(12)(12)(12)} = \frac{1}{1,728} \]

**Example 1.31**

How is the term \(7^{-2}\) written in expanded form?

\[ 7^{-2} = \frac{1}{7^2} = \frac{1}{(7)(7)} \]

**Example 1.32**

How is the term \(10^{-4}\) written in expanded form?

\[ 10^{-4} = \frac{1}{10^4} = \frac{1}{(10)(10)(10)(10)} \]

If a term is given in expanded form, you should be able to determine how it would be written in exponential (or power) form. For example, \((ft)(ft) = ft^2\) or \((3)(3)(3) = 3^3\).

**Example 1.33**

How would the following expanded term be rewritten in exponential form?

\((mm)(mm)(mm)\)

Since the term is multiplied by itself three times, it would be written in exponential form as:

\(mm^3\)
Example 1.34

Write the term written below in exponential form.

\[
\frac{(4)(4)}{(5)(5)(5)}
\]

The exponent for the numerator of the fraction is 2 and the exponent for the denominator is 3. Therefore, the term would be written as:

\[
\frac{(4)^2}{(5)^3}
\]

Since the exponents are not the same, parentheses cannot be placed around the fraction and a single exponent cannot be used.

Example 1.35

Write the following term in exponential form.

\[
\frac{(ft.)(ft.)}{(in.)(in.)}
\]

The exponent of both the numerator and denominator is 2. Since the exponents are the same, parentheses can be used to express this term, if desired.

\[
\frac{(ft.)^2}{(in.)^2}
\]

Perhaps the two most common situations in which you may see powers used with a number or term are in denoting area or volume units (in\(^2\), ft\(^2\), in\(^3\), ft\(^3\)) and in scientific notation.
1.10.2 Scientific Notation

Scientific notation is a method by which any number can be expressed as a term multiplied by a power of 10. The term itself is greater than or equal to 1, but less than 10. Examples of numbers written in scientific notation are shown below.

\[
\begin{align*}
5.4 \times 10^1 \\
1.2 \times 10^3 \\
9.789 \times 10^4 \\
3.63 \times 10^{-2}
\end{align*}
\]

The numbers can be taken out of scientific notation by performing the indicated multiplications as shown.

\[
\begin{align*}
5.4 \times 10^1 &= (5.4)(10) = 54 \\
1.2 \times 10^3 &= (1.2)(10)(10)(10) = 1,200 \\
3.63 \times 10^{-2} &= \left( \frac{3.63}{1} \right) \left( \frac{1}{10} \right) \left( \frac{1}{10} \right) = 0.0363
\end{align*}
\]

An easier way to take a number out of scientific notation is by moving the decimal point the number of places indicated by the exponent.

**Rule 1**

*When a number is taken out of scientific notation, a positive exponent indicates a decimal point move to the right, and a negative exponent indicates a decimal point move to the left.*

Let’s look again at the examples above, by moving the decimal point rather than the multiplication method. The first example is:

\[
5.4 \times 10^1
\]

The *positive* exponent of 1 indicates that the decimal point in 5.4 should be moved one place to the right:
\[ \frac{5.4}{3} = 54 \]

The next example is:

\[ 1.2 \times 10^3 \]

The positive exponent of 3 indicates that the decimal point in 1.2 should be moved three places to the right:

\[ \frac{1.200}{3} = 1200 \]

The next example is:

\[ 9.789 \times 10^4 \]

The positive exponent of 4 indicates that the decimal point should be moved four places to the right:

\[ \frac{9.7890}{3} = 97890 \]

The final example is:

\[ 3.63 \times 10^{-2} \]

The negative exponent of 2 indicates that the decimal point should be moved two places to the left.

\[ \frac{003.63}{3} = 0.0363 \]

**Example 1.36**

Take the number below out of scientific notation.

\[ 7.992 \times 10^5 \]

The positive exponent of 5 indicates that the decimal point should be moved five places to the right.

\[ \frac{7.99200}{3} = 799,200 \]
Example 1.37

Take the number shown out of scientific notation.

\[ 2.199 \times 10^{-3} \]

The negative exponent of 3 indicates that the decimal point should be moved three places to the left.

\[ 002.119 = 0.002199 \]

Although there will be very few instances that you will need to put a number into scientific notation, the method is discussed below.

To put a number into scientific notation, the decimal point is moved the number of places necessary to result in a number between 1 and 9. This number is multiplied by a power of 10, with the exponent equal to the number of places that the decimal point was moved. (Remember that if no decimal point is shown in the number to be converted, it is assumed to be at the end of the number.)

**Rule 2**

*When a number is put into scientific notation, a decimal point move to the left indicates a positive exponent; a decimal point move to the right indicates a negative exponent.*

Now let’s try converting a few numbers into scientific notation, using the same numbers as in the previous examples.

First, let’s convert 54. To obtain a number between 1 and 9, the decimal point should be moved one place to the left means that the exponent is positive.

\[ 54 = 5.4 \times 10^1 \]
The next number to be put into scientific notation is 1,200. To obtain a number between 1 and 9, the decimal point should be moved three places to the left. The number of place moves (3) becomes the exponent of the power of 10, and the move to the left indicates a positive exponent.

\[ 1200 = 1.2 \times 10^3 \]

The next example is 97,890. To obtain a number between 1 and 9, the decimal point should be moved four places to the left, resulting in a positive exponent of 4.

\[ 97890 = 9.789 \times 10^4 \]

The final example is 0.0362. To obtain a number between 1 and 9, the decimal point must be moved two places to the right. This indicates an exponent of 2, and the move to the right requires a negative exponent.

\[ 0.0362 = 3.63 \times 10^{-2} \]

**Example 1.38**

Put the following 4,573,000 in scientific notation. To obtain a number between 1 and 9, the decimal point should be moved six places to the left, resulting in a positive exponent of 6.

\[ 4,573,000 = 4.573 \times 10^6 \]

**Example 1.39**

Convert the decimal 0.000375 into scientific notation. To obtain a number between 1 and 9, the decimal point should be moved four places to the right, resulting in a negative exponent of 4.

\[ 0.000375 = 3.75 \times 10^{-4} \]
1.12 Dimensional Analysis

Dimensional analysis is a tool that you can use to determine whether you have set up a problem correctly. In checking a math setup using dimensional analysis, you work only with the dimensions or units measure and not with the numbers themselves. To use the dimensional analysis method, you must know three things.

1. How to express a horizontal fraction (such as gal/ft$^3$) as a vertical fraction (such as gal/ft$^3$).
2. How to divide by a fraction.
3. How to divide out or cancel terms in the numerator and denominator of a fraction.

These techniques are reviewed briefly below. When you are using dimensional analysis to check a problem, it is often desirable to write any horizontal fractions as vertical fractions, thus:

$$\frac{ft^3}{\text{min}} = \frac{ft^3}{\text{min}}$$

$$\frac{\text{sec}}{\text{min}} = \frac{\text{sec}}{\text{min}}$$

$$\frac{\text{gal}}{\text{min}} = \frac{\text{gal}}{\text{min}}$$

$$\frac{\text{gal}}{ft^3} = \frac{\text{gal}}{ft^3}$$

When a problem involves division by a fraction, the rule is to invert (or turnover) the terms in the denominator and then multiply. For example,

$$\frac{\text{gal}}{\text{min}} \times \frac{\text{gal}}{ft^3}$$

or

$$\frac{\text{gal}}{\text{min}} \times \frac{\text{gal}}{ft^3}$$

or
Once the fraction is in a problem, if any have been rewritten in the vertical form, and division by a fraction has been re-expressed as multiplication as shown above, then the terms can be divided out or canceled. For every term canceled in the numerator of a fraction, a similar term must be canceled in the denominator, and vice versa, as shown below.

\[
\frac{\text{gal}}{\text{min}} \times \frac{\text{ft}^3}{\text{gal}} = \frac{\text{ft}^3}{\text{min}}
\]

\[
\frac{\text{kg}}{\text{day}} \times \frac{\text{day}}{\text{min}} = \frac{\text{kg}}{\text{min}}
\]

\[
\frac{\text{mm}^2}{\text{mm}^2/\text{m}^2} = \frac{1}{\text{mm}^2} = \frac{\text{mm}^2}{\text{m}^2}
\]

You may want to review the concept of powers* before continuing with the following examples in dimensional analysis. (*Mathematics 1.10 - Powers and Scientific Notation)

Suppose you need to convert a 1,200 ft\(^3\) volume to gallons and suppose that you know you will use 7.48 gal/ft\(^3\) in the conversion, but that you don’t know whether to multiply or divide by 7.48. Let’s look at both possible ways and see how dimensional analysis can be used to choose the correct way. *Only the dimensions* will be used to determine if the math setup is correctly.
First, try multiplying the dimensions.

\[ \text{ft}^3 \times \frac{\text{gal}}{\text{ft}^3} \]

Then multiply the numerators and denominators as shown.

\[ \frac{\left(\text{ft}^3\right)\text{gal}}{\text{ft}^3} \]

Finally, cancel common terms to get an answer.

\[ \frac{\left(\text{ft}^3\right)\text{gal}}{\text{ft}^3} = \text{gal} \]

So, by dimensional analysis you know that if you multiply the two dimensions (ft\(^3\) and \(\text{gal}/\text{ft}^3\)), the answer you get will be in gallons, which is what you want. Therefore, since the math setup is correctly. You would then multiply the numbers to obtain the number of gallons.

\[ 1,200 \left(\text{ft}^3\right) \times 7.48 \frac{\text{gal}}{\text{ft}^3} = 8,976 \text{ gal} \]

What would have happened if you had divided the dimensions instead of multiplying? See the terms written below.

\[ \frac{\text{ft}^3}{\text{gal} \times \text{ft}^3} = \frac{\text{ft}^3 \times \text{ft}^3}{\text{gal}} \]

Then multiply the numerators and denominators of the fraction to get an answer.

\[ \frac{\text{ft}^6}{\text{gal}} \]

So had you divided the two dimensions (ft\(^3\) and \(\text{gal}/\text{ft}^3\)), the units of the answer would have been ft\(^6\)/gal, not gallons. Clearly you do not want to divide in making this conversion.
Example 1.40

You want to obtain an answer in square feet. If you are given the two terms 80 ft³/s and 3.5 ft/s, is the following math setup correct?

\[
\left( 80 \, \text{ft}^3/\text{sec} \right) \left( 3.5 \, \text{ft} / \text{sec} \right)
\]

First, only the dimensions are used to determine if the math setup is correctly. By multiplying the two dimensions, you get the expression shown.

\[
\left( \frac{\text{ft}^3}{\text{sec}} \right) \left( \frac{\text{ft}}{\text{sec}} \right)
\]

Then multiply the terms in the numerators and denominators of the fraction.

\[
\left( \frac{\text{ft}^4}{\text{sec}^2} \right)
\]

The math setup is wrong since the dimensions of the answer are not in square feet. Therefore, if you multiply the numbers just as you did the dimensions, the answer will be wrong.

Let’s try division of the two dimensions instead.

\[
\frac{\text{ft}^3/\text{sec}}{\text{ft} / \text{sec}} = \frac{\text{ft}^3}{\text{sec}} \cdot \frac{\text{sec}}{\text{ft}}
\]

Then invert the denominator and multiply to get an answer in ft².

\[
\frac{\text{ft}^3}{\text{sec}} = \left( \frac{\text{ft}^3}{\text{sec}} \right) \left( \frac{\text{sec}}{\text{ft}} \right) = \left( \frac{\text{ft}^3}{\text{sec}} \cdot \frac{\text{sec}}{\text{ft}} \right) = \frac{\text{ft}^3}{\text{ft}} = \text{ft}^2
\]
This math setup is correct since the dimensions of the answer are in square feet (ft²). Therefore, if you divide the numbers as you did the units, the answer will also be correct.

\[
\frac{80 \text{ ft}^3/\text{sec}}{3.5 \text{ ft/} \text{sec}} = 22.86 \text{ ft}^2
\]

**Example 1.41**

Suppose you have two terms, 3 m/s and 6 m², and you wish to obtain an answer in cubic meters per second (m³/s). Is multiplying the two terms the correct math setup?

\[
\frac{m}{s} \times m^2
\]

Then multiply the numerators and denominators of the fraction.

\[
\frac{(m)(m^2)}{s} = \frac{m^3}{s}
\]

The math setup is correctly since the dimensions of the answer are cubic meters per second (m³/s). So if you multiply the numbers, just as you did the dimensions, you will get the correct answer.

\[
3 \frac{m}{s} \times 6m^2 = 18 \frac{m^3}{s}
\]

**Example 1.42**

Suppose you have been given the following problem - “The flow rate in a waterline is 2.3 ft³/sec. What is the flow rate expressed in gallon per minute?” You then set up the math problem as shown below. Use dimensional analysis to determine if this math setup is correctly.

\[
(2.3 \text{ ft}^3/\text{sec})(7.48 \text{ gal/ft}^3)(60 \text{ sec/ min})
\]
Dimensional analysis is used to check the math setup.

\[
\left( \frac{ft^3}{sec} \right) \left( \frac{gal}{ft^3} \right) \left( \frac{sec}{min} \right) = \frac{gal}{min}
\]

This analysis indicates that the math setup is correctly as shown above.

**Example 1.43**

You have been given the following problem - “A channel is 3 feet wide with water flowing to a depth of 2 feet. The velocity in the channel is found to be 1.8 ft/sec. What is the flow rate in the channel in cubic feet per second?” You then set up the math problem as shown below. Use dimensional analysis to determine if this math setup is correctly.

\[
\frac{(3 \text{ ft})(2 \text{ ft})}{1.8 \text{ ft/ sec}}
\]

Dimensional analysis is used to check the math setup.

\[
\left( \frac{ft}{sec} \right) \left( \frac{ft}{ft} \right) = \left( \frac{ft}{sec} \right) \left( \frac{ft}{sec} \right) = \left( \frac{ft}{sec} \right)
\]

Since the dimensions of the answer are incorrect, the math setup shown in Example 1.43 is also incorrect. Had the math setup instead been \((3\text{ ft})(2\text{ ft})(1.8 \text{ ft/ sec})\), the dimensions of the answer would have been correct.

**1.13 Costs**

The formula for “costs” is the total operating costs given or converted to a monthly value divided by total flow for the month. If the average daily flow is given, multiply by the appropriate number of days in the particular month and the result will be cost of treatment per million gallons.
Calculate the cost of treatment per million gallons:

<table>
<thead>
<tr>
<th>Month</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. Flow</td>
<td>6.2 MGD</td>
</tr>
<tr>
<td>Payroll</td>
<td>$40,580 per month</td>
</tr>
<tr>
<td>Power</td>
<td>$8,150 per month</td>
</tr>
<tr>
<td>Chlorine</td>
<td>$2,359 per month</td>
</tr>
<tr>
<td>Chemicals</td>
<td>$3,494 per month</td>
</tr>
</tbody>
</table>

**Operating Costs ($)** = cost per million gallons

Total Flow

\[
\text{Total Flow} = 6.2 \text{ MGD} \times 30 \text{ days} = 186.00 \text{ MG}
\]

\[
\frac{\text{Total Flow}}{\text{Operating Costs}} = \frac{186.00 \text{ MG}}{54,583} = 3.41 \text{ cents/gallon}
\]
Chapter Two
2.0 MEASURING LINES, AREA, AND VOLUME

2.1 Linear Measurement

Linear measurements determine the length or distance along a line or curve, and are generally expressed in English units (inches, feet, yards, miles) or metric units (millimeters, centimeters, meters, kilometers). These measurements of distance are used to determine lengths, perimeters of shapes, diameters of circles, and circumferences of circles.

2.1.1 Perimeters

Perimeters of shapes that are made up of straight lines are determined by adding the length of each side.

*Examples of perimeter of different shapes*

Perimeter = \( 3 + 8 + 2 + 6 + 5 \)  
= 24 feet

Perimeter = \( 7 + 7 + 7 + 7 \)  
= 28 feet

Perimeter = \( 1.5 + 7 + 1.5 + 7 \)  
= 17 feet

*Equation*

Perimeter = \( \text{length}_1 + \text{length}_2 + \text{length}_3 + \text{length}_4 \), etc.
Perimeter calculations can be used to determine how many linear feet of pipe will be necessary for a specific design or how much wire will be needed to fence off an area.

2.2 Circles

There are three main linear measurements of circles. These are - circumference, diameter, and radius. These measurements are necessary for determining areas of circles and volumes of cylinders and spheres.

2.2.1 Calculating Area

Measuring an area determines the size of the surface area a shape. These measurements are normally referred to in units of square inches (in$^2$), square feet (ft$^2$), or square yards (yd$^2$). Metric units used to indicate area are square millimeters (mm$^2$), square centimeters (cm$^2$), and square meters (m$^2$).

Equations for these shapes are presented below.

**Equations**

\[
\text{Rectangle Area} = (\text{length})(\text{width}) = lw
\]

\[
\text{Triangle Area} = \frac{(\text{base})(\text{height})}{2}
\]

\[
\text{Circle Area} = 0.785d^2 \text{ or } \pi r^2
\]

The **diameter** of a circle is the length of a straight line that crosses the center of the circle from one edge of the circle to another. It is twice the length of the radius. It can be determined by the equation given below.
The radius of a circle is the distance from the center of the circle to the edge of the circle. It can be determined by the equation:

\[ r = \frac{d}{2} \]

Where \( d \) = diameter
\( r \) = radius

The circumference of a circle is the distance around the circle and is always equal to 3.1416 times the length of the diameter. This special relationship between the diameter and circumference generates a constant number named pi (pronounced pie) and is designated by the Greek symbol (\( \pi \)). \( \pi = 3.1416 \). If you know the diameter of a circle you can always calculate the circumference using the equation below.

\[ C = \pi d \]

Where \( d \) = diameter
\( C \) = circumference
\( \pi = 3.1416 \)
2.2.2 Circles

The most familiar equation for the area of a circle is $\pi r^2$. The $r$ stands for radius, the distance from the center point of the circle to the edge of the circle. The radius of any circle is equal to one half of the diameter. The area of a circle can also be found by using the equation $A = 0.785d^2$. (The term 0.785 is one fourth of $\pi$.) Example problems finding the area of a circle using both equations follow. Using either equation, you find the same answer for the area of the circle.

\[
\begin{align*}
\text{Area of circle } A & = \pi r^2 \text{ then substitute } d/2 \text{ for } r. \\
(3.1416)\left(\frac{d}{2}\right)^2 & = (3.1416)(1\text{ ft})^2 \\
3.1416 \text{ ft}^2
\end{align*}
\]

\[
\begin{align*}
\text{Area of circle } A & = 0.785d^2 \\
(0.785)(d)^2 & = (0.785)(2\text{ ft})^2 = (0.785)(4\text{ ft}^2) \\
3.1416 \text{ ft}^2
\end{align*}
\]
There are three basic shapes used in water treatment plant calculations: rectangles, triangles, and circles. Equations for these shapes are presented below.

**Equations**

Rectangle Area = \((\text{length})(\text{width}) = lw\)

Triangle Area = \(\frac{(\text{base})(\text{height})}{2}\)

Circle Area = \(0.785d^2\) or \(\pi r^2\)

### 2.3.2 Rectangles

Area of Rectangle A = \((\text{length})(\text{width}) = lw\)

\((4 \text{ feet})(3 \text{ feet})\)

\[= 12 \text{ ft}^2\]

Note: Each square is equal to 1 square foot. Check this calculation by counting the squares.
2.3.3 Triangles

The area of a triangle is equal to the base length of the triangle times the height of the triangle divided by two. The height of the triangle must be measured vertically from the horizontal base.

\[
\text{Area of triangle } A = \frac{(\text{base})(\text{height})}{2}
\]

\[
= \frac{(4 \text{ feet})(3 \text{ feet})}{2}
= \frac{(12 \text{ feet})^2}{2}
= 6 \text{ ft}^2
\]

Note: The area of any triangle is equal to \( \frac{1}{2} \) the area of the rectangle that can be drawn around it. The area of the rectangle is base \( \times \) height. The area of the triangle is \( \frac{1}{2} \) base \( \times \) height.

2.4 Calculating Volumes

Volume measurements represent the amount of space an object occupies. Volume is commonly measured in cubic inches, cubic feet, cubic yards, and gallons.
Metric units used to measure volume are cubic centimeters, cubic meters, and liters.

Volume measurements are closely related to area.

**Equation:** Volume = (Surface Area)(Depth)

The surface area used to calculate volume is the area that represents the basic shape of the object. The shaded areas on the objects below represent surface areas. The depth measurement for these objects is indicated.

### 2.4.1 Rectangular Tanks or Basins

Volume = (area of rectangle)(depth)
Rectangle volume: (area, ft$^2$) (depth)

\[ \left( 4 \text{ feet} \times 3 \text{ feet} \right) \times 6 \text{ feet} \]

\[ = 72 \text{ ft}^3 \]

### 2.4.2 Troughs

Volume = \( \text{area of triangle} \times \text{depth} \)

Trough example: \( \text{area of triangle} \times \text{depth} \)

\[ \frac{\text{base} \times \text{height}}{2} \times \text{depth} \]

\[ = \frac{2 \text{ feet} \times 3 \text{ feet}}{2} \times 5 \text{ feet} \]

\[ = 15 \text{ ft}^2 \]

### 2.4.3 Cylinders

Volume = \( \text{area of circle} \times \text{depth} \)

\[ = 3 \text{ feet} \times 5 \text{ feet} \]

\[ = 15 \text{ ft}^2 \]
Cylinder example:

\[ Volume = \left( \text{area of circle} \right) \times \text{(depth)} \]

\[ = 0.785d^2 \times \text{(depth)} \]

\[ = 0.785(3 \text{ feet})^2 \times (5 \text{ feet}) \]

\[ = 0.785(9 \text{ ft}^2) \times (5 \text{ feet}) \]

\[ = 35.325 \text{ ft}^3 \]

2.4.4 Cones

\[ Volume = \left( \frac{1}{3} \text{ volume of cylinder} \right) \]

Cone example:

\[ Volume = \left( \frac{1}{3} \text{ volume of cylinder} \right) \]

\[ = \frac{0.785d^2 \times \text{(depth)}}{3} \]

\[ = \frac{0.785(2 \text{ feet})^2 \times (4 \text{ feet})}{3} \]

\[ = \frac{0.785(4 \text{ ft}^2) \times (4 \text{ feet})}{3} \]

\[ = \frac{0.785(16 \text{ ft}^3)}{3} = 4.187 \text{ ft}^3 \]
2.4.5 Spheres

\[ \text{Volume} = \frac{\pi d^3}{6} \]

Sphere example

\[ \text{Volume} = \frac{\pi d^3}{6} \]
\[ = \frac{\pi (20 \text{ feet})^3}{6} \]
\[ = \frac{\pi (8,000 \text{ ft}^3)}{6} = 4,188.8 \text{ ft}^3 \]

2.5 Combination Shapes

Sometimes tanks or other containers consist of multiple shapes and there is no representative surface area for the whole shape. In these cases, the volume can often be calculated by breaking the shape down into easily measured parts, calculating the volume for each part, and then adding the volumes together.
Combination examples

Combination tank  =  Cylinder  +  Half a sphere

Combination = Rectangle + Half of Cylinder

Combination Tank = Rectangle Volume + Triangle Volume
Combination Tank = Cone Volume + Cylinder Volume
Chapter Three
3.0 VELOCITY AND FLOW RATES

3.1 Velocity

Velocity is the measurement of motion or the speed at which something is moving. It is expressed by the distance traveled over a specific amount of time. Velocity can be expressed in an unit of distance per any unit of time, as in three miles per year, one mile per second, etc. For the purpose of measuring water’s rate of flow in a channel, pipe, or other conduit, it is usually expressed in feet per second (ft/sec, fps), or feet per minute (ft/min, fpm).

Equation

\[
Velocity (V) = \frac{dist(\text{unit})}{time(\text{unit})}
\]

Example 3.1

The water in a pipe travels 210 feet every three minutes. The velocity of the water would be found as shown.

\[
V = \frac{210 \text{ feet}}{3 \text{ min}} = 70 \text{ ft/min}
\]

To convert this answer to feet per second, multiply by 1 minute/60 seconds (one minute is equal to 60 seconds). This fraction is a simple conversion and does not change the relative value of the answer.

\[
V = \frac{70 \text{ ft}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 1.167 \text{ ft/sec}
\]
3.2 Flow Rates

Measuring the rate of water flow is essential for the efficient operation of treatment plants and distribution systems. Flow rates can be used to determine chemical dosages, water usage of various sources, system efficiency, and future expansion needs. Two types of flow rates are commonly used - current flow rates and average flow rates. Current flow rates measure the flow of water as it is happening. Average flow rates are derived from a record of current flow rates to determine the flow rate over a given period of time, like the average flow per day.

3.2.1 Calculating Flow Rates

Flow rates are a function of surface area times the velocity. For example, if the velocity in the channel below is 1 ft per second, then every second a body of water 1 square foot in area and 1 foot long will pass a given point. The volume of this body of water would be 1 cubic foot. Since one cubic foot of water passes every second, the flow rate is 1 cubic foot per second, or 1 cfs.

![Diagram of a rectangular prism](image)

**Equation**

\[ \text{Flow Rate}(Q) = \text{(Area)}(\text{Velocity}) \]

where:
- \( Q = \text{Flow Rate}, \ ft^3/\text{time unit} \)
- \( A = \text{Area}, \ ft^2 \)
- \( V = \text{Velocity}, \ ft/\text{time unit} \)
Flow rate units of measurement are normally dependent on the unit of measurement used for the velocity variable. If the velocity is determined in feet per second, then the flow rate must be expressed as cubic feet per second. If the velocity is represented as meters per day, then the flow rate must be expressed as cubic meters per day.

**Circular Pipes (assuming the pipe is flowing full)**

Flow Rate = (Circle Area)(Velocity)

\[
\left(\pi r^2\right) \frac{\text{dist}}{\text{time}}
\]

**Circular Pipe Example**

Flow Rate = (Circle Area)(Velocity)

\[
\left(\pi r^2\right) \frac{\text{dist}}{\text{time}}
\]

\[
= (3.1416)(0.5 \text{ ft}^2)(2.5 \text{ ft/sec})
\]

\[
= (3.1416)(0.25 \text{ ft}^2)(2.5 \text{ ft/sec})
\]

\[
= (0.785 \text{ ft}^2)(2.5 \text{ ft/sec})
\]

\[
= 1.9625 \text{ ft}^3/\text{sec}
\]
Rectangular Flow Example

Flow Rate = (Rectangle Area)(Velocity)

= $lw(velocity)$

= $(2\text{ feet})(0.5 \text{ feet})(1.5 \text{ ft / sec})$

= $(1 \text{ ft}^2)(1.5 \text{ ft / sec})$

= $(1.5 \text{ ft}^3 / \text{ sec})$

Triangle (V-notch) Weir Example

Flow Rate = (Triangle Area)(Velocity)

= $\frac{(base)(height)}{2}(velocity)$

= $\frac{(2\text{ feet})(2\text{ feet})}{2}(2\text{ ft / sec})$

= $(2 \text{ ft}^2)(2\text{ ft / sec})$

= $(4 \text{ ft}^3 / \text{ sec})$
3.3 The Continuity Rule

The rule of continuity states that the flow that enters a system must also be the flow that exits the system. The illustration below demonstrates the rule of continuity. It should be understood that the initial flow rate of 11 cfs must be divided between the two branches. The sum of the branch flow rates must equal the initial flow rate. Flow is not gained or lost in these types of problems.

\[ 11 \text{ cfs} = 6 \text{ cfs} + x \text{ cfs} \]
\[ 11 \text{ cfs} - 6 \text{ cfs} = x \text{ cfs} \]
\[ 5 \text{ cfs} = x \text{ cfs} \]

3.4 Flow Rate Unit Conversion

Flow rates can be expressed in a number of different units, including cubic inches per second (in\(^3\)/sec), cubic feet per second (ft\(^3\)/sec), cubic feet per minute (ft\(^3\)/min), gallons per minute (gpm), gallons per day (gpd), and millions of gallons per day (mgd). In water flow calculations it is often necessary to convert flow rates to more appropriate units for calculation purposes.
Example 3.2

Convert 288 cubic inches per second to million gallons per day (mgd).

1. Convert to cubic feet per second
   \[
   \frac{288 \text{in}^3/\text{sec}}{1,728 \text{in}^3/\text{ft}^3} = 0.167 \text{ft}^3/\text{sec}
   \]

2. Convert to cubic feet per minute
   \[
   (0.167 \text{ft}^3/\text{sec})(60 \text{sec/min}) = 10 \text{ft}^3/\text{min}
   \]

3. Convert to gallons per minute (gpm)
   \[
   (10 \text{ft}^3/\text{min})(7.48 \text{gal/ft}^3) = 74.8 \text{gpm}
   \]

4. Convert to gallons per day (gpd)
   \[
   (74.8 \text{gpm})(1,440 \text{min/day}) = 107,712 \text{gpd}
   \]

5. Convert gpd to million gallons per day (mgd)
   \[
   107,712 \text{gpd} = 0.107712 \text{mgd}
   \]

Note: to convert gpd to mgd, simply move the decimal six places to the left. To convert mgd to gpd, move the decimal six places to the right. For additional common conversions and conversion factors, see Chapter 6.
Chapter Four
4.0 Density and Specific Gravity

When we say that one substance is heavier than another, we mean that any given volume of the substance is heavier than the same volume of the other substance. Any given volume of steel, for example, is heavier than the same volume of aluminum. We say that steel is heavier than—or has greater density than—aluminum.

4.1 Density

Using scientific and technical language, the density of a body or material is precisely defined as *the weight per unit of volume*. In the water supply field, perhaps the most common measures of density are pounds per cubic foot (lbs/ft\(^3\)) and pounds per gallon (lbs/gal). The density of a dry material; such as sand, activated carbon, lime, and soda ash, is usually expressed in pounds per cubic foot. The density of a liquid; such as water, liquid alum, or liquid chlorine, can be expressed either as pounds per cubic foot or as pounds per gallon. The density of a gas; such as air, chlorine gas, methane, or carbon dioxide, is normally expressed in pounds per cubic foot.

The density of a substance changes slightly as the temperature of the substance changes. This happens because substances usually increase in size (volume) as they become warmer, as illustrated in Figure 4.1. Because of expansion with warming, the same weight is spread over a larger volume, so the density is lower when a substance is warm than when it is cold.

The effects of pressure and temperature on solids and liquids are very small and are usually ignored. However, temperature and pressure have a significant effect on the density of gases. Whenever the density of a gas is given, the temperature and pressure at that density are usually also given.
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FIGURE 4.1 - Changes in Density Based on Temperature

Table 4.1 indicates how the density of water (usually specified as a constant 62.4 lbs/ft$^3$) varies only slightly with temperature, especially within the water temperature ranges in effect at most water supply operations. Water is unusual in that it is most dense at 39.2°F (4.0°C) and becomes less dense when the temperature rises or falls.

Table 4.2 shows common densities of typical solid, liquid, and gaseous substances. You’ll notice that some of the solids given in the table have density reported as *bulk density*. Bulk density is defined as the weight of a cubic foot of material as it would be shipped from the supplier to the treatment plant. Bulk density is much less than laboratory density because its calculation includes the volume of the air mixed in with the material; the amount of air (and therefore the bulk density) varies according to whether the material comes in rock, crystal, pellet, granular, or powder form. For laboratory purposes the density of pure sodium chloride (table salt) is about 135 lbs/ft$^3$. However, the bulk density of sodium chloride as it is shipped in rock form (rock salt) is only 50 lbs/ft$^3$ to 60 lbs/ft$^3$. This means that over half the volume of a bulk container of rock salt is occupied by air between the individual pieces.
4.2 Specific Gravity

Since density can be expressed as pounds per cubic foot, pounds per gallon, pounds per cubic inch, or even grams per cubic centimeter; it is sometimes difficult to compare the density of one substance with that of another. Specific gravity is one way around this problem. Although there may be many numbers that express the density of the same substance (depending on the units used), there is only one specific gravity associated with each substance (for one particular temperature and pressure).

Table 4.1 - Density of Water

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Density, lbs/ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
</tr>
<tr>
<td>32.0</td>
<td>0</td>
</tr>
<tr>
<td>35.0</td>
<td>1.7</td>
</tr>
<tr>
<td>39.2</td>
<td>4.0</td>
</tr>
<tr>
<td>40.0</td>
<td>4.4</td>
</tr>
<tr>
<td>50.0</td>
<td>10.0</td>
</tr>
<tr>
<td>60.0</td>
<td>15.6</td>
</tr>
<tr>
<td>70.0</td>
<td>21.1</td>
</tr>
<tr>
<td>80.0</td>
<td>26.7</td>
</tr>
<tr>
<td>90.0</td>
<td>32.2</td>
</tr>
<tr>
<td>100.0</td>
<td>37.8</td>
</tr>
<tr>
<td>120.0</td>
<td>48.9</td>
</tr>
<tr>
<td>140.0</td>
<td>60.0</td>
</tr>
<tr>
<td>160.0</td>
<td>71.1</td>
</tr>
<tr>
<td>180.0</td>
<td>82.2</td>
</tr>
<tr>
<td>200.0</td>
<td>93.3</td>
</tr>
<tr>
<td>212.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Another way to observe temperature effects on the specific density of water is graphically. Figure 4.2 shows the density of water as temperature varies. Water has the greatest specific density at about 4°C (39.4°F). At lower temperatures and higher temperatures, water density becomes less. Using the specific density of
water, other specific densities can be evaluated showing the importance of specific gravity. The specific gravity of a substance is the density of that substance relative to a “standard density”.

![Specific Density of Water Versus Temperature](image)

**Figure 4.2 - Specific Density of Water Versus Temperature**

### 4.2.1 Specific Gravity of Solids and Liquids

The standard density used for solids and liquids is that of water, 62.4 lbs/ft³, or 8.34 lbs/gal. Therefore, the specific gravity of a solid or liquid is the density of that solid or liquid *relative to the density of water*. It is the ratio of the density of that substance to the density of water.
### TABLE 4.2- Densities of Various Substances

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbs/ft³</td>
<td>lbs/gal</td>
</tr>
<tr>
<td><strong>Solids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activated carbon *†</td>
<td>8-28 (avg. 12)</td>
<td></td>
</tr>
<tr>
<td>Lime *†</td>
<td>20-50</td>
<td></td>
</tr>
<tr>
<td>Dry alum *†</td>
<td>60-75</td>
<td></td>
</tr>
<tr>
<td>Aluminum (at 20°C)</td>
<td>168.5</td>
<td></td>
</tr>
<tr>
<td>Steel (at 20°C)</td>
<td>486.7</td>
<td></td>
</tr>
<tr>
<td>Copper (at 20°C)</td>
<td>555.4</td>
<td></td>
</tr>
<tr>
<td><strong>Liquids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propane (-44.5°C)</td>
<td>36.5</td>
<td>4.88</td>
</tr>
<tr>
<td>Gasoline†</td>
<td>43.7</td>
<td>5.84</td>
</tr>
<tr>
<td>Water (4°C)</td>
<td>62.4</td>
<td>8.34</td>
</tr>
<tr>
<td>Fluorosilicic acid (30%, -8.1°C)</td>
<td>77.8-79.2</td>
<td>10.4-10.6</td>
</tr>
<tr>
<td>Liquid alum (36°Bé, 15.6°C)</td>
<td>83.0</td>
<td>11.9</td>
</tr>
<tr>
<td>Liquid chlorine (-33.6°C)</td>
<td>97.3</td>
<td>13.01</td>
</tr>
<tr>
<td>Sulfuric acid (18°C)</td>
<td>114.2</td>
<td>15.3</td>
</tr>
<tr>
<td><strong>Gases</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane (0°C, 14.7 psia)</td>
<td>0.0344</td>
<td></td>
</tr>
<tr>
<td>Air (20°C, 14.7 psia)</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>Oxygen (0°C, 14.7 psia)</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>Hydrogen sulfide†</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide†</td>
<td>0.115</td>
<td></td>
</tr>
<tr>
<td>Chlorine gas (0°C, 14.7 psia)</td>
<td>0.187</td>
<td></td>
</tr>
</tbody>
</table>

*Bulk density of substance.

† Temperature and/or pressure not given.

When calculating specific gravity, it is essential that the densities be expressed in the same units. Otherwise the calculation will be wrong. The density of granite rock is about 162 lbs/ft³, and the density of water is 62.4 lbs/ft³. The specific gravity of granite is found by this ratio.

\[
\text{specific gravity} = \frac{\text{density of granite}}{\text{density of water}} = \frac{162 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = 2.60
\]
In this case, the specific gravity (the ratio of the density of granite to the density of water) indicates that a cubic foot of granite weighs about 2 ½ times as much as a cubic foot of water.

Let’s look at another example. The density of SAE 30 motor oil is about 56 lbs/ft$^3$. Its specific gravity is calculated below.

\[
\text{specific gravity} = \frac{56 \text{ lbs/ft}^3}{62.4 \text{ lbs/ft}^3} = 0.90
\]

In other words, specific gravity in this example tells you that oil is only 90% as dense as water. Because a cubic foot of oil weighs less than a cubic foot of water, oil floats on the surface of water. Table 4.3 lists specific gravities for various liquids and solids.

<table>
<thead>
<tr>
<th>Solids</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (20°C)</td>
<td>2.7</td>
</tr>
<tr>
<td>Steel (20°C)</td>
<td>7.8</td>
</tr>
<tr>
<td>Copper (20°C)</td>
<td>8.9</td>
</tr>
<tr>
<td>Activated Carbon *†</td>
<td>0.13-0.45 (avg. 0.19)</td>
</tr>
<tr>
<td>Lime *†</td>
<td>0.32-0.80</td>
</tr>
<tr>
<td>Dry alum *†</td>
<td>0.96-1.2</td>
</tr>
<tr>
<td>Soda ash *†</td>
<td>0.48-1.04</td>
</tr>
<tr>
<td>Coagulant aids (polyelectrolytes)*†</td>
<td>0.43-0.56</td>
</tr>
<tr>
<td>Table salt *†</td>
<td>0.77-1.12</td>
</tr>
<tr>
<td>Liquids</td>
<td></td>
</tr>
<tr>
<td>Liquid alum (36°Bé, 15.6°C)</td>
<td>1.33</td>
</tr>
<tr>
<td>Water (4°C)</td>
<td>1.00</td>
</tr>
<tr>
<td>Fluorosilicic acid (30%, -8.1°C)</td>
<td>1.25-1.27</td>
</tr>
<tr>
<td>Sulfuric acid (18°C)</td>
<td>1.83</td>
</tr>
<tr>
<td>Ferric chloride (30%, 30°C)</td>
<td>1.34</td>
</tr>
</tbody>
</table>

*Bulk density used to determine specific gravity.
†Temperature and/or pressure not given.
Example 4.1

Aluminum weighs approximately 168 lbs/ft$^3$. What is the specific gravity of aluminum?

To calculate specific gravity, compare the weight of a cubic foot of aluminum with the weight of a cubic foot of water. Remember specific gravities for solids and liquids are based on the specific weight of water.

\[
\text{specific gravity} = \frac{\text{density of aluminum}}{\text{density of water}} = \frac{168 \text{ lbs/ft}^3}{62.4 \text{ lbs/ft}^3} = 2.69
\]

Example 4.2

If the specific gravity of certain oil is 0.92, what is the density (in pounds per cubic foot) of that oil?

Approach this problem in the same general way as the previous example. First fill in the given information.

\[
\text{specific gravity of oil} = \frac{\text{density of oil}}{\text{density of water}}
\]

\[
0.92 = \frac{x \text{ lbs/ft}^3}{62.4 \text{ lbs/ft}^3}
\]

Then solve for the unknown value.

\[
(62.4)(0.92) = x
\]

\[
57.41 \text{ lbs/ft}^3 = x
\]

The density of the oil is found to be 57.41 lbs/ft$^3$. 
The most common use of specific gravity in water treatment operations is in gallons-to-pounds conversions. In many cases, the liquids being handled have a specific gravity of 1.00 or very nearly 1.00 (between 0.98 and 1.02), so 1.00 may be used in the calculations without introducing more than a 2 percent error. However, in calculations involving a liquid with a specific gravity less than 0.98 or greater than 1.02 (such as liquid alum), the conversions from gallons to pounds must take specific gravity into account. The technique is illustrated in the two examples that follow.

**Example 4.3**

Suppose you want to pump a certain liquid at the rate of 25 gpm. How many pounds per day will you be pumping if the liquid weighs 74.9 lb/ft$^3$? If the liquid being pumped were water, then you would make the calculations that follow.

\[
(25 \text{ gpm})(8.34 \text{ lbs/gal})(1,440 \text{ min/day}) = 300,240 \text{ lbs/day}
\]

However, the liquid being pumped has a greater density than water; therefore, you will have to adjust the density using the conversion factor of 8.34 lbs/gal. First, determine the specific gravity of the liquid.

\[
\text{specific gravity of the liquid} = \frac{\text{density of the liquid}}{\text{density of water}}
\]

\[
= \frac{74.9 \text{ lbs/ft}^3}{62.4 \text{ lbs/ft}^3} = 1.20
\]

Next, calculate the correction factor.

\[
(8.34 \text{ lbs/gal})(1.20) = 10.01 \text{ lbs/gal}
\]

Then convert the gallon per minute flow rate to pounds per day.

\[
(25 \text{ gpm})(10.01 \text{ lbs/gal})(1,440 \text{ min/day}) = 360,360 \text{ lbs/day pumped}
\]
**Example 4.4**

There are 1,240 gallons of a certain liquid in a tank. If the specific gravity of the liquid is 0.93, how many pounds of liquid are in the tank? Normally, for a conversion from gallons to pounds, the factor 8.34 lbs/gal (the density of water) would be used if the substance’s specific gravity were between 0.98 and 1.02. However, in this example the substance has a specific gravity outside this range, so the conversion factor 8.34 lbs/gal must be adjusted.

Multiply 8.34 lbs/gal by the specific gravity to obtain the adjusted factor.

\[(8.34 \text{ lbs/gal})(0.93) = 7.76 \text{ lbs/gal}\]

Then convert 1,240 gal to pounds using the correction factor.

\[(1,240 \text{ gal})(7.76 \text{ lbs/gal}) = 9.622 \text{ lbs}\]

### 4.2.2 Specific Gravity of Gases

The specific gravity of a gas is usually determined by comparing the density of the gas with the density of air, which is 0.075 lbs/ft³ at a temperature of 20°C and a pressure of 14.7 psia (pounds per square inch absolute) - the pressure of the atmosphere at sea level.* For example, the density of chlorine gas is 0.187 lbs/ft³. Its specific gravity would be calculated as follows:

\[
\text{specific gravity of Cl}_2 \text{ gas} = \frac{\text{density of Cl}_2 \text{ gas}}{\text{density of air}}
\]

\[
= \frac{0.187 \text{ lbs/ft}^3}{0.075 \text{ lbs/ft}^3} = 2.49
\]

This tells you that chlorine gas is about 2 ½ times as dense as air. Therefore, when chlorine gas is introduced into a room, it will concentrate at the bottom of
the room. This is important to know because chlorine is a deadly poisonous gas. Table 4.4 lists specific gravities for various gases.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Specific Gravity</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (0°C; 14.7 psia)</td>
<td>0.07</td>
<td>When released in a room, these gases will first rise to the ceiling area.</td>
</tr>
<tr>
<td>Methane (0°C; 14.7 psia)</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide*</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Air (20°C; 14.7 psia)</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (0°C; 14.7 psia)</td>
<td>1.04</td>
<td>When released in a room, these gases will first settle to the floor area.</td>
</tr>
<tr>
<td>Hydrogen sulfide*</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide*</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>Chlorine gas (0°C; 14.7 psia)</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td>Gasoline vapor*</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

* Temperature and pressure not given.

### 4.3 Pressure, Force, and Head

Force: The push exerted by water on a surface being used to confine it. Force is usually expressed in pounds, tons, grams, or kilograms.

Pressure: The force per unit area. It is commonly expressed as pounds per square inch (psi).

Head: The vertical distance from the water surface to a reference point below the surface. It is usually expressed in feet or meters.

**Equations**

\[ \text{Force (lbs.)} = \text{psi} \times \text{area (in square feet)} \]

\[ \text{Head (feet)} = \text{psi} \times 2.31 \]
\[ psi = \text{head} \times 0.433 \]

OR

\[ psi = \frac{\text{head}}{2.31} \]

where: \( H = \text{Head (in feet)} \)

\( psi = \text{pounds per square inch} \)

Knowing that a cubic foot of water weighs 62.4 pounds, the force of the water pushing down on the one square foot surface area is 62.4 pounds. Using this information, we can determine the pressure in pounds per square inch (psi).

\[
\frac{62.4\text{lbs}}{1\text{ft}^2} = \frac{62.4\text{lbs}}{(1\text{ft})(1\text{ft})}
\]

\[
\frac{62.4\text{lbs}}{(12\text{in})(12\text{in})} = \frac{62.4\text{lbs}}{144\text{in}^2}
\]

\[
\frac{62.4\text{lbs}}{144\text{in}^2} = 0.433\text{lbs/in}^2 \text{ OR } 0.433\text{psi}
\]
Based on the calculation above, a column of water one foot high above one square inch of surface area weighs almost half a pound (0.433 lb.), and is expressed as 0.433psi of pressure. Now that we have determined this factor, it allows us to convert from pressure measured in feet of water to pressure measured in pounds per square inch. The height of water is the most important factor in determining pressures. Use the example below to convert from psi to feet of head.

\[
\frac{1\text{ foot}}{0.433\text{ psi}} = \frac{x\text{ feet}}{1\text{ psi}}
\]

\[
x = \frac{(1\text{ ft})(1\text{ psi})}{0.433\text{ psi}}
\]

\[
x = 2.31\text{ feet}
\]
4.3.1 Head

Head is the ratio between foot pounds of water and pounds, and is measured in feet. For every pound per square inch (psi) of pressure there is 2.31 feet of head.

Equation

\[ \text{Head (in feet)} = \text{psi} \times 2.31 \]

Head is an important measurement tool in hydraulics. It can be used to determine the hydraulic forces in a pipeline and pump requirements.

There are three types of head.
1. Pressure head
2. Elevation head
3. Velocity head

Pressure head is the measurement of the energy in water from pressure. It is the height above a pipe that water will rise to in an open ended tube. Pressure head can be used to plot a hydraulic grade line (HGL).

Elevation head is the measurement of energy in water due to its elevation above a reference point. It is measured from a specific point or reference point, like sea level, to a desired point in the system.

Velocity head is the measurement of the energy in water from its flow. The faster the flow, the greater the energy. Velocity head is also determined by the equation shown below.

\[ \text{velocity head} = \frac{V^2}{2g} = \frac{V^2}{64.4 \text{ ft/sec}^2} \]

Where \( V \) = water velocity

\( 2g \) = 2 times the acceleration of gravity (32.2 ft/sec\(^2\)), or 64.4 ft/sec\(^2\)
4.3.2 *Elevation Head and Pressure Head*

An important concept in water systems is the relationship between pressure head and elevation head. The figure below illustrates an open ended tube attached to a tank to measure head. Under static conditions the water level in the tube would rise to the water level in the tank. This water level would represent the elevation head.

This method of measuring head in a system is impractical. Instead of measuring elevation head, water systems install pressure gages in the system to measure pressure head.

The illustration above shows head in elevation for a body of static water. The head elevation would change if the water were flowing.

The illustration that follows demonstrates the relationship between elevation head and pressure head during static water conditions (when the water is not moving). The water level in the water tank and tubes is at the same time elevation. Therefore the elevation head is equal to the pressure head throughout the system.
Under dynamic conditions (when water is moving in the system) the elevation head and pressure head decrease proportionally as you move away from the tank. The head loss is due to friction losses in the pipe because the water is moving through the pipe.
Chapter Five
5.0 TYPICAL WATER PROBLEMS

5.1 Flow Conversions

GPM to GPD

To convert gallons per minute (GPM) to gallons per day (GPD), multiply by 1,440 (the number of minutes in a day).

\[ 20 \text{ gpm} \times 1440 \text{ min/day} = 28,800 \text{ gpd} \]

GPD to MGD

To convert gallons per day to million gallons per day (MGD), move the decimal point six places to the left (this is the same as dividing by one million).

Example:

\[ \frac{188,000 \text{ gpd}}{1,000,000} = 0.188 \text{ mgd} \]

GPM to MGD

To convert gallons per minutes to million gallons per day, multiply by 1,440 (converting to gpd) and then divide by one million (or move the decimal point six places to the left).

Example 5.1

\[ 16 \text{ gpm} \times 1,440 \text{ min/day} = 23,040 \text{ gpd} \]

\[ \frac{23,040 \text{ gpd}}{1,000,000} = 0.023040 \text{ mgd} \]
Another way to convert GPM to MGD is to use a conversion factor. 1 MGD = 694.4 GPM as shown below. Converting 16 gpm to mgd is done by dividing by 694.4 gpm/mgd.

\[
\frac{1,000,000 \text{ gpd}}{1,440 \text{ min/day}} = 694.4 \text{ gpm}
\]

\[
\frac{16 \text{ gpm}}{694.4 \text{ gpm/mgd}} = 0.023040 \text{ mgd}
\]

**MGD to GPD**

To convert MGD to GPD, multiply by 1,000,000.

**Example 5.2**

\[
0.25 \text{ mgd} \times 1,000,000 = 250,000 \text{ gpd}
\]

**MGD to GPM**

To convert MGD to GPM, multiply by 1,000,000 and then divide by 1,440, or simply multiply by 694.4.

**Example 5.3**

\[
\frac{(0.25 \text{ mgd})(1,000,000)}{1,440} = 173.6 \text{ gpm}
\]

or

\[
(0.25 \text{ mgd})(1,000,000) = 250,000 \text{ gpd}
\]

\[
\frac{250,000 \text{ gpd}}{1,440} = 173.6 \text{ gpm}
\]
or

\[(0.25\text{mgd})(694.4)=173.6\text{gpm}\]

5.2 Chemical Dosing

**Equation**  Chemical Feed in pounds per day (lbs/day)

\[\text{chemical feed (lbs/day)}=(\text{flow, mgd})(\text{dose, mg/L})(8.34)\]

An easy way to visualize and use this equation is in a Davidson Pie Chart seen below.

![Davidson Pie Chart for Chemical Dosing](chart.png)

5.2.1 Chemical Feed

To find the Chemical Feed, in lbs/day, cover the Chemical Feed portion of the pie chart as seen below. What is left uncovered represents the correct equation.

![Chemical Feed Pie Chart](chart2.png)

Chemical Feed in pounds per day is equal to

\[(\text{Flow, mgd})(\text{Dose, mg/L})(8.34)\]
Example 5.4

Determine the chlorinator setting in pounds per day if you have a flow of 200 gpm and your target chlorine dose is 2.0 mg/L.

1. Convert the flow from gpm to mgd.

Multiply flow in gpm by 1,440 (the number of minutes in a day) to convert to gallons per day (GPD).

\[200 \text{ gpm} \times 1,440 \text{ min/day} = 288,000 \text{ gpd}\]

Move the decimal point six places to the left to convert to millions gallons per day (mgd), or divide the flow in gpm by 694.4 to convert directly to mgd.

\[0.288 \text{ mgd}\]

\[\frac{200 \text{ gpm}}{694.4} = 0.288 \text{ mgd}\]

2. Use the equation for chemical feed to determine the chlorinator setting in pounds per day.

\[\text{Chemical Feed, lbs/day} = (\text{Flow, mgd})(\text{Dose, mg/L})(8.34)\]

\[\text{Chemical Feed, lbs/day} = (0.288)(2.0 \text{ mg/L})(8.34)\]

\[\text{Chemical Feed, lbs/day} = 4.8 \text{ lbs/day}\]

5.2.2 Calculating Dose

If you know what the chemical feed and flow are and want to calculate the dose, cover the dose section of the pie chart to set up the correct equation as seen below.
Example 5.5

A 0.52 mgd system is feeding chlorine at a rate of 12 lbs/day. What will be the resulting chlorine dose?

\[
Dose, mg/L = \frac{Chemical \ feed, lbs/day}{(Flow, mgd)(8.34)}
\]

\[
Dose, mg/L = \frac{12 lbs/day}{(0.52 mgd)(8.34)} = 2.76 mg/L
\]

5.2.3 Calculating Flow

If you know what the chemical feed and dose are and want to calculate the flow, cover the flow section of the pie chart set up the correct equation as seen below.
Example 5.6

A treatment plant is feeding 24 lbs/day of alum at a dose of 45 mg/L. What is the flow rate used for the treatment?

\[
\text{Flow, mgd} = \frac{\text{Chemical feed, lbs/day}}{(\text{Dose, mg/L})(8.34)}
\]

\[
\text{Flow, mgd} = \frac{24 \text{ lbs/day}}{(45 \text{ mg/L})(8.34)} = 0.533 \text{ mgd}
\]

5.3 Detention Time

Equation

\[
\text{Detention time, hrs} = \frac{\left(\frac{\text{Tank volume, gal}}{24 \text{ hrs/day}}\right)}{(\text{Flow, gpd})}
\]

An easy way to visualize and use this equation is in a Davidson Pie Chart seen below.
5.3.1 Calculating Detention Time

To determine detention time in hours when the flow and tank volume are known, cover the Detention Time portion of the pie chart as seen below. What is left uncovered is the correct equation.

\[
Detention\ time, \ hrs = \frac{\left(\text{Tank\ volume, gal}\right)\left(24\ hrs/\ day\right)}{(\text{Flow, gpd})}
\]

Example 5.7

A rectangular basin 12 feet long and 9 feet wide is 6 feet deep. It treats a flow of 90,000 gallons per day. Determine the basin detention time in hours.

Equation

\[
Detention\ time, \ hrs = \frac{\left(\text{Tank\ volume, gal}\right)\left(24\ hrs/\ day\right)}{(\text{Flow, gpd})}
\]
Steps to solve the problem.

1. Determine tank volume in gallons.
   \[ V = (\text{length})(\text{width})(\text{depth}) \]
   \[ V = (12 \text{ feet})(9 \text{ feet})(6 \text{ feet}) \]
   \[ V = 648 \text{ ft}^3 \]

2. To convert from cubic feet to gallons multiply by 7.48 gal/ft\(^3\).
   \[ (648 \text{ ft}^3)(7.48 \text{ gal/ft}^3) = 4847 \text{ gallons} \]

3. Calculate the resulting detention time in hours using the equation stated above.
   \[ \text{Detention time, hrs} = \frac{(4847 \text{ gal})(24 \text{ hrs/day})}{(90,000 \text{ gpd})} = 1.29 \text{ hrs} \]

5.3.2 Calculating Flow

If you know what the tank volume and detention times are and want to calculate the flow, cover the flow section of the pie chart to set up the correct equation as seen below.

\[ \text{Flow, gpd} = \frac{(\text{Tank volume, gal})(24 \text{ hrs/day})}{\text{Detention time, hrs}} \]
**Example 5.8**

Determine the required flow in gpd for a setting basin that is 20 feet long, 10 feet wide, and 6 feet deep with a detention time of 3 hours.

Steps to solve the problem.

1. **Determine tank volume in gallons.**
   \[
   V = (\text{length})(\text{width})(\text{depth})
   \]
   \[
   V = (20 \text{ feet})(10 \text{ feet})(6 \text{ feet})
   \]
   \[
   V = 1,200 \text{ ft}^3
   \]

2. **To convert from cubic feet to gallons, multiply by 7.48 gal/ft\(^3\).**
   \[
   (1,200 \text{ ft}^3)(7.48 \text{ gal/ft}^3) = 8,976 \text{ gallons}
   \]

3. **Calculate the resulting flow rate in gpd using the detention time and the equation stated above.**
   \[
   \text{Flow, gpd} = \frac{(\text{Tank volume, gal})(24\text{hrs/day})}{(\text{Detention time, hrs})}
   \]
   \[
   \text{Flow, gpd} = \frac{(8,976 \text{ gal})(24\text{hrs/day})}{(3\text{hrs})} = 71,808 \text{ gpd}
   \]

**5.3.3 Calculating Tank Volume**

This same technique could be used to determine tank volume if you knew the detention time and flow. Cover the portion of the pie chart that is unknown to set up the correct equations as seen below.
\[
\left( \text{Tank volume, gal} \right) \left( \frac{24 \text{ hrs}}{\text{day}} \right) = \left( \frac{\text{Detention time, hrs}}{24 \text{ hrs/day}} \right) \left( \text{Flow, gpd} \right)
\]

\[
\left( \text{Tank volume, gal} \right) = \frac{\left( \frac{\text{Detention time, hrs}}{24 \text{ hrs/day}} \right) \left( \text{Flow, gpd} \right)}{24 \text{ hrs/day}}
\]

**Example 5.9**

Find the tank volume in gallons if a treatment plant is operating at a flow rate of 60,000 gpd and the detention in the settling basin is 4.2 hrs.

\[
\left( \text{Tank volume, gal} \right) = \frac{\left( \frac{4.2 \text{ hrs}}{24 \text{ hrs/day}} \right) \left( 60,000 \text{ gpd} \right)}{24 \text{ hrs/day}} = 10,500 \text{ gal}
\]

**5.4 Well Problems**

The three basic calculations related to water well performance are well yield, drawdown, and specific capacity. These calculations provide information for selecting appropriate pumping equipment and for identifying any changes in the productive capacity of the well.
5.4.1 Well Yield

The well yield is the volume of water that is discharged from well during a specified time period. This discharge may be a result of pumping, as in most cases, or of free flow in the case of a flowing artesian well. Well yield is normally measured as the pumping rate in gallons per minute (gpm). This can be expressed mathematically as

\[
\text{well yield} = \frac{\text{gallons}}{\text{Minutes}}
\]

The easiest method of measuring well yield is to place a flow meter on the downstream, or discharge, side of the pump. However, to determine relatively small well yields, another method often used is measuring the time required to fill a container of known volume. The following examples illustrate the second method of calculating well yield. A similar calculation is discussed elsewhere in this handbook.

Example 5.10

During a test for well yield, the time required to fill a 55gallon barrel was 25 seconds. Based on this pumping rate, what was the well yield in gallons per minute?

\[
\text{well yield} = \frac{\text{gallons}}{\text{Minutes}}
\]

The well yield is to be reported in gallons per minute, so first express the 25 seconds given in the problem as minutes.

\[
\frac{25\text{Seconds}}{60\text{Seconds / Minute}} = 0.42\text{Minutes}
\]

Now fill in the information given and complete the calculation using the equation for well yield.
Example 5.11

If it takes a well pump 41 seconds to fill a 210 gallon barrel, what is the well yield in gallons per minute?

The well yield is to be reported in gallons per minute, so first express the 41 seconds given in the problem as minutes.

\[
\frac{41 \text{ Seconds}}{60 \text{ Seconds / Minute}} = 0.683 \text{ Minutes}
\]

You can solve the well yield problem by filling in the given information and completing the division indicated.

\[
\text{well yield} = \frac{210 \text{ gallons}}{0.683 \text{ Seconds}} = 307 \text{ gpm}
\]

Example 5.12

What is the well yield in gallons per minute if it takes the pump 3.5 minutes to fill a 5ft² tank to a depth of 3 ft? The equation used in calculating well yield was given earlier.

\[
\text{well yield} = \frac{\text{gallons}}{\text{Minutes}}
\]

Before information can be filled in the equation, the gallon volume of the tank must be calculated. The tank is a square tank with a water depth given. The shape of the volume is a square cube. First determine the volume of the cube using the dimensions given.
Next, convert the calculated volume from cubic feet to gallons.

\[
\left(75 \text{ ft}^3\right)\left(7.48 \text{ gal/ft}^3\right) = 561 \text{ gal}
\]

Now you can solve this well yield problem by filling in the given information and completing the calculation.

\[
\text{well yield} = \frac{561 \text{ gallons}}{3.5 \text{ minutes}} = 160.3 \text{ gpm}
\]

5.4.2 Drawdown

The drawdown of a well is the amount the water level drops once pumping begins. As illustrated in Figure 5.1, drawdown is the difference between the static water level (SWL, the level when no water is being taken from the aquifer, either by pumping or by free flow) and the pumping water level (PWL, the level when the pump is in operation). This is expressed mathematically in the equation that follows.

\[
\text{drawdown} = \text{pumping water level} - \text{static water level}
\]
The two examples that follow illustrate how to calculate well drawdown.

**Example 5.13**

The water level in a well is 25 feet below the ground surface when the pump is not in operation (static water level). If the water level is 48 feet below the ground surface when the pump is in operation (pumping water level), what is the drawdown in feet?
Drawdown is the measure of water level *drop* once the pump has been turned on. In this problem, the drawdown is found as shown.

\[
\text{drawdown} = \text{pumping water level} - \text{static water level}
\]

\[
\text{drawdown} = 48 \text{ feet} - 25 \text{ feet} = 23 \text{ feet}
\]

**Example 5.14**

When the pump is not in operation (static water level), the water level in a well is 39 feet below ground surface. The water level drops to 57 feet when the pump is in operation (pumping water level). What is the drawdown in feet?

\[
\text{drawdown} = 57 \text{ feet} - 39 \text{ feet} = 18 \text{ feet}
\]

**5.4.3 Specific Capacity**

The specific capacity of a well is a measure of the well yield per unit of drawdown. It is usually expressed in terms of gallons per minute (gpm) of well yield per foot of drawdown. The equation used to calculate specific capacity is given below.
The next examples demonstrate the calculation of specific capacity of a well.

**Example 5.15**

It takes a well pump 0.6 minutes to fill a 55 gallon barrel. If the drawdown while the pump is in operation is 11 ft, what is the specific capacity of the well? To calculate the specific capacity of the well, you must know the gpm yield and the feet of drawdown. The two calculations are then used to find the specific capacity of the well.

\[
\text{specific \ capacity} = \frac{\text{well \ yield \ gpm}}{\text{drawdown, ft}}
\]

Using the gpm well yield and drawdown information, calculate the specific capacity of the well.

\[
\text{well yield} = \frac{55 \text{ gallons}}{0.6 \text{ minutes}} = 91.7 \text{ gpm}
\]

\[
\text{specific capacity} = \frac{91.7 \text{ gpm}}{11 \text{ ft}} = 8.34 \text{ gpm/ft}
\]

**Example 5.16**

The well yield for a well pump is 170 gpm. When the pump is off the static water level is 46 feet below ground surface. While the pump is operating at capacity, the pumping water level drops to 64 feet below ground surface. What is the specific capacity of the well? To solve the problem, fill in the information given in the equations and complete the calculations.

\[
\text{drawdown} = 64 \text{ feet} - 46 \text{ feet} = 18 \text{ feet}
\]

\[
\text{specific capacity} = \frac{170 \text{ gpm}}{18 \text{ ft}} = 9.44 \text{ gpm/ft}
\]
5.4.4 **Well Disinfection**

The targeted sodium hypochlorite dose to disinfect a well is 100 mg/L. The well casing diameter is 15 inches and the height of the water-filled casing is 40 feet. The sodium hypochlorite solution to be used for disinfection is 5.25% (contains 52,500 mg/L chlorine). How many gallons chlorine (sodium hypochlorite) are required to disinfect the well?

**Equation**

\[
\text{Chlorine, gal} = \frac{(\text{volume, gal})(\text{dose, mg/L})}{\text{chlorine solution, mg/L}}
\]

1. Determine the casing volume in gallons using the volume equation for a cylinder. Use 15 inches ÷ 12 inches/ft = 1.25 feet diameter.

\[
V = (0.785)(d)^2(depth, \text{ ft})
\]

\[
V = (0.785)(1.25 \text{ ft})^2(40 \text{ ft})
\]

\[
V = 49.06 \text{ ft}^3
\]

2. To convert from cubic feet to gallons, multiply by 7.48 gal/ft³.

\[
49.06 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 366.97 \text{ gallons}
\]

3. Calculate the required chlorine in gallons using the equation stated above.

\[
\text{Chlorine, gal} = \frac{(\text{volume, gal})(\text{dose, mg/L})}{\text{chlorine solution, mg/L}}
\]

\[
\text{Chlorine, gal} = \frac{(366.97 \text{ gal})(100 \text{ mg/L})}{52,500 \text{ mg/L}}
\]

\[
\text{Chlorine, gal} = 0.7 \text{ gal}
\]
Note: Sometimes concentrations are listed as parts per million (ppm). One ppm is equal to one milligram per liter (mg/L).

### 5.4.5 Disinfecting Pipe Sections

Disinfecting pipe sections uses the same steps that we just completed to disinfect a well casing. Pipe sections are simply cylindrical volumes. Once the dimensions of the pipe section are known, the volume can be calculated and converted to gallons. An example problem is given below for you to practice disinfection calculations.

#### Example 5.17

To disinfect an 8-inch diameter water main 400 feet long, an initial chlorine dose of 400 mg/L is expected to maintain a chlorine residual of over 300 mg/L during a three-hour disinfection period. A 5.25 percent sodium hypochlorite solution will be used for disinfection and it contains 0.45 lbs chlorine per gallon. How many gallons of the sodium hypochlorite solution are needed to disinfect the 8-inch pipe section?

1. Determine the volume of water in the pipe in gallons using the volume equation for a cylinder. First, convert the diameter in inches to diameter in feet. 8 inches ÷ 12 inches / ft = 0.667 ft diameter. Then calculate the pipe volume.

   \[ V = 0.785 \times (d)^2 \times \text{length, ft} \]
   \[ V = 0.785 \times (0.667 \text{ ft})^2 \times 400 \text{ ft} \]
   \[ V = 139.7 \text{ ft}^3 \]

2. To convert from cubic feet to gallons multiply by 7.48 gal/ft³.

   \[ 139.7 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 1,045 \text{ gallons} \]
3. Determine the pounds of chlorine needed using the standard dosage equation shown.

\[
\text{Chlorine, lbs} = (\text{volume, MG})(\text{Dose, mg/L})(8.34)
\]

\[
1,045 \text{ gallons} = 0.001045 \text{ MG} \quad \text{(Move decimal point left 6 places)}
\]

\[
\text{Chlorine, lbs} = (0.001045 \text{ MG})(400 \text{ mg/L})(8.34) = 3.49 \text{ lbs}
\]

4. Calculate gallons of 5.25% hypochlorite solution needed using equation below.

\[
\text{Hypochlorite, gal} = \frac{(\text{Chlorine, lbs})}{\left(\frac{\text{lbs chlorine}}{\text{gal}}\right)}
\]

\[
\text{Hypochlorite, gal} = \frac{(3.49 \text{ lbs})}{(0.45 \text{ lbs/gal})} = 7.76 \text{ gallons}
\]

### 5.4.6 Disinfecting Storage Tanks

Disinfection of storage tanks is done much the same as disinfection of pipe sections and well casings. First you must find the volume of water in the storage tank, which depends on its shape. Then convert the volume to gallons, and finally calculate the amount of chlorine needed for disinfection. An example calculation is provided for you to practice.

**Example 5.18**

A storage tank 25 feet in diameter and 10 feet deep is taken off line for maintenance. To disinfect it before use, an initial chlorine dose of 100 mg/L is expected to create a chlorine residual of more than 50 mg/L for a 24-hour period. A 12 percent sodium hypochlorite solution is used for disinfection and it contains 1.1 pounds of chlorine per gallon. How many gallons of 12 percent sodium hypochlorite solution are needed for disinfection of the storage tank?
1. Determine the volume of water in the tank in gallons using the volume equation for a cylinder.

\[ V = (0.785)(d^2)(\text{depth, ft}) \]

\[ V = (0.785)(25\text{ ft})^2(10\text{ ft}) = 4,906.3\text{ ft}^3 \]

2. To convert from cubic feet to gallons multiply by 7.48 gal/ft\(^3\).

\[ 4,906.3\text{ ft}^3 \times 7.48\text{ gal/ft}^3 = 36,699\text{ gallons} \]

3. Determine pounds of chlorine needed.

\[ \text{Chlorine, lbs} = \left( \text{volume, MG} \right) \left( \text{Dose, mg/L} \right) (8.34) \]

\[ \text{Chlorine, lbs} = (0.036699\text{MG})(100\text{ mg/L})(8.34) = 30.6\text{ lbs} \]

4. Calculate the gallons of 12% hypochlorite solution needed.

\[ \text{Hypochlorite, gal} = \frac{(\text{Chlorine, lbs})}{\left( \frac{\text{lbs}}{\text{chlorine/gal}} \right)} \]

\[ \text{Hypochlorite, gal} = \frac{(30.6\text{ lbs})}{(1.1\text{ lbs/gal})} = 27.8\text{ gallons} \]

5.4.7 Chlorine Demand

Chlorine demand is defined as the amount of chlorine used up in the reaction following disinfection based on the dosage applied and the residual that remains after a period of time. The equation for chlorine demand is shown below. A more complete chlorine demand definition is given in Appendix A.

\[ \text{chlorine dosage} - \text{chlorine residual} = \text{chlorine demand} \]
It is important to note that the residual chlorine needed to calculate these types of problems is the total chlorine residual, not the free chlorine residual. Using the free chlorine residual to find chlorine demand will result in an error because it ignores the combined chlorine residual in solution.

Example 5.19

What is the chlorine demand in milligrams per liter if the chlorine dose is 3.2 mg/L and the chlorine residual is 0.3 mg/L?

Equation

\[
\text{Chlorine demand, mg/L} = \frac{\text{Dose, mg/L} - \text{residual, mg/L}}{}
\]

1. Calculate the chlorine demand.

\[
\text{Chlorine demand, mg/L} = 3.2\text{mg/L} - 0.3\text{mg/L} = 2.9\text{mg/L}
\]

The chlorine dosage is equal to the chlorine demand plus the residual. This new equation is found by rearranging the initial equation given earlier.

Equation

\[
\text{Dose, mg/L} = \frac{\text{Chlorine demand, mg/L} + \text{residual, mg/L}}{}
\]

The chlorine residual is equal to the chlorine dosage minus the chlorine demand. This equation also is a rearrangement of the initial equation.

Equation

\[
\text{residual, mg/L} = \frac{\text{dose, mg/L} - \text{chlorine demand, mg/L}}{}
\]
5.5 Filtration Rates

Filtration rates are determined using the flow of water through the cross-sectional area of the filter media and are usually expressed in gallon per minute per square foot of surface area (gpm/ft\(^2\)). Monomedia (sand only) filters typically can be operated up to 3 gpm/ft\(^2\). Dual media (sand and anthracite or sand and GAC) filters normally can be operated up to 4 gpm/ft\(^2\), however; filtration rates greater than 4 gpm/ft\(^2\) can be obtained with proper demonstration and approval from Ohio EPA. Filtration rates up to about 6 gpm/ft\(^2\) are possible depending on pretreatment and filter media design considerations. Calculation of filtration rates are part of the operational duties for water treatment plant operators. The equation used to calculate filtration rates is given below.

**Equation**

\[
\text{Filtration rate, gpm/ft}^2 = \frac{\text{Flow, gpm}}{\text{Surface area, ft}^2}
\]

**Example 5.20**

If a sand filter is 18 feet wide by 24 feet long and treats a flow of 750 gpm, what is the filtration rate in gallons per minute per square foot (gpm/ft\(^2\)) of filter area?

1. Determine the surface area of the filter using the formula for the area of a rectangle.

   \[
   \text{Rectangle Area} = (\text{length})(\text{width})
   \]

   \[
   \text{Filter area} = (18 \, \text{ft})(24 \, \text{ft}) = 432 \, \text{ft}^2
   \]

2. Calculate the filtration rate in gallons per minute per square foot.

   \[
   \text{Filtration rate, gpm/ft}^2 = \frac{750 \, \text{gpm}}{432 \, \text{ft}^2} = 1.74 \, \text{gpm/ft}^2
   \]
Example 5.21

A dual media filter containing sand and anthracite is 12 feet long and 8 feet wide. The flow meter indicates a filter effluent flow of 0.36 mgd. Find the flow rate in gpm/ft^2.

First, convert the flow rate in mgd to gpm.

\[
(0.36 \text{ mgd})(694.4 \text{ gpm/ mgd}) = 250 \text{ gpm}
\]

Second, find the surface area of the filter media.

\[
(12 \text{ feet})(8 \text{ feet}) = 96 \text{ ft}^2
\]

Next, calculate the filtration rate using the area of the filter.

\[
\frac{250 \text{ gpm}}{96 \text{ ft}^2} = 2.6 \text{ gpm/ ft}^2
\]

Example 5.22

A rapid sand filter is operating at 2.4 gpm/ft^2 and measures 14 feet wide and 20 feet long. Using this information, find the flow rate of the filter in mgd.

First, find the surface area of the filter media.

\[
(14 \text{ feet})(20 \text{ feet}) = 280 \text{ ft}^2
\]

Second, use the filtration rate to find the flow rate in gpm for the filter.

\[
(2.4 \text{ gpm/ ft}^2)(280 \text{ ft}^2) = 672 \text{ gpm}
\]
Next, convert the flow rate in gpm to mgd.

\[
\frac{672 \text{ gpm}}{694.4 \text{ gpm/mgd}} = 0.968 \text{ mgd}
\]

**Example 5.23**

A rapid sand filter is operating at 450 gpm and provides a filtration rate of 2.5 gpm/ft\(^2\). Assuming the filter measures 10 feet wide, find the length of the filter.

First, find the area of the filter using the filtration rate and the flow rate.

\[
\frac{450 \text{ gpm}}{2.5 \text{ gpm/ft}^2} = 180 \text{ ft}^2
\]

Next, find the length of the filter using the filter area and the width.

\[
\frac{180 \text{ ft}^2}{10 \text{ feet}} = 18 \text{ feet, length}
\]

**Example 5.24**

A filter measures 12 feet wide and 16 feet long. The filter influent valve is closed, but the filter effluent valve remains open during a flow rate test. After 3 minutes the water level in the filter has dropped 16-inches. Find the filtration rate in gpm/ft\(^2\) and the filter flow rate in mgd.

First, find the surface area of the filter media.

\[
(12 \text{ feet})(16 \text{ feet}) = 192 \text{ ft}^2
\]

Next, find the volume (gallons) of water that passed through the media in the 3 minute time interval. Assume the area found above and convert the drop in inches to feet.
\[
\frac{16\text{in.}}{12\text{in./ft}} = 1.333 \text{feet}
\]

\[
(192\text{ft}^2)(1.333\text{ft}) = 255.9 \text{ft}^3
\]

\[
(255.9 \text{ft}^3)(7.48\text{gal/ft}^3) = 1,914\text{gallons}
\]

Finally, find the filtration rate in gpm/ft\(^2\) and the flow rate in mgd.

\[
\frac{1,914\text{gallons}}{3\text{min.}} = 638\text{gpm}
\]

\[
\frac{638\text{gpm}}{192\text{ft}^2} = 3.32\text{gpm/ft}^2
\]

\[
\frac{638\text{gpm}}{694.4\text{gpm/mgd}} = 0.919\text{mgd}
\]

**Example 5.25**

A rapid sand filter that measures 12 feet wide and 18 feet long has a water level that is 5 feet above the filter media. After operating the filter for 12 minutes, the operator finds the influent valve was closed and the water level dropped to 2.1 feet above the media surface. During this same operating period, the rate of flow was measured at 405 gpm. Is the flow meter measuring the water flow too fast, too slow, or about right?

First, find the surface area of the filter media and the volume (gallons) of water filtered.

\[
(12\text{feet})(18\text{feet}) = 216\text{ft}^2
\]

\[5\text{ft} - 2.1\text{ft} = 2.9\text{ft\hspace{1em}drop}\]
\[
\left(216\,ft^2\right)\left(2.9\,ft\right) = 626.4\,ft^3
\]

\[
\left(626.4\,ft^3\right)\left(7.48\,gal/\,ft^3\right) = 4,685.5\,gallons
\]

Second, find the flow rate using the volume of water filtered and the time the filter was operating.

\[
\frac{4,685.5\,gallons}{12\,\text{min.}} = 390\,gpm
\]

Next, evaluate the flow meter measurement versus the actual flow rate calculated. The flow meter read 405 gpm, while the actual flow rate was found to be 390 gpm. The flow meter therefore is measuring too fast. In fact, the meter is reading about 4 percent fast.

### 5.6 Backwash Flow

Filter backwash is done by pushing water backwards up through the filter media. This reversal of flow expands the filter media and cleans suspended solids from the filter bed. Backwash rates generally range from 15 gpm/ft\(^2\) to about 20 gpm/ft\(^2\). The equation to calculate backwash rates is given below.

**Equation**

\[
\text{Backwash rate, gpm/ft}^2 = \frac{\text{Backwash flow, gpm}}{\text{Surface area, ft}^2}
\]

**Example 5.26**

Calculate the backwash flow in gpm required to backwash a filter at 15 gallons per minute per square foot. The filter surface area is 432 square feet.

\[
15\,\text{gpm/ft}^2 = \frac{\text{Backwash Flow, gpm}}{432\,\text{ft}^2}
\]
\[
\left(15 \text{ gpm/ft}^2\right)\left(432 \text{ ft}^2\right) = \text{Backwash Flow, gpm}
\]

\[
6,480 \text{ gpm/ft}^2 = \text{Backwash Flow, gpm}
\]

**Example 5.27**

A rapid sand filter that measures 10 feet wide and 14 feet long is backwashed using a pump with a capacity of 2,450 gpm. Calculate the backwash rate in gpm/ft^2.

First, find the surface area of the filter media.

\[
(10 \text{ ft})(14 \text{ ft}) = 140 \text{ ft}^2
\]

Next, calculate the backwash rate using the pump capacity and the filter area.

\[
\frac{2,450 \text{ gpm}}{140 \text{ ft}^2} = 17.5 \text{ gpm/ft}^2
\]

**5.6.1 Inches of Rise per Minute**

Backwash rates also can be expressed as inches of rise per minute. The example below shows the conversion from gpm/ft^2 to inches of rise/minute. Backwash rates expressed in inches rise/minute always are a number greater than the backwash rate expressed in gpm/ft^2.

\[
\left(17.5 \frac{\text{gpm}}{\text{ft}^2}\right)\left(\frac{\text{ft}^3}{7.48 \text{gal}}\right)\left(\frac{12 \text{ in}}{\text{ft}}\right) = 28.1 \text{ in rise/ min}
\]

Looking closer at the calculation above, the last two terms are just conversion factors. Analyzing only the two conversion factors gives a new conversion factor to change from gpm/ft^2 to inches rise/minute, and from inches rise/minute to gpm/ft^2. Using this new conversion factor is shown in the examples that follow.
\[
\frac{12 \text{ in} / \text{ft}}{7.48 \text{ gal} / \text{ft}^3} = \frac{1.6 \text{ in} / \text{ft}^2}{\text{gal}}
\]

**Example 5.28**

A filter is backwashed at a rate of 16.8 gpm/ft\(^2\). Find the backwash rate expressed in inches rise/minute.

\[
\left(\frac{16.8 \text{ gpm}}{\text{ft}^2}\right) \left(\frac{1.6 \text{ in} / \text{ft}^2}{\text{gal}}\right) = 26.88 \text{ in rise / min}
\]

You should now see that multiplying the backwash rate in gpm/ft\(^2\) by 1.6 converts the rate to express it in inches rise/minute. It also should be understood that dividing a backwash rate in inches rise/minute by 1.6 converts the rate expressed in gpm/ft\(^2\). This is demonstrated below.

**Example 5.29**

A filter is backwashed at a rate of 26.88 inches rise/minute. Find the backwash rate expressed in gpm/ft\(^2\).

\[
\left(\frac{26.88 \text{ in rise / min}}{1.6}\right) = 16.8 \text{ gpm / ft}^2
\]

**Example 5.30**

A rapid sand filter that measures 10 feet wide and 14 feet long is washed using a backwash pump at a rate of 28 inches rise/minute. Calculate the backwash rate in gpm/ft\(^2\). (The filter area is not needed for this problem since we have a new conversion factor for backwash rates.)

\[
\left(\frac{28 \text{ in rise / min}}{1.6}\right) = 17.5 \text{ gpm / ft}^2
\]
**Example 5.31**

A rapid sand filter is backwashed at 16.3 gpm/ft$^2$ and measures 14 feet wide and 20 feet long. Using this information, find the backwash rate in inches rise/minute.

$$(16.3 \text{ gpm/ft}^2)(1.6) = 26.1 \text{ in} \hspace{1em} \text{rise/ min}$$

**Example 5.32**

A rapid sand filter that measures 12 feet wide and 18 feet long has a water level that is 1.1 feet above the filter media. After opening the backwash valve, the water level in the filter rises to 6.4 feet above the media surface over a 2-minute time interval. Calculate the backwash rate in inches rise/minute and in gpm/ft$^2$.

First, find the inches of rise in the filter during the 2-minute time interval. (The filter area is not needed to find the rise in water level since the measurements are given.)

$$6.4 \text{ ft} - 1.1 \text{ ft} = 5.3 \text{ ft}$$

$$(5.3 \text{ ft})(12 \text{ in/ft}) = 63.6 \text{ inches rise}$$

Next, find the rate of rise in inches per minute used for backwash.

$$\frac{63.6 \text{ in}}{2 \text{ min}} = 31.8 \text{ in rise/ min}$$

Finally, since we have a conversion factor to calculate gpm/ft$^2$ directly from the rise rate, we can easily find the backwash rate expressed in gpm/ft$^2$.

$$\left(\frac{31.8 \text{ in rise/ min}}{1.6}\right) = 19.88 \text{ gpm/ft}^2$$
5.7 Surface Overflow Rate

The faster the water leaves a sedimentation tank, or clarifier, the more turbulence is created and the more suspended solids are carried out with the effluent water. Overflow rate—the speed at which water leaves the sedimentation tank—is controlled by an increase or decrease in flow rate to the tank.

The surface overflow rate is a measurement of the amount of water leaving a sedimentation tank per square foot of tank surface area. The treatment plant operator must be able to determine the surface overflow rate that produces the best-quality effluent leaving the tank. High velocities can and will result in increased suspended solids and turbidity in the effluent water. This is due in part to settled solids being picked up with the high velocity and carried back into the water stream that exits the tank. High horizontal velocities also prevent suspended solids from settling and carry them through the tank with the water flow.

Surface overflow rate is expressed as the gallons per day of flow up and over each square foot of tank surface. Calculations of surface overflow rate are made using the equation below.

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

Notice that the depth of the sedimentation tank is not a consideration in the calculation of surface overflow rate. Figure 5.2 depicts a surface overflow for both rectangular and circular tanks.
Example 5.33

The flow to a treatment plant is 1.2 mgd. If the sedimentation tank is 70 feet long 15 feet wide, and 7 feet deep, what is the surface overflow rate in gpd/ft²?

\[ 1.2 \text{mgd} = 1,200,000 \text{gpd} \] (move decimal right 6 places)

\[
\text{Surface area, ft}^2 = (\text{length})(\text{width}) = (70 \text{ ft})(15 \text{ ft}) = 1,050 \text{ ft}^2
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{1,200,000 \text{gpd}}{1,050 \text{ft}^2} = 1,143 \text{gpd/ft}^2
\]
**Example 5.34**

A circular sedimentation basin with a 55-ft. diameter receives a flow of 2,075,000 gpd. What is the surface overflow rate in gpd/ft²?

\[
\text{Surface area, } ft^2 = 0.785d^2 = 0.785(55 \text{ ft})(55 \text{ ft}) = 2,375 \text{ ft}^2
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{2,075,000 \text{ gpd}}{2,375 \text{ ft}^2} = 873.7 \text{ gpd/ft}^2
\]

In the previous two examples, the surface overflow rate was the unknown factor. However, *any one* of three factors (surface overflow rate, water flow rate, or surface area) might be unknown. If the other two factors are known, the same mathematical setup can be used to solve for the unknown value.

**Example 5.35**

A 20-foot diameter tank has a surface overflow area of 896.4 gpd/ft². What is the daily flow to the tank?

\[
\text{Surface area, } ft^2 = 0.785d^2 = 0.785(20 \text{ ft})(20 \text{ ft}) = 314 \text{ ft}^2
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
896.4 \text{ gpd/ft}^2 = \frac{\text{flow, gpd}}{314 \text{ ft}^2}
\]

\[
(896.4 \text{ gpd/ft}^2)(314 \text{ ft}^2) = \text{flow, gpd} = 281,470 \text{ gpd}
\]
Example 5.36

A sedimentation tank receives a flow of 5.4 mgd. If the surface overflow rate is 689 gpd/ft$^2$, what is the surface area of the sedimentation tank?

Surface overflow rate, gpd/ft$^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}$

$689 \text{ gpd/ft}^2 = \frac{5,400,000 \text{ gpd}}{\text{Tank surface area, ft}^2}$

$\text{Tank surface area, ft}^2 = \frac{5,400,000 \text{ gpd}}{689 \text{ gpd/ft}^2} = 7,837.4 \text{ ft}^2$

5.8 Weir Overflow Rate

The faster the water leaves a sedimentation tank, or clarifier, the more turbulence is created and the more suspended solids are carried out with the effluent water. Overflow rate—the speed at which water leaves the sedimentation tank—is controlled by an increase or decrease in flow rate to the tank.

The **weir overflow rate** is a measurement of the amount of water leaving a sedimentation tank per linear foot of weir length. In simple terms, *weir overflow rate* is an expression indicating the velocity at which water travels upward in the tank to reach the effluent weirs. High velocities can and will result in increased suspended solids and turbidity in the effluent water. This is due to settled solids being picked up with the high velocity and carried back into the water stream that exits the tank.

In most cases, weirs have two equal sides, which double the weir length per running foot of weir. The treatment plant operator must be able to determine the weir overflow rate that produces the best-quality effluent leaving the tank.
Weir overflow is expressed as the gallons per day flow up and over each linear foot of tank weir. Calculations of weir overflow rate are made using the equation given below.

\[
\text{Weir overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{weir length, ft}}
\]

Notice that the depth of the sedimentation tank is not a consideration in the calculation of the weir overflow rate. Figure 5.3 depicts weir overflow for both rectangular and circular tanks.

**FIGURE 5.3 A-Weirs for Rectangular Tank**

**FIGURE 5.3 B-Weir for Circular Tank**
Example 5.37

A rectangular sedimentation tank is 40 feet wide, 100 feet long, and 14 feet deep. The tank has four (4) finger type weirs extending 24 feet into the tank from the effluent wall (see Figure 5.3 A). If the flow to the tank is 2,500 gpm, find the weir overflow rate for sedimentation.

First, find the total weir length remembering that each weir has two sides.

\[ 4 \text{ weirs} \times 24 \text{ feet} \times 2 \text{ sides} = 192 \text{ feet total weir length} \]

Next, convert the flow rate in gpm to gpd. (We will assume the tank is operated 24 hours per day.

\[ (2,500\text{ gpm})(1,440 \text{ min/ day}) = 3,600,000 \text{ gpd} \]

Finally, calculate the weir overflow rate using the equation given.

\[ \text{Weir overflow rate, gpd} / \text{ ft}^2 = \frac{\text{flow, gpd}}{\text{weir length, ft}} \]

\[ \text{Weir overflow rate, gpd} / \text{ ft}^2 = \frac{3,600,000 \text{ gpd}}{192 \text{ ft}} = 18,750 \text{ gpd} / \text{ ft} \]
Example 5.38

Using the same sedimentation tank in Example 5.37 above, assume the effluent wall has three rectangular openings in the wall that serve as the effluent weirs. If each opening is 4 feet wide, calculate the weir overflow rate for the tank.

First, find the total length of weir for the tank.

\[
3 \text{ weirs} \times 4 \text{ feet length} = 12 \text{ feet total weir length}
\]

Next, calculate the weir overflow rate based on the flow rate found in Example 5.37.

\[
\text{Weir overflow rate, gpd/ft} = \frac{3,600,000 \text{ gpd}}{12 \text{ ft}} = 300,000 \text{ gpd/ft}
\]

One should be able to see how the proper weir length becomes necessary for sedimentation. The 300,000 gpd/ft weir overflow rate is more than 15 times greater than typical design standards. This overflow rate likely would produce a very high exit velocity and would result in significant solids carryover from the tank.

Example 5.39

A circular tank with a diameter of 40 feet has a peripheral weir (near the outside wall or around the periphery) placed 2 feet inside the tank wall (see Figure 5.3 B). If the flow rate through the tank is 2,200,000 gpd, find the weir overflow rate for the tank.

First, find the diameter of the peripheral weir. Since it is 2 feet inside the tank wall, we must use two times that dimension to find the weir diameter.

\[
40 \text{ feet} - (2)(2 \text{ feet}) = 36 \text{ feet weir diameter}
\]
Next, find the weir length using the equation for circumference of a circle $C=\pi d$.

$$C = \pi d = (3.14)(36 \text{ ft}) = 113.1 \text{ ft} \quad \text{weir length}$$

Finally, calculate the weir overflow rate using the equation given.

$$\text{Weir overflow rate, gpd/ft} = \frac{2,200,000 \text{ gpd}}{113.1 \text{ ft}} = 19,452 \text{ gpd/ft}$$

**Example 5.40**

A circular clarifier has a diameter of 52 feet. The clarifier has radial launders that each measure 16-inches wide and 19 feet long (see Figure 5.3 C). If the clarifier is treating 2.5 mgd, what is the weir overflow rate?

First, find the total length of weir. (Remember these weirs have 2 sides.)

$$8 \text{ weirs } \times 19 \text{ feet } \times 2 \text{ sides} = 304 \text{ ft} \quad \text{total weir length}$$

Next, calculate the weir overflow rate using the flow rate provided. Remember to convert the flow rate in mgd to gpd.

$$\text{Weir overflow rate, gpd/ft} = \frac{2,500,000 \text{ gpd}}{304 \text{ ft}} = 8,224 \text{ gpd/ft}$$

**5.9 Pressure**

Pressure is the amount of force for a given unit area, usually expressed in pounds per square inch. The concept of pressure was given in Chapter 4.

**Equation**

$$\text{psi} = \text{head, ft.} \times 0.433$$
or

\[ \text{psi} = \frac{\text{head, ft.}}{2.31} \]

**Example 5.41**

The top of a water tower is 60 feet above ground level. You want to fill the tower to a level 55 feet above ground. What pressure will a gauge at ground level read when the water level in the tower is at 55 feet?

\[ \text{psi} = 55 \text{ ft} \times 0.433 = 23.8 \text{ psi} \]

or

\[ \text{psi} = \frac{55 \text{ ft}}{2.31} = 23.8 \text{ psi} \]

The gauge at the base of the tower will indicate 23.8 psi when the water level in the tower is 55 above ground level.

**Example 5.42**

The level of water in a 70 foot water standpipe is unknown. However, a pressure gauge located at the base of the standpipe indicates 27.3 psi. Determine the level of the water in the standpipe.

\[ 27.3 \text{ psi} = (x \text{ ft}) (0.433) \]

\[ \frac{27.3 \text{ psi}}{0.433} = (x \text{ ft}) = 63.05 \text{ ft} \]

or

\[ 27.3 \text{ psi} = \frac{x \text{ ft}}{2.31} \]

\[ (27.3 \text{ psi})(2.31) = x \text{ ft} = 63.05 \text{ ft} \]
The water level in the standpipe is located 63.05 feet above ground level.

### 5.9 Pump Horsepower and Efficiency

Pumps are machines that are used to lift water from one elevation to another elevation and thus deliver water under pressure. Pump horsepower is the energy necessary to lift water the height required and is known as water horsepower. Horsepower calculations are made using the conversion factors and equations given below.

\[
1 \text{ Horsepower} = 746 \text{ watts of power}
\]

\[
1 \text{ Horsepower} = 0.746 \text{ kilowatts of power}
\]

\[
\text{water horsepower (whp)} = \left( \frac{\text{flow, gpm}}{\text{head, ft}} \right) \frac{960}{3,960}
\]

**Example 5.43**

A pump must pump 1,500 gallons per minute against a total head of 30 feet. What water horsepower is required to do the work?

\[
\text{whp} = \frac{(1,500 \text{gpm})(30 \text{ ft})}{3,960} = 11.4
\]

Note: Dividing by 3,960 in the equation is derived by converting gallons per minute to foot pounds per minute and then dividing by 33,000 foot pounds per minute to calculate horsepower. This gives a new conversion factor 3,960.

The previous sample problem does not take into account that a motor, driven by electric current, is required drive a pump to do the work. Neither the pump nor motor are 100 percent efficient due to friction and slippage. Not all the power supplied by the motor to the pump (brake horsepower) is used to lift the water
(water horsepower). Not all electric current driving the motor (motor horsepower) is used to make the pump work.

Pumps usually are between 50% and 85% efficient and electric motors are generally between 80% and 95% efficient. These efficiency ratings are provided in manufacturer’s information. Losses in electric current, couplings, bearings, and friction all contribute to loss of efficiency in pump-motor systems. Therefore, the water horsepower needed to deliver flow must be increased (brake horsepower) to drive the pump, which must be increased (motor horsepower) to compensate for the overall losses in the pump system. This is illustrated in Figure 5.4.

FIGURE 5.4 - Illustration of Pump and Motor Efficiencies

**Pump and Efficiency Equations**

\[
\text{brake horsepower (bhp)} = \frac{(\text{flow, gpm})(\text{head, ft})}{(3,960)(\text{pump eff, %})}
\]

\[
\text{motor horsepower (mhp)} = \frac{(\text{flow, gpm})(\text{head, ft})}{(3,960)(\text{pump eff, %})(\text{motor eff, %})}
\]

\[
\text{pump efficiency, %} = \frac{\text{whp}}{\text{bhp}} \times 100
\]

\[
\text{motor efficiency, %} = \frac{\text{bhp}}{\text{mhp}} \times 100
\]
overall efficiency, % = \( \frac{\text{whp}}{\text{mhp}} \times 100 \)

**Example 5.44**

In the previous sample, a pump must provide 1,500 gallons per minute against a total head of 30 feet. Water horsepower required to deliver the water was calculated to be 11.4 whp. Water horsepower does not take into account pump and motor efficiencies. Suppose that the motor efficiency is 85 percent and the pump efficiency is 90 percent. What would the overall horsepower requirement be?

**Equation**

\[
\text{Overall horsepower} = \left( \frac{\text{whp}}{\text{motor eff, %}} \right) \left( \frac{\text{pump eff, %}}{\text{motor eff, %}} \right)
\]

\[
\text{Overall horsepower} = \frac{11.4\text{whp}}{(0.90)(0.85)} = 14.9\text{hp}
\]

**Example 5.45**

If 11 Kilowatts (kW) of power are supplied to a motor, and the brake horsepower is known to be 13 bhp, what is the efficiency of the motor?

1 Horsepower = 0.746 kilowatts power

1. Convert kilowatts to horsepower.

\[
\text{mhp} = \frac{11\text{kW}}{0.746\text{kW/hp}} = 14.75
\]

2. Calculate the percentage efficiency of the motor.
motor  efficiency, % = \frac{bhp}{mhp} \times 100

\text{motor  efficiency, %} = \frac{13bhp}{14.75mhp} \times 100 = 88.1\%

\textbf{Example 5.46}

\textbf{Pumping Costs}

If the motor horsepower needed for a pumping job is 22 mhp, and the cost for power is $0.08 per kilowatt-hour (kwh), what is the cost of operating the motor for two hours?

1. Convert horsepower to kilowatts.

\( kW = (mhp)(0.746kW/hp) \)

\( kW = (22mhp)(0.746kW/hp) = 16.4kW \)

2. Multiply kilowatts by time.

\( (16.4kW)(2hrs) = 32.8kwh \)

3. Multiply kilowatt-hours by the cost per kwh.

\( (32.8kwh)(\$0.08/kwh) = \$2.62 \)

Total cost for two hours operating time is $2.62.

\textbf{5.11 Pumping Rates}

The rate of flow produced by a pump is expressed as the volume of water pumped during a given period of time. The mathematical equation used for
pumping rate problems can usually be determined from the verbal statement of the problem.

VERBAL: What is the pumping rate in “gallons per minute”?

MATH: \[ X = \text{pumping rate, } \frac{\text{gallons}}{\text{min}} \]

VERBAL: What is the pumping rate in “gallons per hour”?

MATH: \[ X = \text{pumping rate, } \frac{\text{gallons}}{\text{hour}} \]

The number of gallons pumped during a period can be determined either by a flow meter or by measuring the number of gallons pumped into or out of a tank.

**Example 5.47**

The totalizer of the meter on the discharge side of your pump reads in hundreds of gallons. If the totalizer shows a reading of 10800 at 1:00 p.m. and 31200 at 1:30 p.m., what is the pumping rate expressed in gallons per minute?

The problem asks for pumping rate in \( \text{gallons per minute (gpm)} \), so the mathematical setup is as shown below.

\[ \text{pumping rate} = \frac{\text{gallons}}{\text{Minute}} \]

To solve the problem, fill in the blanks (number of gallons and number of minutes) in the equation. The total gallons pumped are determined from the totalizer readings.

\[ 31,200 \text{gal} - 10,800 \text{gal} = 20,400 \text{gal} \]
The volume was pumped between 1:00 p.m. and 1:30 p.m., for a total of 30 minutes. From this information calculate the gpm pumping rate.

\[ \text{pumping rate} = \frac{20,400 \text{ gallons}}{30 \text{ minutes}} = 680 \text{ gpm} \]

Instead of using totalizer readings to calculate the average pumping rate for a period of a few minutes or hours (as in Example 5.47), you can read the instantaneous pumping rate or flow rate - the flow rate or pumping rate at one particular moment - directly from many flow meters. Other flow meters require that you perform calculations to determine the instantaneous flow rate as illustrated in the example that follows.

**Example 5.48**

The venturi meter on the discharge side of your pump has a throat diameter of 4 inches. The head differential between the high-pressure tap and the low-pressure tap is 1.5 ft. Use the nomograph shown in Figure 5.5 to determine the pumping rate in gallons per minute.

To determine the gallon per minute pumping rate, first determine the cubic feet per second pumping rate from the nomograph. Then convert the flow rate to gallons per minute.

Draw a line on the nomograph from 4 inches on the diameter of throat section scale to 1.5 feet on the head differential scale. The point where the line crosses the middle scale indicates the approximate flow rate of 0.85 ft\(^3\)/sec. Now convert the cubic-feet-per-second pumping rate to gallons per minute.
When there is no meter on the discharge side of the pump, you can determine the pumping rate by measuring the number of gallons pumped into or out of a tank during a given time period. Let’s look at three examples of determining total gallons pumped demonstrated by Figure 5.6.
In the first example (Figure 5.6 A), the pump is discharging into an empty tank with the outlet valve to the tank closed. The total gallons pumped during the given time are the number gallons in the tank at the end of the pumping test.

Since it is not always possible or practical to pump into an empty tank, the pumping test is sometimes conducted by pumping into a tank that already contains water (Figure 5.6 B). The outlet valve is closed and the total gallons pumped (shaded area) during the given time is determined from the rise in water level.

In Figure 5.6 C, the pump is located on the outlet side of the tank. To conduct a pumping test, the inlet valve of the tank is shut off. When the pump is turned on, the total gallons pumped (shaded area) during the given time is determined from the drop in water level.
FIGURE 5.6- Determine Pumping Rate Based on Tank Flow
(Crosshatched Area Indicates Volume Pumped)
Example 5.49

During a 15 minute pumping test, 15,820 gallons were pumped into an empty rectangular tank (Figure 5.7). What is the pumping rate in gallons per minute?

The problem asks for the pumping rate in gallons per minute, so the mathematical setup below is used.

\[
pumping \ rate = \frac{gallons}{Minute}
\]

Fill in the information given and perform the calculations to complete the problem.

\[
pumping \ rate = \frac{15,820 \ gallons}{15 \ Minutes} = 1,055 \ gpm
\]
Example 5.50

An empty rectangular tank (Figure 5.8) 8 meters long and 6 meters wide can hold water to a depth of 1.5 meters. If this tank is filled by a pump in 55 minutes, what is the pumping rate in gallons per minute (gpm)?

In this example, the entire tank was filled during the 55-minute pumping test. Therefore the total volume pumped is equal to the capacity of tank in gallons.

\[ Volume = (\text{area})(\text{depth}) \]

\[ Volume = (8\text{meters})(6\text{meters})(1.5\text{meters}) = 72\text{m}^3 \]

Convert this volume to gallons. Assume one cubic meter is 264.2 gallons. This conversion factor is shown below.

\[ \left( \frac{\text{m}^3}{1} \right) \left( \frac{1.000\text{L}}{\text{m}^3} \right) \left( \frac{\text{gal}}{3.785\text{L}} \right) = 264.2\text{gal/m}^3 \]

\[ (72\text{m}^3)(264.2\text{gal/m}^3) = 19,022.4\text{gal} \]

Then use the total volume pumped and the time period of the pumping test (55 minutes) to calculate the pumping rate.

\[ \text{pumping rate} = \frac{\text{gallons}}{\text{Minute}} \]

\[ \text{Example 5.50} \]

FIGURE 5.8 - Schematic for Example 5.50
pumping rate = \frac{19,022.4 \text{ gal}}{55 \text{ min}} = 346 \text{ gpm}

**Example 5.51**

A tank 40 feet in diameter is filled with water to a depth of 3 feet (Figure 5.9). To conduct a pumping test, the outlet valve to the tank is closed and the pump is allowed to discharge into the tank. After 75 minutes the water level rose 5.25 feet. What is the pumping rate in gallons per minute?

![Figure 5.9 - Schematic for Example 5.51](image)

In this problem, the total volume pumped is represented by the cross-hatched area on the diagram (tank diameter = 40 feet and water depth = 2.25 feet).

Calculate the volume pumped in cubic feet.

\[
Volume = 0.785 (d)^2 (\text{depth})
\]

\[
Volume = 0.785 (40 \text{ ft})^2 (2.25 \text{ ft}) = 2,826 \text{ ft}^3
\]

Now convert the cubic foot volume to gallons.

\[
(2,826 \text{ ft}^3) \left(7.48 \text{ gal/ft}^3\right) = 21,138 \text{ gal}
\]
The pumping test was conducted over a period of 75 minutes. Using the volume pumped (in gallons) and the time (in minutes) it took pump the total volume, calculate the pumping rate in gallons per minute.

\[
pumping\ rate = \frac{21,138\ gallons}{75\ Minutes} = 281.8\ gpm
\]

**Example 5.52**

A one (1.0) hour pumping test is run on a pump located on the outlet side of a tank (Figure 5.10). The inlet valve is closed and the pump is started. At the end of the test, the water level in the tank has dropped 1 meter. If the tank water depth before pumping was 2 meters, what is the pumping rate in gallons per minute?

The total volume pumped is represented by the crosshatched area on the Diagram. (Notice that information pertaining to the water depth before pumping is not needed in solving this problem. The drop in the water level is the essential depth information.)

![Diagram](image)

**FIGURE 5.10- Schematic for Example 5.52**

Calculate the total volume pumped in cubic meters and convert to gallons.

\[
Volume = (15m)(9m)(1m) = 135m^3
\]

\[
(135m^3)(264.2\ gal/m^3) = 35,667\ gal
\]
Convert one (1.0) hour to minutes.

\[(1 \text{ hr})(60 \text{ min/hr}) = 60 \text{ min}\]

Now determine the pumping rate.

\[\text{pumping rate} = \frac{35,667 \text{ gal}}{60 \text{ min}} = 594.5 \text{ gpm}\]

Quite often tanks have an influent flow that is different from the effluent flow. Under these operations, a tank can either be filling (increasing water level) or draining (decreasing water level). Typical clear well operations are a good example of such operations. If the plant production rate is more than the high service pumping rate, the clear well level will rise. If the high service flow rate is greater than the plant production rate, the clear well level will fall. The trick to solving these problems is to find the difference in flow rate - either flow into or flow out of the tank - based on the flow rates given. The examples that follow show the calculations needed to solve these types of problems.

**Example 5.53**

A clear well has a water depth of 8 feet at 8:00 am. The clearwell measures 30 feet wide and 55 feet long. The plant is producing water at a rate of 1.2 mgd at the same time a 350 gpm high service pump is moving finished water to the distribution system. Find whether the clearwell level is rising or falling and then find out how long it will take (in hours) for the clearwell level to reach 12 feet.

First, find out the difference in flow rates. This will help you determine if the clearwell level is rising or falling.

\[(1.2 \text{ mgd})(694.4 \text{ gpm/mgd}) = 833 \text{ gpm in}\]

\[833 \text{ gpm} - 350 \text{ gpm} = 483 \text{ gpm excess going in}\]
Based on the calculations, more flow is going into the clearwell than is being pumped out, so the clearwell level is rising.

Next, calculate the volume of water (gallons) being added to the clearwell.

\[
12 \text{ ft} - 8 \text{ ft} = 4 \text{ ft} \quad \text{added}
\]

\[
(4 \text{ ft})(30 \text{ ft})(55 \text{ ft}) = 6,600 \text{ ft}^3 \quad \times \quad 7.48 \text{ gal} / \text{ ft}^3 = 49,368 \quad \text{gallons}
\]

Finally, calculate the detention time needed to raise the clearwell level 4 feet. (The detention time is based on the excess flow into the clearwell.)

\[
\frac{49,368 \text{ gallons}}{483 \text{ gpm}} = \frac{102 \text{ min}}{60 \text{ min/ hr}} = 1.7 \text{ hours}
\]

**Example 5.54**

A treatment plant is producing 500 gpm during its operation. During this time, the clearwell level is found to be 16 feet. A 900 gpm high service pump is operating to pump water to the distribution system. Based on plant experience, the clearwell level cannot go below 3.5 feet of the high service pumps lose suction. If the clearwell diameter is 30 feet, how long can the plant maintain the current operations before the high service pump loses suction?

First, find the difference in pumping rates.

\[
900 \text{ gpm \ out} - 500 \text{ gpm \ in} = 400 \text{ gpm \ excess \ out}
\]
Next find the volume of water (gallons) that can be pumped from the clearwell before it falls to the 3.5 ft level.

\[ 16 \text{ ft} - 3.5 \text{ ft} = 12.5 \text{ ft pumped out} \]

\[ (12.5 \text{ ft})(30 \text{ ft})^2(0.785) = 8.831.25 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 66,058 \text{ gallons} \]

Finally, find the detention time to pump down the clearwell based on the excess flow rate being pumped out.

\[ \frac{66,058 \text{ gallons}}{400 \text{ gpm}} = \frac{165 \text{ min}}{60 \text{ min/hr}} = 2.75 \text{ hours} \]
5.13 Hardness

Sometimes in water chemistry, it is not important to know exactly which impurities a sample of water contains, but merely what combined effect those impurities have. A common example of this is hardness.

Hardness is a measurement of the effects that water impurities such as magnesium and calcium have on corrosion, scaling, and soap consumption. Water from one source might contain a great deal of magnesium and little else; or it might contain a great deal of calcium and little else; or it might contain magnesium, some calcium, and traces of some similarly behaving heavy elements, such as strontium. In each case it would be considered “hard water,” water that has noticeable effects associated with hardness. Furthermore, the laboratory test used to determine hardness would show the same result, whether the hardness was the result of calcium, magnesium, or a combination of elements.

Calcium carbonate (CaCO₃) is one of the more common causes of hardness, and the total hardness of water is usually expressed in terms of CaCO₃. Suppose a lab report read total hardness of 180 mg/L as CaCO₃. This means that the lab has not determined exactly what chemicals are causing the water’s hardness, but that their combined effect is the same as if the water contained exactly 180 mg/L of CaCO₃ and no other chemicals. By expressing the hardness of every sample in terms of how much calcium carbonate it might contain, the hardness of any two samples can be compared more easily.

Measuring hardness in terms of CaCO₃ is so convenient that even when the lab determines exactly what chemicals are in sample, the result may still be expressed as CaCO₃. A water quality lab report could read as follows:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>calcium</td>
<td>125 mg/L as CaCO₃</td>
</tr>
<tr>
<td>total hardness</td>
<td>150 mg/L as CaCO₃</td>
</tr>
<tr>
<td>bicarbonate alkalinity</td>
<td>122 mg/L as CaCO₃</td>
</tr>
<tr>
<td>total alkalinity</td>
<td>130 mg/L as CaCO₃</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>23 mg/L as CaCO₃</td>
</tr>
</tbody>
</table>
In softening and other water treatment operations, you may need to convert hardness expressed in terms of one chemical to hardness expressed in terms of another, usually CaCO$_3$. In calculating problems where hardness is expressed as 100 mg/L of chemical A and you want it expressed as in mg/L of chemical B, you are interested in what weight of chemical B has the same chemical-combining power as 100 mg of chemical A. The question can be solved using equivalent weights. Using the ratio of equivalent weights (EW) between the initial substance (1) and the desired substance (2), the newly expressed concentration can be determined and expressed in the proper terms. The equation for converting concentration using this equivalent weight method is given below.

$$\left( \frac{EW_2}{EW_1} \right) \left( \frac{Concentration\ Q_{1}}{Concentration\ Q_{2}} \right)$$

where EW = equivalent weight

The following examples illustrate the calculations needed.

**Example 5.55**

A water sample contains 136 mg/L of calcium as Ca$^{+2}$ ion. What is the concentration of calcium expressed as CaCO$_3$? For the equivalent weight (EW) of calcium use 20 grams; for the equivalent weight (EW) of CaCO$_3$ use 50 grams.

First find the equivalent weight ratio between calcium and CaCO$_3$.

$$\frac{EW_2}{EW_1} = \frac{50(CaCO_3)}{20(Ca^{+2})} = 2.5$$

Now calculate the concentration expressed as CaCO$_3$ from the concentration as calcium.

$$(2.5)\left(136\text{ mg/L}\right) = \left(340\text{ mg/L as CaCO}_3\right)$$

The calculations just performed demonstrate the meaning and use of “equivalent weights.” In practice, this simple calculation is commonly used to find the
The equivalent concentration of the desired (“new”) measure as compared to the concentration of the given (“old”) measure. Equivalent weights for a number of substances can be found in the literature. Common equivalent weights for substances in softening calculations are given below.

<table>
<thead>
<tr>
<th>Substance</th>
<th>EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium carbonate (CaCO₃)</td>
<td>50</td>
</tr>
<tr>
<td>Calcium ion (Ca²⁺)</td>
<td>20</td>
</tr>
<tr>
<td>Magnesium ion (Mg²⁺)</td>
<td>12.15</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>22</td>
</tr>
<tr>
<td>Bicarbonate alkalinity (HCO₃⁻)</td>
<td>61</td>
</tr>
</tbody>
</table>

**Example 5.56**

A lab report shows a concentration of magnesium at 17 mg/L as Mg²⁺, and a concentration of carbon dioxide (CO₂) at 3 mg/L as CO₂. Express these concentrations in mg/L as CaCO₃. Use 12.15 grams for the equivalent weight of magnesium (Mg²⁺); and use 22 grams for the equivalent weight of carbon dioxide (CO₂). As in the last example, 50 grams is the equivalent weight of CaCO₃.

First find the equivalent weight ratio between magnesium and CaCO₃.

\[
\frac{EW_2}{EW_1} = \frac{50(CaCO_3)}{12.15(Mg^{2+})} = 4.12
\]

Now calculate the concentration expressed as CaCO₃ from the concentration as magnesium.

\[
(4.12)(17mg/L) = \left(\frac{70mg/L}{CaCO_3}\right)
\]

Next find the equivalent weight ratio between CO₂ and CaCO₃.

\[
\frac{EW_2}{EW_1} = \frac{50(CaCO_3)}{22(CO_2)} = 2.27
\]

Now calculate the concentration expressed as CaCO₃ from the concentration as CO₂.
\[(2.27)(3\, \text{mg/L}) = 6.8\, \text{mg/L as CaCO}_3\]

These types of conversions are commonly used in lime softening and lime/soda softening calculations to properly express concentrations in the units needed. Lime softening and lime/soda softening are described in greater detail in advanced water classes.
5.14 Fluoridation Calculations

There are three chemical compounds commonly used in water fluoridation. These chemicals are:

- sodium fluoride, NaF
- sodium fluorosilicate, Na$_2$SiF$_6$ (also sodium silicofluoride)
- fluosilicic acid, H$_2$SiF$_6$ (also hydrofluosilicic acid)

Since each compound is used for its fluoride ion (F$^+$) content, it is important to determine the exact amount of fluoride ion available in a given fluoride compound. This amount depends on two factors:

- the weight of fluoride relative to the total weight of the compound
- the purity of the compound

**Example 5.57**

Find the percentage of fluoride ion contained to sodium fluoride, NaF. Find the molecular weight of sodium fluoride by adding the atomic weights of the individual elements.

\[
\text{Weight of Na} = 23 \text{ grams} \\
\text{Weight of F} = 19 \text{ grams} \\
\text{Weight of NaF} = 42 \text{ grams}
\]

Then divide the weight of the fluoride ion by the total molecular weight of the compound and multiply by 100, as follows:

\[
\frac{19g}{42g} F^+(100) = 45.2\% F^+ \text{in NaF}
\]
**Example 5.58**

The commercial strength of the sodium fluoride in Example 5.57 is between 95 and 98 percent. That is, each 100 pound bag of chemical compound delivered to the plant contains 95 pounds to 98 pounds of sodium fluoride and 2 pounds to 5 pounds of impurities. How much fluoride ion is contained in each 100 pound bag of commercial sodium fluoride?

From Example 5.57 you know that if it contained pure sodium fluoride, each 100 pound bag would have 45 percent or \((0.45)(100 \text{ lbs}) = 45 \text{ lbs}\) fluoride ion. However, the bags contain slightly impure NaF. Therefore, each bag holds only 95 percent to 98 percent of what it would if the NaF were 100 percent pure. The amount of fluoride ion in 100 pounds of NaF is \((45 \text{ lbs})(0.95) = 42.75 \text{ lbs} \text{ of } F^+\) (43%) to \((45 \text{ lbs})(0.98) = 44.1 \text{ lbs} \text{ of } F^+\) (44%).

**Example 5.59**

Find the percentage of fluoride ion contained sodium fluorosilicate \((Na_2SiF_6)\). Find the molecular weight of sodium fluorosilicate by adding the atomic weights of the individual elements as follows:

<table>
<thead>
<tr>
<th>Atoms</th>
<th>Total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of Na</td>
<td>23 grams 2</td>
</tr>
<tr>
<td>Weight of Si</td>
<td>28 grams 1</td>
</tr>
<tr>
<td>Weight of F</td>
<td>19 grams 6</td>
</tr>
<tr>
<td>Weight of (Na_2SiF_6)</td>
<td>42 grams</td>
</tr>
</tbody>
</table>

Then divide the total weight of the fluoride ion by the molecular weight of the compound and multiply by 100.

\[
\frac{114 \text{ g}}{188 \text{ g}} \frac{F^+}{(100)} = 60.6\% F^+ \text{ in } Na_2SiF_6
\]

\[
\frac{114 \text{ g}}{188 \text{ g}} \frac{NaF}{NaF}
\]
Example 5.60

The commercial strength of the sodium fluorosilicate in Example 5.59 is normally 98.5 percent. That is, each 100 pound bag contains 98.5 pounds of the compound and 1.5 pounds of impurities. How much fluoride ion does each 100 pound bag contain?

From Example 5.59, you know that if it contained pure sodium silicofluoride, each bag would hold 60.6 percent, or 60.6 lbs of fluoride ion. However, the bags contain slightly impure Na₂SiF₆, with only 98.5 percent of the weight of each bag being pure material. The amount of fluoride ion in 100 pounds of Na₂SiF₆ is (60.6 lbs)(0.985) = 59.69 lbs of F⁺ (59.7%).

Example 5.61

Find the percentage of fluoride ion contained in hydrofluosilicic acid, H₂SiF₆. Find the molecular composition of hydrofluosilicic acid by adding the atomic weights of the individual elements.

<table>
<thead>
<tr>
<th></th>
<th>Atoms</th>
<th>Total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of H</td>
<td>1 gram</td>
<td>2</td>
</tr>
<tr>
<td>Weight of Si</td>
<td>28 grams</td>
<td>1</td>
</tr>
<tr>
<td>Weight of F</td>
<td>19 grams</td>
<td>6</td>
</tr>
<tr>
<td>Weight of Na₂SiF₆</td>
<td>42 grams</td>
<td>144 g</td>
</tr>
</tbody>
</table>

Then divide the total weight of the fluoride ion by the molecular weight of the compound and multiply by 100.

$$\frac{114 \text{ g} \cdot F^+}{144 \text{ g} \cdot NaF} (100) = 79.2\% \text{ in } NaF$$
Example 5.62

The commercial strength of the hydrofluosilicic acid in Example 5.61 is quite variable, ranging from 20 percent to 35 percent pure. That is, each pound of commercial acid contains 0.2 pounds to 0.35 pounds of pure acid. The remainder of the liquid, 0.65 pounds to 0.8 pounds consists of impurities and water. The density of the commercial acid is about 10.56 lbs/gal. How much fluoride ion is contained in each gallon of acid?

From Example 5.61, you know that if the hydrofluosilicic acid were 100 percent pure, each pound would contain 79.2 percent, or 0.792 pounds of fluoride ion. However, commercial hydrofluosilicic acid is very dilute, containing about 23 percent pure acid. To determine the weight of fluoride ion contained in 1 pound of commercial (dilute) acid, multiply the percentage of pure acid by the chemical purity of the commercial acid.

The weight of fluoride ion in 1 pound of commercial acid is about 18.22 percent.

\[
(0.792)(0.23) = 0.1822 \text{ or } 18.22\% \ F^+
\]

Remember that the acid has a density of 10.56 lbs/gal. Each pound of acid contains about 0.182 pounds of fluoride ion. Therefore, 1 gallon of acid contains 10.56 times that amount, or \((10.5)(0.16) = 1.68\) pounds of fluoride ion.

Example 5.63

A water treatment plant fluoridates by direct addition of commercial hydrofluosilicic acid. The strength of the acid is 25 percent and the density is 10.56 lbs/gal. The treated water flow rate is 1 mgd. What is the fluoride ion dosage needed in order to provide 1 mg/L fluoride ion to the water?

Example 5.61 showed the fluoride ion content of pure hydrofluosilicic acid to be 79.2 percent.
To adjust for the dilution, multiply the ion content by the strength of the commercial acid, as in Example 5.62.

\[(0.792)(0.25) = 0.198 \text{ or } 19.8\% \text{ F}^+\]

Each pound of commercial acid contains 0.198 pounds of fluoride ion. The acid density is 10.56 lbs/gal. Therefore, find the weight of fluoride ion per gallon of commercial acid as follows:

\[
\left( \frac{0.197\text{lbs}}{1\text{lb acid}} \right) \left( \frac{10.56\text{lbs/gal}}{1\text{lb}} \right) = 2.08\text{lbs/gal}
\]

For each gallon of commercial acid added to the water, 2.08 pounds of fluoride ion are added.

If the desired fluoride dosage is 1 mg/L, this is equivalent to:

\[(1\text{mg/L})(8.34)(1\text{mgd}) = 8.34\text{lbs/MG}\]

Since the flow rate is 1 mgd, the weight of pure fluoride ion needed is 8.34 lb/day. The number of gallons of commercial acid needed to achieve this dosage is found below.

\[
\frac{8.34\text{lbs/day}}{2.08\text{lbs/gal F}^+} = 4.01\text{gpd acid}
\]

**Example 5.64**

How many pounds of NaF are required to fluoridate 1 mgd to a level of 1 mg/L? The NaF used is 95 percent pure.

The fluoride ion content of 95 percent pure NaF is 42.75 percent (see Example 5.57). Since the flow rate is 1 mgd, the desired dosage of 1 mg/L is equivalent to 8.34 lbs/MG or 8.34 lbs/day. To solve the problem, determine the amount of NaF
needed to achieve an 8.34 lb/day dosage of fluoride ion. Note that only 42.75 percent of each pound of NaF is fluoride ion. To get 8.34 pounds of F\(^+\) will require the addition of a little more than 16 pounds of NaF.

\[
(42.75\%) \left( \frac{lbs}{day} \cdot 95\% NaF \right) = 8.34 lbs / day \ F^+
\]

\[
(0.4275) \left( \frac{lbs}{day} \cdot 95\% NaF \right) = 8.34 lbs / day \ F^+
\]

\[
\left( \frac{lbs}{day} \cdot 95\% NaF \right) = \frac{8.34 lbs / day}{0.4275} = 19.5 lbs / day \ NaF
\]

**Example 5.65**

An important feature of NaF is its relatively constant solubility. The strength of a NaF solution is consistently 4 percent by weight within the range of temperatures common in water treatment (0\(^\circ\)C to 25\(^\circ\)C). How much solution would have to be added each day to that meet a dosage requirement of 19.4 lbs/day? What would this dosage requirement be in milliliters per minute (mL/min)?

You know that the desired dosage is 19.4 lbs/day as NaF. Because sodium fluoride solution has relatively constant strength, you can find the amount of solution added using the equation below.

\[
(4\%) \left( \text{solution added} \right) = 19.4 lbs / day
\]

\[
(0.04) \left( \text{solution added} \right) = 19.4 lbs / day
\]

\[
\left( \text{solution added} \right) = \frac{19.4 lbs / day}{0.04} = 485 lbs / day
\]
The density of a four percent (4%) NaF solution is about 1.03 g/mL. Find the dosage of NaF needed in mL/sec using this information.

\[
\left( \frac{485\text{lbs}}{\text{day}} \right) \left( \frac{453.6\text{g}}{\text{lb}} \right) \left( \frac{\text{mL}}{1.03\text{g}} \right) \left( \frac{\text{day}}{1,440\text{min}} \right) = 148.3\text{mL/min}
\]

**Example 5.66**

A shipment of 98.5 percent pure sodium fluorosilicate has an average fluoride content of 59.7 percent (see Example 5.59). How many pounds of Na$_2$SiF$_6$ should be added daily to treat 1 mgd to a fluoride ion level of 1 mg/L? Follow the same type of procedure shown in Example 5.64.

\[
(59.7\%) \left( \frac{\text{lbs}}{\text{day}} \right) \left( 98.5\% \text{Na}_2\text{SiF}_6 \right) = 8.34 \text{lbs/day} \quad F^+
\]

\[
(0.597) \left( \frac{\text{lbs}}{\text{day}} \right) \left( 98.5\% \text{Na}_2\text{SiF}_6 \right) = 8.34 \text{lbs/day} \quad F^+
\]

\[
\left( \frac{\text{lbs}}{\text{day}} \right) \left( 98.5\% \text{Na}_2\text{SiF}_6 \right) = \frac{8.34 \text{lbs/day}}{0.597} = 13.97 \text{lbs/day} \quad \text{Na}_2\text{SiF}_6
\]

**Example 5.67**

The Na$_2$SiF$_6$ from Example 5.66 is mixed with water to make a solution of 0.5 percent by weight. How much solution (in gpm) must be added daily to treat 1 mgd to a fluoride ion level of 1 mg/L? Follow the same type of procedure described in Example 5.65.

\[
(0.5\%) \left( \frac{\text{solution added}}{} \right) = 13.97 \text{lbs/day}
\]

\[
(0.005) \left( \frac{\text{solution added}}{} \right) = 13.97 \text{lbs/day}
\]

\[
\left( \frac{\text{solution added}}{} \right) = \frac{13.97/\text{day}}{0.005} = 2,794 \text{lbs/day}
\]
Such a weak solution would be about the same density as water, 8.34 lbs/gal. The feed rate of the 0.5 percent solution in gallons per day can be found as follows:

\[
\frac{2.794 \text{ lbs/day}}{8.34 \text{ lbs/gal}} = \frac{335 \text{ gal/day}}{1440 \text{ min/day}} = 0.23 \text{ gpm}
\]

**Example 5.68**

The natural fluoride ion concentration of a water supply is 0.2 mg/L. How many pounds of sodium fluorosilicate must be used each day to treat 502,000 gpd of water to a level of 1 mg/L? (\(\text{Na}_2\text{SiF}_6\) is typically 98.5 percent pure.)

Raising the fluoride level from 0.2 mg/L to 1 mg/L requires increasing the fluoride ion concentration by 0.8 mg/L. Determine feed rate in pounds per day.

\[
\text{feed rate } F^+, \text{ lbs/day} = (\text{dose}) (\text{flow rate}) (8.34)
\]

\[
\text{feed rate } F^+, \text{ lbs/day} = (0.8 \text{mg/L}) (0.502 \text{mgd}) (8.34) = 3.35 \text{ lbs/day}
\]

So 3.35 pounds of 100 percent pure fluoride ion should be added every day. Commercial grade \(\text{Na}_2\text{SiF}_6\) contains only 59.7 percent pure fluoride ion that must be added and the chemical purity is 98.5 percent. Compute the proper dosage as shown below.

\[
(59.7\%) \left( \frac{\text{lbs/day}}{100\%} \right) F^+ = 3.35 \text{ lbs/day } F^+
\]

\[
(0.597 \left( \frac{\text{lbs/day}}{100\%} \right) F^+ = 3.35 \text{ lbs/day } F^+
\]

\[
\left( \frac{\text{lbs/day}}{100\%} \right) F^+ = \frac{3.35 \text{ lbs/day}}{0.597} F^+ = 5.6 \text{ lbs/day } \text{Na}_2\text{SiF}_6
\]
\[
\left(98.5\%\right)\left(\text{lbs/day Na}_2\text{SiF}_6\right) = 5.6\text{lbs/day Na}_2\text{SiF}_6
\]

\[
\left(0.985\right)\left(\text{lbs/day Na}_2\text{SiF}_6\right) = 5.6\text{lbs/day Na}_2\text{SiF}_6
\]

\[
\left(\text{lbs/day Na}_2\text{SiF}_6\right) = \frac{5.6\text{lbs/day}}{0.985} = 5.7\text{lbs/day Na}_2\text{SiF}_6
\]

**Example 5.69**

How many gallons of water are required to dissolve 5.57 lb of \(\text{Na}_2\text{SiF}_6\), at a temperature of 15.6\(^\circ\)C? The solubility of \(\text{Na}_2\text{SiF}_6\) is 0.62 g/100 mL at 15.6\(^\circ\)C.

First convert to English units of measure.

\[
\left(\frac{0.62\text{g}}{100\text{mL}}\right)\left(\frac{3.785\text{mL}}{\text{gal}}\right)\left(\frac{\text{lb}}{453.6\text{g}}\right) = 0.052\text{lbs/gal}
\]

This means that each gallon of water dissolves 0.052 pounds of \(\text{Na}_2\text{SiF}_6\). Therefore, to determine how many gallons are required to dissolve 5.57 pounds of \(\text{Na}_2\text{SiF}_6\), you know how many units of 0.052 pounds there are in 5.57 pounds. Stated mathematically, this is expressed below.

\[
dilution \text{ water} = \frac{5.57\text{lbs}}{0.052\text{lbs/gal}} = 107.1\text{gal}
\]

**Example 5.70**

At what rate should the chemical metering pump be set to pump the fluoride solution of Example 5.69 into the water system? The treatment plant flow is constant at a rate of 0.5 mgd. Give the answer in gallons per hour (gph).
Since the 107.1 gallon supply of fluoride solution is one day’s supply, and since the plant flow rate is constant, the fluoride solution must be added uniformly throughout the 24-hour period.

\[
\text{Solution feed setting} = \frac{107.1 \text{gal}}{24 \text{hrs}} = 4.46 \text{gph}
\]

**Example 5.71**

The natural fluoride concentration of the source water is found to be 0.35 mg/L. It is desired to produce finished water with a fluoride content of 1.0 mg/L. The plant is pumping at a rate of 1,200 gpm and uses 23\% liquid hydrofluorosilicic acid (H\textsubscript{2}SiF\textsubscript{6}) for fluoride adjustment. If the liquid fluoride weighs 10.56 pounds per gallons, how many gallons per day of H\textsubscript{2}SiF\textsubscript{6} are needed for treatment?

Example 5.61 showed the fluoride ion content of pure H\textsubscript{2}SiF\textsubscript{6} acid to be 79.2 percent. To adjust for the 23\% liquid fluoride, multiply the ion content by the strength of the commercial liquid fluoride. Then calculate the fluoride dose requested.

\[
(0.792)(0.23) = 0.1822 \quad \text{or} \quad 18.22\% \quad F^-
\]

\[
1 \quad \text{mg/L} - 0.35 \text{mg/L} = 0.65 \text{mg/L} \quad \text{added}
\]

\[
\frac{1,200 \text{gpm}}{694.4 \text{gpm/mgd}} = 1.728 \text{mgd}
\]

\[
(0.65 \text{mg/L})(8.34)(1.728 \text{mgd}) = \frac{9.37 \text{lbs/day}}{0.1822} = 51.4 \text{lbs} \quad H_2SiF_6 / \text{day}
\]

\[
\frac{51.4 \text{lbs}}{10.56 \text{lbs/gal}} = 4.9 \text{gpd} \quad H_2SiF_6
\]
Example 5.72

A lime softening plant is adding sodium silicofluoride \( \text{Na}_2\text{SiF}_6 \) for fluoride adjustment. Lime softening removes 0.2 mg/L of fluoride ion during treatment. The plant produces 0.9 mgd and adds fluoride downstream of the filters after softening. If the raw water fluoride concentration is 0.5 mg/L, how many pounds per day of \( \text{Na}_2\text{SiF}_6 \) are needed for fluoridation? Assume the fluoride compound is 98.5 percent pure.

In Example 5.59, we found that \( \text{Na}_2\text{SiF}_6 \) contains 60.6 percent fluoride ion. Multiplying the percent fluoride in by the chemical purity gives the amount of fluoride ion in the compound. Then find the fluoride dose requested.

\[
(0.606)(0.985) = 0.5969 \quad \text{or} \quad 59.69\% \quad F^-
\]

\[
1 \quad \text{mg} / L - 0.5 \quad \text{mg} / L + 0.2 \quad \text{mg} / L \quad \text{lost} = 0.7 \quad \text{mg} / L \quad \text{added}
\]

\[
(0.7 \quad \text{mg} / L)(8.34)(0.9 \quad \text{mgd}) = \frac{5.25 \quad \text{lbs} / \text{day}}{0.5969} = 8.8 \quad \text{lbs} \quad \text{Na}_2\text{SiF}_6 / \text{day}
\]

Example 5.73

Assume that the liquid fluoride in Example 5.71 is fed using a chemical metering pump. How many milliliters per minute (mL/min) of liquid fluoride must be fed to adjust the fluoride ion content as calculated? (Assume the plant operates 16 hours per day.)

\[
\frac{4.9 \quad \text{gpd}}{16 \quad \text{hrs} / \text{day}} = 0.3063 \quad \text{gph}
\]

\[
\left( \frac{0.3063 \quad \text{gph}}{60 \quad \text{min} / \text{hr}} \right) = (0.005105 \quad \text{gpm})(3.785 \quad \text{ml} / \text{gal}) = 19.32 \quad \text{mL} / \text{min}
\]
Example 5.74

A chemical metering pump is used for fluoride application in Example 5.73. If the metering pump has a maximum feed capacity of 0.65 gph and is operating at 75 percent stroke, at what speed should the metering pump be set?

First understand that the basic equation for metering pump output or feed rate.

\[
Output, \ gph = (capacity, \ gph)\times (%stroke)\times (%speed)
\]

Next, rearrange the equation to solve for % speed as shown.

\[
\frac{Output, \ gph}{(capacity, \ gph)\times (%stroke)} = (%speed)
\]

Finally, place the known information in the equation and solve for % speed.

\[
\frac{0.3063 \ gph}{(0.65 \ gph)\times (0.75)} = (%speed) = 0.628 \ or \ 63\%
\]

Example 5.75

It is found that 6.5 gallons per day (gpd) of $\text{H}_2\text{SiF}_6$ are needed for fluoridation during treatment. The fluoride metering pump has a maximum feed capacity of 0.55 gallons per hour (gph). The operator sets the pump speed initially at 60 percent. Based on the fluoride feed needed, what stroke setting set the operator use for the metering pump? (Assume the plant is operating 24 hours per day.)
Start again with the feed pump equation and rearrange it to solve for %stroke as shown. Then place the information into the equation and solve for % stroke.

\[
\text{Output, gph} = \left( \frac{\text{capacity, gph} \times \text{% stroke} \times \text{% speed}}{\text{Output}} \right)
\]

\[
\frac{\text{Output, gph}}{\left( \frac{\text{capacity, gph} \times \text{% speed}}{\text{Output}} \right)} = \text{% stroke}
\]

\[
\frac{6.5 \text{gpd}}{24 \text{hr/day}} = 0.271 \text{gph}
\]

\[
\frac{0.271 \text{gph}}{(0.55 \text{gph})(0.60)} = \text{% stroke} = 0.821 \text{ or } 82\% \text{ stroke}
\]
5.15 Lime-Soda Ash Softening Calculations

Two basic methods for calculating lime and soda ash dosages are:
- the conventional method
- the conversion-factor method

The conventional method, although much longer, is helpful in understanding the chemical and mathematical relationships involved in softening. The conversion-factor method is simpler and quicker and is the more practical method to use in day-to-day operations.

In both methods of calculation, the lime and soda ash dosages required are dependent on the carbonate and noncarbonate constituents in the water. Although hard water will always require lime, it may not always need soda ash. Lime is used to remove carbonate hardness, and both lime and soda ash are needed to remove noncarbonate hardness.

To determine whether lime only or both lime and soda ash are needed, the total hardness of the water must be compared with the total alkalinity. In some areas of the United States, the only alkalinity occurring naturally in water is bicarbonate alkalinity. In these areas, many labs report only the bicarbonate alkalinity concentration or only the total alkalinity concentration, assuming that the operator will be aware that, for the water tested, total alkalinity = bicarbonate alkalinity. However, to be certain of the characteristics of the water tested, an operator should request a detailed lab report showing the total alkalinity as well as the bicarbonate, carbonate, and hydroxide alkalinities.

Table 5.5 shows how to determine the levels of carbonate and noncarbonate hardness based on the laboratory results for total hardness (TH) and total alkalinity (TA). Noncarbonate hardness (NCH) is simply the difference between the total hardness and the total alkalinity.

\[ TH - TA = NCH \]
TABLE 5.5 - Noncarbonate and Carbonate Hardness Based on Total Hardness and Total Alkalinity

<table>
<thead>
<tr>
<th>Laboratory Results</th>
<th>Noncarbonate Hardness</th>
<th>Carbonate Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH less than TA</td>
<td>0</td>
<td>TH</td>
</tr>
<tr>
<td>TH = TA</td>
<td>0</td>
<td>TH</td>
</tr>
<tr>
<td>TH greater than TA</td>
<td>TH - TA</td>
<td>TA</td>
</tr>
</tbody>
</table>

A total hardness less than or equal to total alkalinity indicates two important facts about lime and soda ash dosages. These important facts are:

- The noncarbonate concentration is zero, so only lime treatment will be required.
- The amount of lime normally added to treat magnesium noncarbonate hardness (for example, magnesium chloride, MgCl₂) is not required.

The chemical equation that follows is used to determine lime dosage requirements when TH is less than or equal to TA.

\[
\text{Lime dose} = [CO_2] + [TA] + [Mg] + \left[\text{Excess OH}\right] 
\]  

The brackets\([\ ]\) in the equation mean “the concentration.” Therefore, when total hardness is less than or equal to total alkalinity, the lime dosage equals the sum of the concentrations of carbon dioxide, total hardness, and magnesium, plus any excess lime (OH alkalinity) desired.

In most operating situations, more lime will be needed than is indicated by the chemical equations. This additional amount, called “excess lime” is added either to speed to the reactions or to force them to react more completely. It is common practice to add between 10 mg/L to 50 mg/L of excess lime (as CaCO₃). An equivalent amount of excess soda ash (Na₂CO₃) must also be added with the lime in order to remove the excess calcium ions added with the lime. To remove 1 mg/L of excess lime requires 1.06 mg/L of soda ash.
When total hardness is greater than total alkalinity, carbonate and noncarbonate hardness constituents are present in the water. This means that both lime and soda ash will be needed in treating for hardness. Lime is used to remove carbonate hardness constituents and both lime and soda ash are used to remove noncarbonate hardness constituents in the water. The chemical equations shown below are used to determine lime and soda ash dosage requirements.

\[
\text{Lime dose} = [CO_2] + [HCO_3^-] + [Mg] + \left[\text{Excess OH}\right] \quad (C-2)
\]

\[
\text{Soda ash dose} = [TH] - [HCO_3^-] + [\text{Excess}] \quad (C-3)
\]

The lime dosage equals the sum of the concentrations of carbon dioxide, bicarbonate alkalinity, and magnesium, plus any excess lime desired. The soda ash dosage is equal to the total hardness, minus the bicarbonate alkalinity, plus any excess soda ash desired. Note that when the bicarbonate alkalinity (HCO\textsubscript{3}) is equal to the total alkalinity (TA), Equation C-3 can be written.

\[
\text{Soda ash dose} = [TH] - [TA] + [\text{Excess}] \quad (C-4)
\]

And, as shown in Table 5.5, when the total hardness (TH) is greater than the total alkalinity, TH - TA = noncarbonate hardness (NCH). Under these conditions, Equation C-4 can be written.

\[
\text{Soda ash dose} = [NCH] + [\text{Excess}] \quad (C-5)
\]

The two ions that most commonly cause hardness in water are calcium (Ca\textsuperscript{+2}) and magnesium (Mg\textsuperscript{+2}). Although aluminum, strontium, iron, manganese, barium, and zinc ions can also cause hardness, they are not usually present in large enough concentrations to cause a significant increase in hardness. Consequently it is usually assumed without much sacrifice in accuracy, that:

\[
[\text{Total hardness}] = [\text{Ca}] + [\text{Mg}] \quad (C-6)
\]
When only calcium and magnesium are measured in the laboratory, the total hardness can be found from Equation C-6. When the laboratory measures both total hardness and calcium, Equation C-6 can be used to determine the magnesium concentration.

In some cases, total hardness, calcium, and magnesium are all measured in the laboratory. When this occurs, total hardness should be used for Equation C-3 and Equation C-4, instead of the sum of calcium and magnesium, because hardness includes the effects of all hardness-causing ions.

Equations C-1 through C-6 are the basis for determining lime and soda ash dosages through either the conventional or the conversion-factor method. Before these equations can be used, the concentrations of CO₂, total hardness, magnesium, bicarbonate alkalinity (HCO₃⁻), and excess lime must be expressed in “mg/L as CaCO₃”. Usually when a laboratory test is made for CO₂, the results are reported in “mg/L as CO₂”. Similarly, a magnesium concentration would be reported in “mg/L as Mg,” and a bicarbonate alkalinity would either be reported in “mg/L as HCO₃⁻” or in “mg/L as CaCO₃”.

Since these concentrations are not all expressed in the same units of measure, they cannot be added together. However, each concentration can be converted to “mg/L as CaCO₃” (the units commonly used to express hardness). After all laboratory results are converted to these units, they can be used in Equation C-1 through Equation C-6.

The conventional and conversion-factor methods are based on the theory that all reactions occur in definite proportions to the compounds involved. More specifically, the reactions occur in definite proportion to the equivalent weight of the reacting ions or compounds. The difference between the two methods is that, in the conversion-factor method, some of the conversion calculations (such as conversion from “mg/L as HCO₃⁻” to “mg/L as CaCO₃”) are shortened by using conversion factors for the part of the calculation that has been completed.
5.14.1 Conventional Method

Given the total hardness, calcium, magnesium, bicarbonate alkalinity, total alkalinity, and free carbon dioxide concentrations from laboratory test results; the conventional method uses equivalent weights to convert all hardness data to milligrams per liter as CaCO$_3$. Then the CaCO$_3$ concentrations are used to calculate the quantity of lime and soda ash needed. This consists of six steps, which are summarized below and explained in detail in the examples that follow.

**Step 1:** Convert all data to concentrations CaCO$_3$, using the following equivalent weights:

\[
\begin{align*}
Ca^{+2} &= 20 \\
Mg^{+2} &= 12.15 \\
HCO_3^- &= 61 \\
CO_2 &= 22 \\
CaCO_3 &= 50
\end{align*}
\]

Example:

\[
5\text{mg/L as CO}_2 = (5\text{mg/L})\left(\frac{50}{22}\right) = 11.35\text{mg/L as CaCO}_3
\]

**Step 2:** Determine whether lime only or both lime and soda ash will be required in treating the hardness constituents (Use Table 5.1).

**Step 3:** Calculate the lime dosage or lime and soda ash dosage (in mg/L as CaCO$_3$). When total hardness is less than or equal to total alkalinity, use Equation C-1.

When total hardness is greater than total alkalinity, use Equation C-2 and Equation C-3.

\[
\text{Lime dose} = [CO_2] + [HCO_3^-] + [Mg] + \left[\text{Excess } OH\right] \tag{C-2}
\]
If noncarbonate hardness is given, Equation C-5 can be used for the soda ash dosage.

\[ \text{Soda ash dose} = [NCH] + [Excess] \] \hspace{1cm} (C-5)

**Step 4:** Convert lime and soda ash dosage expressed as CaCO\(_3\) to dosages expressed as CaO and as Na\(_2\)CO\(_3\), respectively, using the following equivalent weights:

\[ \begin{align*} 
\text{CaCO}_3 &= 50 \\
\text{CaO} &= 28 \\
\text{Na}_2\text{CO}_3 &= 53
\end{align*} \]

Example:

\[ 227\text{mg/L Lime as CaCO}_3 = (227\text{mg/L})(\frac{28}{50}) = 127\text{mg/L as CaO} \]

**Step 5:** Adjust dosages for the purity of the lime or soda ash used. If lime is 90 percent pure, the calculation below is used.

\[ \frac{127\text{mg/L}}{0.90} = 141\text{mg/L} \]
Step 6: Convert these adjusted dosages to pounds per million gallons or pounds per day.

\[(mg/L)(8.34) = lbs/ MG\]

\[(mg/L)(8.34)(mgd) = lbs/ day\]

The examples that follow illustrate softening calculations using the conventional method.

**Example 5.76**

The laboratory returned the test results below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>100 mg/L as Ca(^{+2})</td>
</tr>
<tr>
<td>Total hardness</td>
<td>300 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>250 mg/L as HCO(_3^-)</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>205 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Carbon dioxide (CO(_2))</td>
<td>25 mg/L as CO(_2)</td>
</tr>
</tbody>
</table>

Using the equivalent weight procedure, you can make the conversions as follows:

\[
\left(100 \text{ mg/L as Ca}\right)\left(\frac{50}{20}\right) = 250 \text{ mg/L as CaCO}_3
\]

\[
\left(250 \text{ mg/L as HCO}_3^-\right)\left(\frac{50}{61}\right) = 205 \text{ mg/L as CaCO}_3
\]

\[
\left(25 \text{ mg/L as CO}_2\right)\left(\frac{50}{22}\right) = 56.8 \text{ mg/L as CaCO}_3
\]

Note: No conversions are needed for total alkalinity and total hardness since the lab results are expressed as CaCO\(_3\).
**Example 5.77**

The laboratory returned the following test results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>45 mg/L as Mg(^{2+})</td>
</tr>
<tr>
<td>Total hardness</td>
<td>280 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>245 mg/L as HCO(_3^-)</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>202 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Carbon dioxide (CO(_2))</td>
<td>20 mg/L as CO(_2)</td>
</tr>
</tbody>
</table>

(a) Express each concentration as CaCO\(_3\).

(b) According to step 2 in the softening calculations (and Table 5.1), will lime only or lime and soda ash be required in treating the hardness constituents?

(c) Using the equivalent weight procedure, as in Example 5.73, make the conversions as follows:

\[
\left(45 \text{mg/L as Mg}\right)\left(\frac{50}{12.15}\right) = 185 \text{mg/L as CaCO}_3
\]

\[
\left(245 \text{mg/L as HCO}_3^-\right)\left(\frac{50}{61}\right) = 201 \text{mg/L as CaCO}_3
\]

\[
\left(20 \text{mg/L as CO}_2\right)\left(\frac{50}{22}\right) = 45.4 \text{mg/L as CaCO}_3
\]

Note: No conversions are needed for total alkalinity and total hardness since the lab results are expressed as CaCO\(_3\).

(d) In the example, total hardness (280 mg/L as CaCO\(_3\)) is greater than total alkalinity (202 mg/L as CaCO\(_3\)). As shown in Table 5.1, the water will have both noncarbonate and carbonate hardness constituents and will and will therefore require both lime and soda ash treatment.
Example 5.78

The laboratory test results for a water sample were as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>32 mg/L as Mg$^{2+}$</td>
</tr>
<tr>
<td>Total hardness</td>
<td>345 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>156 mg/L as HCO$_3^-$</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>128 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Carbon dioxide (CO$_2$)</td>
<td>5 mg/L as CO$_2$</td>
</tr>
</tbody>
</table>

(a) Determine whether lime alone or lime and soda ash will be required in treating the hardness constituents.

(b) Calculate the lime dosage or lime and soda ash dosages in mg/L as CaCO$_3$.
   (Assume no excess lime or soda ash is to be added.)

(c) The total hardness (345 mg/L as CaCO$_3$) is great than the total alkalinity (128 mg/L as CaCO$_3$). Therefore, according to Table 5.1, water will have both carbonate and noncarbonate hardness constituents and will require both lime and soda ash treatment.

(d) Before calculating the lime and soda ash dosages, express all concentrations in terms of CaCO$_3$.

\[
\left\{32\text{mg/L as Mg} \cdot \left(\frac{50}{12.15}\right)\right\} = 132\text{mg/L as CaCO}_3
\]

\[
\left\{156\text{mg/L as HCO}_3^- \cdot \left(\frac{50}{61}\right)\right\} = 128\text{mg/L as CaCO}_3
\]

\[
\left\{5\text{mg/L as CO}_2 \cdot \left(\frac{50}{22}\right)\right\} = 11.4\text{mg/L as CaCO}_3
\]

Note: No conversions are needed for total alkalinity and total hardness since the lab results are expressed as CaCO$_3$. 

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Now use the dosage equations shown in step 3.

\[
\text{Lime dose} = [CO_2] + [HCO_3^-] + [Mg] +\left[\text{Excess } OH\right] \\
\text{(C-2)}
\]

\[
\text{Soda ash dose} = [TH] - [HCO_3^-] + [\text{Excess}] \\
\text{(C-3)}
\]

\[
\text{Lime dose} = [11.4 \text{mg/L}] + [128 \text{mg/L}] + [133 \text{mg/L}] + [0 \text{mg/L}] = 272.4 \text{mg/L as CaCO}_3
\]

\[
\text{Soda ash dose} = [345 \text{mg/L}] - [128 \text{mg/L}] + [0 \text{mg/L}] = 217 \text{mg/L as CaCO}_3
\]

If instead of magnesium ion concentrations, a calcium ion concentration is given in the test results, then the magnesium ion concentration can still be calculated (by the use of Equation C-6 and the total hardness). The lime dose can then be determined in the usual manner.

**Example 5.79**

The laboratory returned the following results of testing:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>50 mg/L as Ca(^{2+})</td>
</tr>
<tr>
<td>Total hardness</td>
<td>150 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>149 mg/L as HCO(_3^-)</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>130 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Carbon dioxide ((CO_2))</td>
<td>10 mg/L as CO(_2)</td>
</tr>
</tbody>
</table>

Calculate the lime dosage in mg/L as CaCO\(_3\) and, if needed, the soda ash dosage in mg/L. (Assume no excess lime or soda ash are added.) Since the total alkalinity (130 mg/L) is less that the total hardness, the water has both carbonate and noncarbonate hardness constituents. Therefore, both lime and soda ash will be required. Before the lime and soda ash dosages can be determined, all the
concentrations must be expressed in similar terms (as CaCO$_3$). Use the equivalent weight procedure to make the conversions to “mg/L as CaCO$_3$”:

$$
\begin{align*}
(50 \text{mg/L as Ca}) \left( \frac{50}{20} \right) &= 125 \text{mg/L as CaCO}_3 \\
(149 \text{mg/L as HCO}_3^-) \left( \frac{50}{61} \right) &= 122 \text{mg/L as CaCO}_3 \\
(10 \text{mg/L as CO}_2) \left( \frac{50}{22} \right) &= 22.7 \text{mg/L as CaCO}_3
\end{align*}
$$

Note: No conversions are needed for total alkalinity and total hardness since the lab results are expressed as CaCO$_3$.

Next, determine the concentration of magnesium. Total hardness is basically calcium ion concentration plus concentration. Mathematically this is:

$$
\left[ \text{Total hardness} \right] = [Ca] + [Mg] \quad (C-6)
$$

In this example, two of these factors are known, total hardness and calcium. So, write the known information into the equation and solve for magnesium.

$$
[150 \text{mg/L}] = [125 \text{mg/L}] + [Mg]
$$

Now solve for the unknown value, making sure that all concentrations in the above equation are expressed in terms of the same constituent (as CaCO$_3$). Since calcium represents 125 mg/L of the total 150 mg/L hardness, magnesium represents the balance of the hardness.

$$
[150 \text{mg/L}] - [125 \text{mg/L}] = [25 \text{mg/L Mg}]
$$
Keep in mind that this calculation, though accurate enough, is not exact. There may be small amounts of hardness-producing cations other than calcium and magnesium. It is likely that if the magnesium ion concentration were measured, it would be slightly less than the 25 mg/L calculated above.

Now the lime and soda ash dosages can be calculated.

\[
\text{Lime dose} = [22.7 \text{mg} / \text{L}] + [122 \text{mg} / \text{L}] + [25 \text{mg} / \text{L}] + [0 \text{mg} / \text{L}] = 169.7 \text{mg} / \text{L} \text{ as CaCO}_3
\]

\[
\text{Soda ash dose} = [150 \text{mg} / \text{L}] - [122 \text{mg} / \text{L}] + [0 \text{mg} / \text{L}] = 28 \text{mg} / \text{L} \text{ as CaCO}_3
\]

Dosages expressed as CaCO$_3$ are useful in order to simplify and standardize the calculation process. However, these dosages are not useful operationally until they are expressed as lime or as soda ash. Once they have been expressed in terms of their own equivalent weight, the operator can use the dosages to dispense the correct amount of chemical. Examples 5.80 and 5.81 illustrate this calculation.

**Example 5.80**

Using the lime and soda ash dosages given in Example 5.79, determine these dosages expressed in terms of quicklime (lime as CaO) and soda ash (Na$_2$CO$_3$), respectively.

To solve this problem, make the equivalent weight conversions. Do this by multiplying the dosages by the equivalent weight of the chemical being changed to, and dividing that result by the equivalent weight of the chemical being changed from.

\[
\text{Lime dose} = (169.9 \text{mg} / \text{L}) \left( \frac{28}{50} \right) = 95.1 \text{mg} / \text{L} \text{ as CaO}
\]

\[
\text{Soda ash dose} = (28 \text{mg} / \text{L}) \left( \frac{53}{50} \right) = 29.7 \text{mg} / \text{L} \text{ as Na}_2\text{CO}_3
\]
Example 5.81

The most current laboratory data sheet shows the following water characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>140 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Total hardness</td>
<td>180 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>220 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>220 mg/L as CaCO$_3$</td>
</tr>
<tr>
<td>Carbon dioxide (CO$_2$)</td>
<td>6 mg/L as CaCO$_3$</td>
</tr>
</tbody>
</table>

Find the concentration of quicklime (lime as CaO) and soda ash (Na$_2$CO$_3$), if needed. (Assume that no excess lime or soda ash is to be added.) Since the laboratory has reported the results as CaCO$_3$, the problem can be solved by beginning with Step 2.

In this example, total hardness (180 mg/L as CaCO$_3$) is less than total alkalinity (220 mg/L as CaCO$_3$). Based on Table 5.1, lime alone can be added. The equation used to calculate lime dosage as CaCO$_3$ (Equation C-1) utilizes magnesium concentration information. Therefore, calculate the magnesium concentration by using total hardness and calcium concentration information.

\[
\left[ \text{Total hardness} \right] = [Ca] + [Mg] \quad \text{(C-6)}
\]

Insert the known information in the equation and solve for the unknown magnesium concentration.

\[
[180\text{mg/L}] = [140\text{mg/L}] + [Mg]
\]

\[
[180\text{mg/L}] - [140\text{mg/L}] = [40\text{mg/L}]
\]

Because total hardness is less than total alkalinity, Equation C-1 should be used in determining lime dosage requirements:
\[ \text{Lime dose} = [CO_2] + [TA] + [Mg] + \left[ \text{Excess OH} \right] \]  

\[ \text{Lime dose} = [6 \text{mg/L}] + [180 \text{mg/L}] + [40 \text{mg/L}] + [0 \text{mg/L}] = 226 \text{mg/L as CaCO}_3 \]

Note: that if Equation C-3 and Equation C-4 are used with data indicating a total hardness less than the total alkalinity, then the soda ash dosage calculation will result in a zero or negative number. Thus, Equation C-3 is the equation that must be used.

To complete this problem, use the equivalent weight calculation to convert mg/L as CaCO₃ to mg/L as CaO.

\[ \text{Lime dose} = (226 \text{mg/L}) \left( \frac{28}{50} \right) = 126.6 \text{mg/L as CaO} \]

Once the mg/L concentrations of lime and soda ash have been calculated, the information is expressed in the more practical dosage terms of pounds per million gallons or pounds per day, as noted in step 6 of the chemical softening calculations. The examples that follow illustrate this calculation.

**Example 5.82**

How many pounds of lime per day would be needed to soften the raw water in Example 5.81 at the rate of 640,000 gpd?

This is a typical mg/L to pounds per day calculation. To convert 126.6 mg/L as CaO to pounds per day, insert the known information in Equation C-1:

\[ (\text{mg/L})(8.34)(\text{mgd}) = \text{lbs/day} \]

\[ (126.6 \text{mg/L})(8.34)(0.640 \text{mgd}) = 675.7 \text{lbs/day CaO} \]
The lime and soda ash used in water softening treatment are not always 100 percent pure. Suppose, for example, that quicklime is only 95 percent pure (contains only 95 percent CaO). This would mean that if a dosage of 60 mg/L of quicklime were required, 63.2 mg/L would actually have to be added to the water to compensate for the impurity of the commercial lime.

To calculate the actual dosage needed of a chemical that is less than 100 percent pure, remember that the general equation for percent problems.

\[
Percent = \frac{\text{part}}{\text{whole}} \times 100
\]

In calculations for dosages of chemicals with less than 100 percent purity, the “whole” is the amount of 100% pure chemical actually measured into the water, the “percent” is the purity of the commercial chemical; and the ”part” is the calculated dosage of commercial chemical that is required for the treatment process. This is summarized below.

\[
Whole = \frac{\text{part}}{\text{percent}} \quad \text{Actual dose} = \frac{60 \text{mg/L}}{0.95} = 63.2 \text{mg/L}
\]

**Example 5.83**

Assume that 675.7 lbs/day of CaO are required for treating water. How many pounds per day of 90 percent pure quicklime will actually be required? Keep in mind that the answer to this problem will be slightly more than 675.7 lbs/day. To determine the required dosage of the 90 percent pure chemical that is actually used, insert the information in the equation: (Express the percent purity as a decimal.)

\[
Actual \ dose = \frac{675.7 \text{mg/L}}{0.9} = 750.8 \text{mg/L}
\]
Remember that whenever the purity of the chemical used to less than 100 percent, the actual dosage will be some greater number than the calculated dosage.

**Example 5.84**

It has been calculated that 95.1 mg/L quicklime as CaO and 29.7 mg/L soda ash as Na₂CO₃ are required in treating water. The quicklime to be used is 94 percent pure, the soda ash is 100 percent pure, and the plant flow at the time is 1,100 gpm (1,584 mgd). How many pounds per day of quicklime and soda ash should be used?

First, calculate the pounds per day required for the line and soda ash.

\[
\left(95.1 \text{ mg/L Lime}\right) \left(8.34 \text{ mg/L mgd}\right) = 1,256 \text{ lbs/day CaO}
\]

\[
\left(29.7 \text{ mg/L soda ash}\right) \left(8.34 \text{ mg/L mgd}\right) = 392 \text{ lbs/day Na₂CO₃}
\]

Now calculate the adjustment to compensate for the impurity of the chemicals. Assume lime is 94 percent pure and soda ash is 100 percent pure as stated.

\[
\text{Actual Lime dose} = \frac{1,256 \text{ lbs/day}}{0.94} = 1,336 \text{ lbs/day}
\]

Since soda ash was assumed to be 100 percent pure, no adjustment was needed. The actual dosage is 392 pounds per day.

It is common practice to add more lime than determined by calculation. Doing so increase the reaction speed and improve the completeness of the reaction. The next two examples illustrate the use of excess-lime information in the calculation of lime and soda dosages.
Example 5.85

A raw water sample has the following water quality characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>152 mg/L as Ca^{+2}</td>
</tr>
<tr>
<td>Magnesium</td>
<td>29 mg/L as Mg^{+2}</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>317 mg/L as HCO_{3}^-</td>
</tr>
<tr>
<td>Carbon dioxide (CO_{2})</td>
<td>9 mg/L as CaCO_{3}</td>
</tr>
</tbody>
</table>

It was decided to include excess lime and soda ash doses of 35 mg/L as CaCO_{3}. Including this excess, calculate the lime dosage (89 percent pure) and soda ash (100 percent pure) dosage (a) in mg/L as lime or soda ash; (b) in pounds per million gallons; and (c) in pounds per day. Assume a plant flow of 479,500 gpd.

(a) First express all data in terms of mg/L as CaCO_{3}.

\[
\begin{align*}
(152\text{mg/L as Ca}) \left( \frac{50}{20} \right) &= 380\text{mg/L as CaCO}_{3} \\
(29\text{mg/L as Mg}) \left( \frac{50}{12.15} \right) &= 119.5\text{mg/L as CaCO}_{3} \\
(317\text{mg/L as HCO}_{3}^-) \left( \frac{50}{61} \right) &= 259.8\text{mg/L as CaCO}_{3} \\
(9\text{mg/L as CO}_{3}) \left( \frac{50}{22} \right) &= 20.4\text{mg/L as CaCO}_{3}
\end{align*}
\]

Now calculate the lime and soda ash requirements based on Equation C-2 and Equation C-3.

\[
\text{Lime dose} = [CO_{2}] + [HCO_{3}^-] + [Mg] + [\text{Excess} \ OH] \tag{C-2}
\]
Soda ash dose = \[TH - HCO_3^- + \text{Excess}\]  
\[\text{(C-3)}\]

Lime dose = \[20.4\text{mg/L} + 259.8\text{mg/L} + 119.5\text{mg/L} + 35\text{mg/L} = 434.7\text{mg/L as CaCO}_3\]

\[\text{total hardness} = \text{[Ca]} + \text{[Mg]}\]

\[\text{total hardness} = 380\text{mg/L} + 119.5\text{mg/L} = 499.5\text{mg/L}\]

Soda ash dose = \[499.5\text{mg/L} - 259.8\text{mg/L} + 35\text{mg/L} = 274.7\text{mg/L as CaCO}_3\]

Next, express the dosages as lime or soda ash.

Lime dose = \(434.7\text{mg/L} \times \left(\frac{28}{50}\right) = 243.4\text{mg/L as CaO}\)

Soda ash dose = \(274.7\text{mg/L} \times \left(\frac{53}{50}\right) = 291.2\text{mg/L as Na}_2\text{CO}_3\)

Finally, adjust for chemical purity.

Actual Lime dose = \(\frac{243.4\text{mg/L}}{0.89} = 273.5\text{mg/L}\)

No purity adjustment is needed for soda ash, so the soda ash dosage is 291.2 mg/L as Na\(_2\)CO\(_3\).

(b) Convert from a dosage to pounds per million gallons is found by multiplying the dosage by 8.34 as follows:

\[lbg\ Lime/MG = (273.5\text{mg/L}(8.34) = 2280\text{lbs/MG}\]
\[ \text{lbs} \text{ soda ash} / \text{MG} = (291.2 \text{mg} / \text{L}) \left( \frac{8.34}{429} \right) = 2.429 \text{lbs} / \text{MG} \]

(c) Similarly, the pounds per day can be found as follows:

\[
\begin{align*}
(2.280 \text{lbs Lime} / \text{MG})(0.4795 \text{mgd}) &= 1.093 \text{lbs / day} \\
(2.492 \text{lbs soda ash} / \text{MG})(0.4795 \text{mgd}) &= 1.195 \text{lbs / day}
\end{align*}
\]

**Example 5.86**

The test results for a raw water sample were returned from the laboratory as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>66 mg/L as Ca(^{2+})</td>
</tr>
<tr>
<td>Magnesium</td>
<td>13 mg/L as Mg(^{2+})</td>
</tr>
<tr>
<td>Total hardness</td>
<td>220 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>156 mg/L as HCO(_3^-)</td>
</tr>
<tr>
<td>Carbon dioxide (CO(_2))</td>
<td>5 mg/L as CaCO(_3)</td>
</tr>
</tbody>
</table>

The plant flow on January 4\(^{th}\) averaged 1.187 mgd. How many pounds of quicklime (88 percent pure) and soda ash (100 percent pure) should have been used that day? It is common practice at this plant to add 26 mg/L excess lime and soda ash as CaCO\(_3\). Begin by converting all the constituent concentrations to concentrations in mg/L as CaCO\(_3\).

\[
\left(66 \text{ mg/L as Ca}\right) \left(\frac{50}{20}\right) = 165 \text{ mg/L as CaCO}_3
\]

\[
\left(13 \text{ mg/L as Mg}\right) \left(\frac{50}{12.15}\right) = 53.6 \text{ mg/L as CaCO}_3
\]
Next, calculate lime dosage as CaCO$_3$ according to Equation C-2.

\[
\text{Lime dose} = [CO_2] + [HCO_3^-] + [Mg] + \left[\text{Excess } OH\right]
\]  

\[
\text{Lime dose} = [11.4mg/L] + [127.9mg/L] + [53.6mg/L] + [26mg/L] = 218.9mg/L \text{ as } CaCO_3
\]

In a similar manner calculate the soda ash dosage according to Equation C-3.

\[
\text{Soda ash dose} = [TH] - [HCO_3^-] + [\text{Excess}]
\]  

\[
\text{Soda ash dose} = [220mg/L] - [127.9mg/L] + [26mg/L] = 118.1mg/L \text{ as } CaCO_3
\]

Notice that total hardness, calcium, and magnesium were all measured in the laboratory. In such cases, it is best to use total hardness in the soda ash calculation because the sum of calcium and magnesium can be slightly smaller (220 mg/L as CaCO$_3$, versus 218.6 mg/L as CaCO$_3$).

The dosages calculated so far must now be expressed in terms of the equivalent weight of the softening chemicals used (as CaO or as Na$_2$CO$_3$).

\[
\text{Lime dose} = (218.9mg/L)\left(\frac{28}{50}\right) = 122.6mg/L \text{ as } CaO
\]

\[
\text{Soda ash dose} = (118.1mg/L)\left(\frac{53}{50}\right) = 125.2mg/L \text{ as } Na_2CO_3
\]
These are the concentrations needed if the quicklime and soda ash are 100 percent pure. But the quicklime used is 88 percent pure; therefore, adjust the quicklime dosage by dividing the calculated dosage by the actual purity of the lime used.

\[
\text{Actual Lime dose} = \frac{122.6 \text{mg/L}}{0.88} = 139.3 \text{mg/L}
\]

The soda ash used was 100 percent, so no adjustment needs be made.

Finally, based on the average flow rate for the day, given as 1.187 mgd, determine the total pounds of lime and soda ash to be used per day.

\[
\left( 139.3 \text{mg/L Lime} \right) \times 8.34 \times (1.187 \text{mgd}) = 1,379 \text{lbs/day CaO}
\]

\[
\left( 125.2 \text{mg/L soda ash} \right) \times 8.34 \times (1.187 \text{mgd}) = 1,239 \text{lbs/day Na}_2\text{CO}_3
\]

### 5.14.2 Conversion Factor Method

All of the equivalent weight conversions required in the conventional method can be combined into conversion factors, as shown in Table 5.2. These factors, multiplied by the concentration of the corresponding constituent, in units of either mg/L or pounds per million gallons, to determine the softening dosages. To find the total lime dosage, sum the amounts of lime needed to remove carbon dioxide, bicarbonate alkalinity, and magnesium; then add that sum to the excess lime required (if any). The total soda ash dosage is found similarly. Add the amount of soda ash for removing noncarbonate hardness to any excess soda ash required. The final step is to adjust the dosage based on the actual purity of the lime and soda ash.
### TABLE 5.2 - Factors for Converting Constituent Concentrations to Softening Chemical Dosages

<table>
<thead>
<tr>
<th>Constituent Concentration</th>
<th>Conversion Factor * to Determine Required Amount of Lime (as CaO)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L</td>
</tr>
<tr>
<td>Carbon dioxide, mg/L as CO₂</td>
<td>1.27</td>
</tr>
<tr>
<td>Bicarbonate alkalinity, mg/L as CaCO₃</td>
<td>0.56</td>
</tr>
<tr>
<td>Magnesium, mg/L as Mg</td>
<td>2.31</td>
</tr>
<tr>
<td>Excess lime, mg/L as CaCO₃</td>
<td>0.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constituent Concentration</th>
<th>Conversion Factor * to Determine Required Amount of Soda Ash (as Na₂CO₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L</td>
</tr>
<tr>
<td>Noncarbonate hardness, mg/L as CaCO₃</td>
<td>1.06</td>
</tr>
<tr>
<td>Excess soda ash, mg/L as CaCO₃</td>
<td>1.06</td>
</tr>
</tbody>
</table>

* Multiply constituent concentration by conversion factor to determine softening chemical dosage in units noted.

### Example 5.87

The following test results were provided by the laboratory:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>9 mg/L as Mg⁺²</td>
</tr>
<tr>
<td>Noncarbonate hardness</td>
<td>95 mg/L as CaCO₃</td>
</tr>
<tr>
<td>Bicarbonate alkalinity</td>
<td>205 mg/L as CaCO₃</td>
</tr>
<tr>
<td>CO₂</td>
<td>25 mg/L as CO₂</td>
</tr>
</tbody>
</table>

Assuming no excess lime is needed, find the correct dosages in mg/L for lime (90% CaO) and soda ash (99% Na₂CO₃) required to remove all hardness. First, check to see that the data are expressed in the same terms noted in Table 5.2. In this case they are. If the terms had disagreed, it would have been necessary to convert to the appropriate terms by using the equivalent weight method. Proceed with the calculations, beginning with the lime calculations. Multiply the constituent concentrations by the respective conversion factors to obtain the lime dosage for each constituent.
\[ CO_2 (25)(1.27) = 31.75 \text{ mg/L as CaO} \]
\[ HCO_3^- (205)(0.56) = 114.8 \text{ mg/L as CaO} \]
\[ Mg^{2+} (9)(2.31) = 20.79 \text{ mg/L as CaO} \]
\[ \text{Total lime dosage} = 167.34 \text{ mg/L as CaO} \]

Now adjust the lime dosage for purity.

\[
\text{Actual Lime dose} = \frac{167.34 \text{ mg/L}}{0.90} = 185.93 \text{ mg/L}
\]

Next find the soda ash dosage

\[
\text{Soda ash dosage} (95)(1.06) = 100.70 \text{ mg/L as Na}_2\text{CO}_3
\]

Then adjust the soda ash dose for purity:

\[
\text{Actual soda ash dose} = \frac{100.7 \text{ mg/L}}{0.99} = 101.72 \text{ mg/L}
\]

**Example 5.88**

The following laboratory test results show the hardness of the raw-water supply:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>50 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Total hardness</td>
<td>200 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>100 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>Noncarbonate hardness</td>
<td>100 mg/L as CaCO(_3)</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>20 mg/L as CaCO(_3)</td>
</tr>
</tbody>
</table>

Note that for this water supply, the total alkalinity is the same as the bicarbonate alkalinity. The objective is to remove all CO\(_2\) and carbonate hardness while reducing magnesium to 5 mg/L as CaCO\(_3\) and noncarbonate hardness to 75 mg/L as CaCO\(_3\). Calculate the required dosages in pounds per million gallons. The
quicklime used is 88 percent pure, and the soda ash is 98 percent pure. No excess lime or soda ash are added.

The first step is to determine the carbonate hardness and the noncarbonate hardness (NCH). The total hardness is greater than the total alkalinity. From Table 5.2:

\[
\begin{align*}
\text{Carbonate hardness} &= \text{Total alkalinity} \\
&= \text{bicarbonate (HCO}_3^\text{) alkalinity} \\
&= 100 \text{ mg/L as CaCO}_3 \\
\text{Noncarbonate hardness} &= \text{total hardness} - \text{total alkalinity} \\
&= 200 \text{ mg/L} - 100 \text{ mg/L} \\
&= 100 \text{ mg/L as CaCO}_3
\end{align*}
\]

Now list the amount of each constituent to be removed:

- Magnesium: \(50 \text{ mg/L} - 5 \text{ mg/L} = 45 \text{ mg/L as CaCO}_3\)
- Carbonate hardness: \(100 \text{ mg/L as CaCO}_3\)
- Noncarbonate hardness: \(100 \text{ mg/L} - 75 \text{ mg/L} = 25 \text{ mg/L as CaCO}_3\)
- CO\(_2\): \(20 \text{ mg/L as CaCO}_3\)

Next, convert to the units as needed shown.

\[
\left(45 \text{ mg/L as CaCO}_3 \right) \left(\frac{12.15}{50}\right) = 10.94 \text{ mg/L as Mg}
\]

\[
\left(20 \text{ mg/L as CaCO}_3 \right) \left(\frac{22}{50}\right) = 8.8 \text{ mg/L as CO}_2
\]

Then, calculate the required dosages.

\[
\left(10.94 \text{ mg/L as Mg}\right) \left(19.27\right) = 210.8 \text{ lbs/MG as CaO}
\]
\[
\left( \frac{8.8 \text{ mg} / \text{L as CO}_2}{10.63} \right) = 93.5 \text{ lbs/MG as CaO}
\]

\[
\left( \frac{100 \text{ mg} / \text{L as CaCO}_3}{4.67} \right) = 467 \text{ lbs/MG as CaO (Carbonate hardness)}
\]

**Total lime dosage** = 210.8 + 93.5 + 467 = 771.3 lbs/MG

\[
\left( \frac{25 \text{ mg} / \text{L as CaCO}_3}{8.84} \right) = 221 \text{ lbs/MG as Na}_2\text{CO}_3 (\text{Noncarbonate hardness})
\]

**Total soda ash dosage** = 221 lbs/MG

Finally, adjust for purity:

\[
\text{Actual Lime dose} = \frac{771.3 \text{ lbs/MG}}{0.88} = 876.56 \text{ lbs/MG}
\]

\[
\text{Actual soda ash dose} = \frac{221 \text{ lbs/MG}}{0.98} = 225.5 \text{ lbs/MG}
\]

**Example 5.89**

Based on the following hardness data, calculate the lime and soda ash dosages for complete removal at an average daily flow rate of 1.137 mgd. Excess lime and soda ash are added at the rate of 27 mg/L as CaCO₃. The soda ash used is 100 percent pure. The quicklime is 90 percent pure. Give results in milligrams per liter. For this water, total alkalinity and bicarbonate alkalinity are the same.

- Magnesium: 15.8 mg/L as Mg
- Total hardness: 215 mg/L as CaCO₃
- Bicarbonate alkalinity: 185 mg/L as CaCO₃
- CO₂: 25.8 mg/L as CO₂
These lab values are in the correct units for use with Table 5.2. First, determine the noncarbonate hardness.

\[
NCH = TH - TA
= 215 \text{ mg/L} - 185 \text{ mg/L}
= 30 \text{ mg/L as CaCO}_3
\]

Then, use factors from Table 5.2 to determine the dosages.

\[
\left(15.8 \text{ mg/L as Mg}\right)\left(2.31\right) = 36.5 \text{ mg/L as CaO}
\]

\[
\left(25.8 \text{ mg/L as CO}_2\right)\left(1.27\right) = 32.8 \text{ mg/L as CaO}
\]

\[
\left(185 \text{ mg/L as CaCO}_3\right)\left(0.56\right) = 103.6 \text{ mg/L as CaO (Carbonate hardness)}
\]

\[
\left(27 \text{ mg/L as CaCO}_3\right)\left(0.56\right) = 15.1 \text{ mg/L as CaO (Excess lime)}
\]

Total lime dosage = 36.5 + 32.8 + 103.6 + 15.1 = 188 mg/L as CaO

\[
\left(30 \text{ mg/L as CaCO}_3\right)\left(1.06\right) = 31.8 \text{ mg/L as Na}_2\text{CO}_3 (Noncarbonate hardness)
\]

\[
\left(27 \text{ mg/L as CaCO}_3\right)\left(1.06\right) = 28.6 \text{ mg/L as Na}_2\text{CO}_3 (Excess soda ash)
\]

Total soda ash dosage = 31.8 + 28.6 = 60.4 mg/L as Na\textsubscript{2}CO\textsubscript{3}

Next, adjust for chemical purity.

\[
Actual \ Lime \ dose = \frac{188 \text{ mg/L}}{0.90} = 208.9 \text{ mg/L as CaO}
\]

No adjustment is needed for soda ash since it is 100% pure.
5.16 Recarbonation Calculations

There are three possible reactions involved when carbon dioxide is used to stabilize lime-softened water. Equation C-7 shows that dissolved calcium carbonate will react with carbon dioxide (CO₂) to form calcium bicarbonate. Equations C-7 through C-9 show that excess lime will also react with carbon dioxide, forming either calcium carbonate precipitate or soluble calcium bicarbonate.

\[
\text{Equation C-7: } \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca(HCO}_3)_2 \\
\text{Calcium carbonate + Carbon dioxide + Water} \rightarrow \text{Calcium bicarbonate}
\]

\[
\text{Equation C-8: } \text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \\
\text{Excess lime + Carbon dioxide} \rightarrow \text{Calcium carbonate + Water}
\]

\[
\text{Equation C-9: } \text{Ca(OH)}_2 + 2\text{CO}_2 \rightarrow \text{Ca(HCO}_3)_2 \\
\text{Excess lime + Two moles of Carbon dioxide} \rightarrow \text{Calcium bicarbonate}
\]

The conditions described by these equations can and do occur together. Consequently, the carbon dioxide dosage needed for recarbonation is the amount needed to reduce calcium carbonate to a desired level and to eliminate excess lime completely. The amount of calcium carbonate present is measured by the alkalinity test and is assumed to be equal to the carbonate alkalinity. The amount of excess lime present, also measured by the alkalinity test, is assumed equal to the hydroxide alkalinity.

The correct carbon dioxide dosage involves adding 0.44 mg/L of CO₂ for every 1 mg/L of carbonate alkalinity or 1 mg/L of hydroxide alkalinity expressed as CaCO₃.
That is, removing 5 mg/L as CaCO$_3$ of carbonate alkalinity and 5 mg/L as CaCO$_3$ of hydroxide alkalinity will require $(5+5)(0.44)=4.4$ mg/L of CO$_2$ as CO$_2$.

**Example 5.90**

The laboratory results of water quality analyses below were reported for water in the process of treatment. Calculate the correct CO$_2$ dosage.

<table>
<thead>
<tr>
<th>Type of Alkalinity</th>
<th>Raw Water</th>
<th>After Lime-Soda Ash Softening</th>
<th>Desired after Recarbonation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicarbonate (HCO$_3^-$)</td>
<td>250</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Carbonate (CO$_3^{2-}$)</td>
<td>0</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Hydroxide (OH$^-$)</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

First, find out how much carbonate and hydroxide alkalinity must be removed. For carbonate alkalinity, subtract the desired concentration from the concentration resulting from the lime-soda ash treatment.

Carbonate (CO$_3$) alkalinity to be removed

\[
35 \text{ mg/L (softened)} - 30 \text{ mg/L (recarbonated)} = 5 \text{ mg/L removed}
\]

Hydroxide (OH) alkalinity to be removed

\[
40 \text{ mg/L (softened)} - 0 \text{ mg/L (recarbonated)} = 40 \text{ mg/L removed}
\]

Then add the two alkalinitities to find the combined amount to be removed.

\[
5 \text{ mg/L (CO}_3\text{) } + 40 \text{ mg/L (OH)} = 45 \text{ mg/L as CaCO}_3
\]

Finally, find the carbon dioxide (CO$_2$) dosage.

\[
\text{CO}_2 \text{ dosage } = (45 \text{ mg/L as CaCO}_3) \times 0.44 = 19.8 \text{ mg/L as CO}_2
\]
Example 5.91

Water quality after softening was found to have the parameters and concentrations below. Find the carbon dioxide dose needed to treat the water as shown.

<table>
<thead>
<tr>
<th>Type of Alkalinity</th>
<th>Raw Water</th>
<th>After Lime-Soda Ash Softening</th>
<th>Desired after Recarbonation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicarbonate (HCO₃⁻)</td>
<td>265</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>Carbonate (CO₃²⁻)</td>
<td>0</td>
<td>56</td>
<td>27</td>
</tr>
<tr>
<td>Hydroxide (OH⁻)</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

First, find out how much carbonate and hydroxide alkalinity must be removed. For carbonate alkalinity, subtract the desired concentration from the concentration resulting from the lime-soda ash treatment.

Carbonate (CO₃⁻) alkalinity to be removed

\[
56 \text{ mg/L (softened)} - 27 \text{ mg/L (recarbonated)} = 29 \text{ mg/L removed}
\]

Hydroxide (OH⁻) alkalinity to be removed

\[
30 \text{ mg/L (softened)} - 0 \text{ mg/L (recarbonated)} = 30 \text{ mg/L removed}
\]

Then add the two alkalinities to find the combined amount to be removed.

\[
29 \text{ mg/L (CO₃⁻)} + 30 \text{ mg/L (OH⁻)} = 59 \text{ mg/L as CaCO₃}
\]

Finally, find the carbon dioxide (CO₂) dosage.

\[
CO₂ \text{ dosage} = (59 \text{ mg/L as CaCO₃}) \times 0.44 = 26 \text{ mg/L as CO₂}
\]
Example 5.92

Water quality after softening was found to have the parameters and concentrations below. Find the carbon dioxide dose needed to treat the water as shown.

<table>
<thead>
<tr>
<th>Type of Alkalinity</th>
<th>Raw Water</th>
<th>After Lime-Soda Ash Softening</th>
<th>Desired after Recarbonation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicarbonate (HCO₃⁻)</td>
<td>180</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Carbonate (CO₃²⁻)</td>
<td>0</td>
<td>34</td>
<td>22</td>
</tr>
<tr>
<td>Hydroxide (OH⁻)</td>
<td>0</td>
<td>16</td>
<td>0</td>
</tr>
</tbody>
</table>

First, find out how much carbonate and hydroxide alkalinity must be removed. For carbonate alkalinity, subtract the desired concentration from the concentration resulting from the lime-soda ash treatment.

Carbonate (CO₃) alkalinity to be removed

\[
34 \text{ mg/L (softened)} - 22 \text{ mg/L (recarbonated)} = 12 \text{ mg/L removed}
\]

Hydroxide (OH) alkalinity to be removed

\[
16 \text{ mg/L (softened)} - 0 \text{ mg/L (recarbonated)} = 16 \text{ mg/L removed}
\]

Then add the two alkalinitities to find the combined amount to be removed.

\[
12 \text{ mg/L (CO₃)} + 16 \text{ mg/L (OH)} = 28\text{mg/L as CaCO₃}
\]

Finally, find the carbon dioxide (CO₂) dosage.

\[
CO₂ \text{ dosage} = (28 \text{ mg/L as CaCO₃}) \times 0.44 = 12.3 \text{ mg/L as CO₂}
\]
5.17 Ion Exchange Softening Calculations

Ion exchange softening is a relatively simple process in water treatment, although attention must be paid to the details and the necessary process equations. Hardness in water is made up mostly of calcium ions and magnesium ions known as cations (positively charged ions). These cations trade places (or exchange places) with sodium (Na\(^+\)) ions that adhere to ion exchange media. Typical ion exchange media holds a lot of sodium ions on its surface until they are exchanged for calcium ions and magnesium ions during the softening process. The exchanging of ions continues until the sodium ions on the media are used up, which indicates exhaustion of the media for softening. The ion exchange softening process is illustrated in the chemical equations below. In these equations symbolizes the ion exchange media.

\[
2NaR + Ca(HCO_3)_2 \rightarrow CaR + 2NaHCO_3
\]

\[
2NaR + Mg(HCO_3)_2 \rightarrow MgR + 2NaHCO_3
\]

\[
2NaR + Ca(SO_4)_2 \rightarrow CaR + Na_2SO_4
\]

\[
2NaR + Mg(SO_4)_2 \rightarrow MgR + Na_2SO_4
\]

It is important to understand that all calcium and magnesium ions are removed by the ion exchange media until all the sodium is used up. The hardness of water leaving the ion exchange softener is therefore; zero hardness. Water with a hardness of zero is very corrosive and unstable. For these reasons, softened water is blended and mixed with non-softened (raw or source) water to produce a desirable finished water hardness. A measured amount of raw water usually is bypassed around the softening process and blended with the softened water just downstream of the ion exchange softener. The normal softening and blending process is shown in Figure 5.11. Once the ion exchange media becomes exhausted, hardness will begin breaking through the softener and will be found in the softener outlet.
Once the ion exchange media is exhausted, the media must be regenerated with sodium ions. This is accomplished using salt solution or brine. Food grade rock salt is mixed with water to create a saturated salt solution. In general, saturated salt solution has the characteristics given in Table 5.3.

<table>
<thead>
<tr>
<th>% solution, by weight</th>
<th>26.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.1972</td>
</tr>
<tr>
<td>Weight, pounds/gallon</td>
<td>9.985</td>
</tr>
<tr>
<td>Pounds salt/gallon solution</td>
<td>2.596</td>
</tr>
</tbody>
</table>

To provide more even distribution of salt and sodium ions into the softener and ion exchange media, a dilute brine solution is made from the saturated brine. Dilution water is mixed with the saturated brine to prepare the desired dilute brine solution. Normally, a dilute brine solution of about five (5) percent salt is used for regeneration of ion exchange media. The dilute brine passes through the ion exchange media and the sodium ions replace the calcium ion and magnesium ions that are attached to the media. This process is similar to the softening process, but in reverse.

\[
CaR + 2NaCl \rightarrow 2NaR + CaCl_2
\]

\[
MgR + 2NaCl \rightarrow 2NaR + MgCl_2
\]
The spent brine (CaCl$_2$ and MgCl$_2$) is a waste product that must either be treated or diluted for discharge to the environment. Where there is a receiving stream that can accept the spent brine, operating practice is to discharge the brine to the stream and allow dilution to a concentration no more than 250 mg/L as chlorides. In other cases, holding ponds are used to store the spent brine until it can be diluted for discharge.

The capacity of ion exchange media to collect calcium and magnesium ions is known as the exchange capacity. All ion exchange materials or medias (zeolites and synthetic resin types) have maximum exchange capacities. The normal capacity ranges for ion exchange media types are summarized below along with the salt regeneration required.

<table>
<thead>
<tr>
<th>Media type</th>
<th>Exchange Capacity</th>
<th>Regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>grains per cubic foot</td>
<td>lbs. salt / cubic foot</td>
</tr>
<tr>
<td>Greensand</td>
<td>2,800</td>
<td>1.26</td>
</tr>
<tr>
<td>Processed Greensand</td>
<td>5,500</td>
<td>2.47</td>
</tr>
<tr>
<td>Sulfonated Coal</td>
<td>8,200</td>
<td>3.69</td>
</tr>
<tr>
<td>Synthetic Zeolite</td>
<td>11,000</td>
<td>4.95</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>12,500</td>
<td>5.63</td>
</tr>
<tr>
<td>Polystyrene Resin</td>
<td>28,000</td>
<td>12.6</td>
</tr>
</tbody>
</table>

Over time, the exchange capacity of ion exchange media will diminish. Age and breakage of the media as well as fouling depletes the exchange capacity resulting in less throughput for each run cycle. Fouling of the media with organics, turbidity, and iron and manganese can result in depleting of the media’s exchange capacity. At a point, it is better to replace the ion exchange media rather than to operate with the reduced exchange capacity. That point normally is found by economic calculations. Proper care of the ion exchange media will maintain its useful life expectancy. Ion exchange media has been known to last up to 40 years.

The use of the unit “grain” is very common in this branch of water treatment. It is used in such terms as grains per cubic foot and grains per gallon (gpg). The following conversion factors will be useful in converting these somewhat old-fashion units to more familiar units.
There are eight ion exchange softening process calculations that you must become familiar with. These eight equations set up the basic operations and handling of ion the exchange process. Make sure you can calculate the equations below to become proficient with ion exchange softening operations. Examples of each calculation and the equations needed are provided.

- hardness removal capacity,
- gallons softened per cycle,
- bypass calculations,
- length of softener cycle,
- salt requirements,
- brine regeneration,
- brine dilution, and
- dilution water needs.

### 5.16.1 Hardness Removal Capacity

Removal of hardness during ion exchange softening is based on the volume of media in the ion exchange softener and the exchange capacity of the media. The equation below demonstrates the calculation. Hardness is expressed in grains, not mg/L.

\[
\text{grains removed} = \left( \text{volume media, ft}^3 \right) \times \left( \text{exchange capacity, grains/ft}^3 \right)
\]

**Example 5.93**

A treatment unit contains 20 ft³ of cation exchange media that has a rated removal capacity of 20,000 grains per cubic foot. What is the total hardness removal capacity in grains?
Since each cubic foot of material can remove 20,000 grains of hardness and there are 20 ft$^3$ of media, the answer can be found in one multiplication.

\[
(20 \text{ ft}^3)(20,000 \text{ grains/ft}^3) = 400,000 \text{ grains removed}
\]

**Example 5.94**

An ion exchange softener contains cation exchange media that has an exchange capacity of 28,000 grains per cubic foot. The softener is 6 feet in diameter and has 4 feet of media depth. What is the total hardness removal capacity in grains?

\[
0.785(6 \text{ ft})^2(4 \text{ ft}) = 113.04 \text{ ft}^3
\]

\[
(113.04 \text{ ft}^3)(28,000 \text{ grains/ft}^3) = 3,165,120 \text{ grains removed}
\]

**Example 5.95**

An ion exchange softener is 8 feet in diameter and contains 54-inches of ion exchange media. If the exchange capacity of the media is 12,500 grains/ft$^3$, how many grains of hardness can be removed between regeneration cycles?

\[
\frac{54 \text{ inches}}{12 \text{ inches/ft}} = 4.5 \text{ ft media depth}
\]

\[
0.785(8 \text{ ft})^2(4.5 \text{ ft}) = 226.08 \text{ ft}^3
\]

\[
(226.08 \text{ ft}^3)(12,500 \text{ grains/ft}^3) = 2,826,000 \text{ grains removed}
\]

**Example 5.96**

An up flow ion exchange softener measures 8 feet wide and 12 feet long. The softener is filled with 65-inches of high capacity ion exchange media for softening.
The manufacturer’s information states the exchange capacity of the media is 32,000 gr/ft$^3$. Find the hardness removal capacity in grains for the softener.

\[
\frac{\text{65 inches}}{12 \text{ inches/ft}} = 5.42 \text{ ft media depth}
\]

\[
(8 \text{ ft})(12 \text{ ft})(5.42 \text{ ft}) = 520.32 \text{ ft}^3
\]

\[
(520.32 \text{ ft}^3)(32,000 \text{ grains/ft}^3) = 16,650,240 \text{ grains removed}
\]

**Example 5.97**

The exchange capacity of ion exchange media is 24,000 grains/ft$^3$. During a softener cycle it was determined that 2,450,000 grains of hardness were removed before regeneration was needed. If the ion exchange softener measures 5 feet wide and 5 feet long, how much media depth (in feet) was placed in the softener?

This example can be calculated by rearranging the equations already known as shown. Once the volume of media is known, the depth can be found using the equations to find volume.

\[
\left( \frac{\text{volume media, ft}^3}{\text{exchange capacity, grains/ft}^3} \right) = \text{grains removed}
\]

\[
\left( \text{volume media, ft}^3 \right) = \frac{\text{grains removed}}{\text{exchange capacity, grains/ft}^3}
\]

\[
\left( \text{volume media, ft}^3 \right) = \frac{2,450,000 \text{ grains removed}}{24,000 \text{ grains/ft}^3} = 102.08 \text{ ft}^3
\]

\[
\frac{102.08 \text{ ft}^3}{(5 \text{ ft})(5 \text{ ft})} = 4.08 \text{ ft media depth}
\]
**Example 5.98**

The exchange capacity of ion exchange media is 26,000 grains/ft$^3$. During a softener cycle it was determined that 3,673,800 grains of hardness were removed before regeneration was needed. If the circular ion exchange softener has 5 feet of media depth, what is the diameter of the softener in feet?

This example can be calculated by rearranging the equations already known as shown in Example 5.97. Once the volume of media is known, the area of the circular component can be found using the equations to find volume. Then you can find the diameter using the equation for the area of a circle.

\[
\text{volume, media, ft}^3 = \frac{\text{grains removed}}{\text{exchange capacity, grains/ft}^3}
\]

\[
\left(\text{volume, media, ft}^3\right) = \frac{3,673,800 \text{grains removed}}{26,000 \text{grains/ft}^3} = 141.3 \text{ft}^3
\]

\[
\frac{141.3 \text{ft}^3}{(5 \text{ ft})} = 28.26 \text{ ft}^2 \text{ media surface area}
\]

\[
0.785 (\text{diameter, ft})^2 = \text{area, ft}^2
\]

\[
\text{Diameter, ft} = \sqrt{\frac{\text{area, ft}^2}{0.785}} = \sqrt{\frac{28.26 \text{ ft}^2}{0.785}} = 6.0 \text{ ft diameter}
\]

**5.16.2 Gallons Softened Per Cycle**

Knowing the hardness removal provided under ion exchange softening allows you to find the volume of water in gallons that can be treated through a softener before regeneration is needed. This calculation is similar to a detention time problem because of the units cancelling that is done. The equation for calculating
the gallons softened per cycle is shown below. Examples using this equation follow.

\[
\frac{\text{grains hardness removed}}{\text{gpg hardness in feed water}} = \text{gallons softened per cycle}
\]

**Example 5.99**

The raw water (feed water) hardness applied to an ion exchange softener is 20 gpg. If the softener can remove 3,165,120 grains of hardness during the run cycle, how many gallons of water are softened by the unit between regeneration periods?

\[
\frac{3,165,120 \text{ grains}}{20 \text{ gpg}} = 158,256 \text{ gallons}
\]

**Example 5.100**

An ion exchange softener removes 2,450,000 grains of hardness during a run cycle. If the raw water hardness is 345 mg/L, how many gallons of water can be softened before regeneration is needed? Remember to convert mg/L to gpg for this problem.

\[
\frac{345 \text{ mg/L}}{17.1} = 20.18 \text{ gpg}
\]

\[
\frac{2,450,000 \text{ grains}}{20.18 \text{ gpg}} = 121,407 \text{ gallons}
\]

**Example 5.101**

The raw water hardness is found to be 550 mg/L. Raw water is applied to an ion exchange softener for hardness removal. If the softener can remove 3,673,800
grains of hardness during its operation, how many gallons of softened water are produced before regeneration?

\[
\frac{550 \text{mg/L}}{17.1} = 32.16 \text{gpg}
\]

\[
\frac{3,673,800 \text{grains}}{32.16 \text{gpg}} = 114,235 \text{gallons}
\]

**Example 5.102**

An ion exchange softener removes 2,450,000 grains of hardness during its operation and produces 90,674 gallons of softened water before regeneration. Based on this information, what was the raw water hardness applied to the softener in mg/L?

Again, this is a different way of working a problem. Start with a known equation and rearrange it to solve for a new equation to find what is needed.

\[
\frac{\text{grains hardness removed}}{\text{gpg hardness in feed water}} = \text{gallons softened per cycle}
\]

\[
\frac{\text{grains hardness removed}}{\text{gallons softened per cycle}} = \text{gpg hardness in feed water}
\]

\[
\frac{2,450,000 \text{grains}}{90,674 \text{gallons}} = 27.02 \text{gpg hardness in raw water}
\]

\[
(27.02 \text{gpg})(17.1) = 462 \text{mg/L}
\]
5.16.3 **Bypass Calculations**

Since ion exchange softening removes all hardness to zero, a measured amount of raw water (or ion exchange feed water) must be bypassed around the softener and blended with the softened water. (Refer to Figure 11.) These bypass calculations are needed to produce the hardness that you want in the finished water. The amount of water that bypasses the softener is based on the desired hardness and the raw water hardness as shown in the equation below.

\[ \frac{FH}{RH} \times 100 = \% \text{ bypass} \]

where \( FH \) = finished hardness
\( RH \) = raw hardness

**Example 5.103**

The raw water hardness applied to an ion exchange softener is measured at 348 mg/L. If you want the finished water hardness to be 120 mg/L, what percent of water must be bypassed around the softener?

\[ \frac{120 \text{mg/L}}{348 \text{mg/L}} \times 100 = 34.5\% \text{ bypass} \]

**Example 5.104**

After blending softened water and raw water following an ion exchange softener, the blended water hardness is 125 mg/L. If the raw water hardness was 26.9 gpg, what percent bypass was used to blend the raw water and softened water?

\[ (26.9 \text{gpg})(17.1) = 460 \text{mg/L} \]

\[ \frac{125 \text{mg/L}}{460 \text{mg/L}} \times 100 = 27.2\% \text{ bypass} \]
Example 5.105

The raw water applied to ion exchange softening is measured at 630 mg/L. According to the bypass flow meter, 19.3 percent of the raw water bypasses softening and is blended after the softener. What should be the finished water hardness after blending?

Again, rearrangement of a known equation allows you to solve this problem.

\[
\frac{FH}{RH} \times 100 = \% \text{ bypass}
\]

\[
\frac{\% \text{ bypass}}{100} (RH) = FH
\]

\[
\frac{19.3\% \text{ bypass}}{100} (630 \text{ mg/L}) = 122 \text{ mg/L}, FH
\]

Example 5.106

The finished water after blending softened water with raw water bypass is found to be 105 mg/L. According to the bypass flow meter, 37.6 percent of the raw water bypasses softening and is blended after the softener. Estimate the raw water hardness applied to the softener using the data given.

Again, rearrangement of a known equation allows you to solve this problem.

\[
\frac{FH}{RH} \times 100 = \% \text{ bypass}
\]

\[
\frac{FH}{\% \text{ bypass}} \times 100 = RH
\]
Example 5.107

Raw water used for ion exchange softening treatment is measured at 480 mg/L. The bypass flow meter is set to bypass a portion of raw water flow around the softener to blend the desired finished water hardness. If the raw water flow is 350 gpm and the bypass flow is 108 gpm, find the percent bypass around the softener, the finished water hardness in mg/L and the finished water hardness in gpg.

\[
\frac{108 \text{ gpm, bypass}}{350 \text{ gpm, raw}} \times 100 = 30.9\% \text{ bypass}
\]

\[
\frac{30.9\% \text{ bypass}}{100} (480 \text{ mg/L}) = 148 \text{ mg/L, FH}
\]

\[
\frac{148 \text{ mg/L}}{17.1} = 8.65 \text{ gpg, FH}
\]

5.16.4 Length of Softener Run Cycle

Like the gallons softened per cycle, the length of softener run cycles is similar to a detention time problem. Once you know the percent bypass and the raw water flow, you can find the flow through the softener. Using the flow through the softener and the gallons softened per cycle, you can calculate the length of each softener run cycle before regeneration is needed. The equation used to find the length of a softener cycle is given below.

\[
\text{run length, min.} = \frac{\text{gallons softened per cycle}}{\text{gpm flow to softener}}
\]
Example 5.108

An ion exchange plant is operating at a raw water flow of 250 gpm and uses 94 gpm bypass flow around the softener. Each softener cycle produces 110,640 gallons of softened water. Find the flow through the softener and the length of the softener run cycle in hours.

\[
250 \text{ gpm} \text{ raw} - 94 \text{gpm bypass} = 156 \text{gpm to softener}
\]

\[
\frac{110,640 \text{gallons softened}}{156 \text{gpm}} = 709.2 \text{min}
\]

\[
\frac{709.2 \text{min}}{60 \text{min/ hr}} = 11.8 \text{hrs.}
\]

Example 5.109

A treatment plant is operating at a raw water flow rate of 420 gpm. A 26% bypass is used to blend raw water with softened water from an ion exchange unit. The softener can treat 3,650,780 grains of hardness before regeneration is needed and the raw water hardness is 540 mg/L. Find the bypass flow (gpm), the softener flow (gpm), and the length of the softener run cycle (hours).

\[
(420 \text{gpm})(0.26) = 109 \text{gpm bypass flow}
\]

\[
420 \text{gpm raw} - 109 \text{gpm bypass} = 311 \text{gpm to softener}
\]

\[
\frac{540 \text{mg/L}}{17.1} = 31.58 \text{ gpg, RH}
\]

\[
\frac{3,650,780 \text{ grains}}{31.58 \text{ gpg}} = 115,604 \text{gallons softened}
\]
115,604 \text{gallons softened} \div 311 \text{gpm} = 371.7 \text{min}

\frac{371.7 \text{min}}{60 \text{min/ hr}} = 6.2 \text{hrs.}

\textbf{Example 5.110}

The raw water hardness is measured at 615 mg/L and is softened using the ion exchange process. The finished water hardness needed is 120 mg/L. The plant flow rate is measured at 375 gpm. The softener is 8 feet in diameter and contains 6 feet of ion exchange media. The media exchange capacity is 28,000 grains/ft³. Find the grains of hardness removed during ion exchange softening, the gallons of water softened before regeneration is needed, the bypass flow in gpm, the flow through the softener in gpm, and the length of the softener run cycle in hours. This problem has a number of steps so we will take them one at a time.

First, find the hardness removal capacity of the media.

\[ 0.785(8 \text{ ft})^2(6 \text{ ft}) = 301.44 \text{ ft}^3 \]

\[ (301.44 \text{ ft}^3)(28,000 \text{ gr/ ft}^3) = 8,443,320 \text{ grains removed} \]

Second, find the gallons of water softened before regeneration is needed.

\[ \frac{615 \text{mg/L}}{17.1} = 35.96 \text{gpg, RH} \]

\[ \frac{8,443,320 \text{ grains}}{35.96 \text{gpg}} = 234,798 \text{gallons softened} \]

Third, find the bypass flow rate and the flow rate through the softener.
\[
\frac{120 \text{mg} / L, FH}{615 \text{mg} / L, RH} \times 100 = 19.51\% \text{ bypass}
\]

\[(375 \text{gpm})(0.1951) = 73 \text{gpm bypass}\]

\[375 \text{gpm} - 73 \text{gpm} = 302 \text{gpm to softener}\]

Finally, calculate the length of the softener run cycle.

\[
\frac{234,798 \text{gallons softened}}{302 \text{gpm}} = 777.5 \text{min}
\]

\[
\frac{777.5 \text{min}}{60 \text{min/hr}} = 12.96 \text{hrs.}
\]

### 5.16.5 Salt Requirements

Sodium chloride (salt) solution is used to regenerate ion exchange media following a softener run cycle to prepare the media for the next run. The amount of salt required for regeneration is based on the salt requirements of the specific ion exchange media provided. Generally, the higher the exchange capacity is for the media, the higher the salt requirement. For most synthetic resin materials, the salt requirement may range from about 10 pounds per cubic foot of media to about 13 pounds per cubic foot of media. Salt requirements are usually specified by the media manufacturer.

The amount of salt needed for regeneration of an ion exchange softener is based on the type of media supplied, the slat requirement of the media, and the volume of media within the softener. The equation to calculate the amount of salt needed for regeneration follows.

\[
\text{ft}^3 \text{ media} \times \text{salt requirement, lbs/ft}^3 = \text{lbs salt required}
\]
Example 5.111

An ion exchange softener contains 120 cubic feet of synthetic exchange media that has a salt requirement of 12.6 pounds per cubic foot. Find the amount of salt needed (in pounds) to regenerate the softener.

\[
(120 \text{ ft}^3)(12.6 \text{lvs/ft}^3) = 1,512 \text{ lvs needed}
\]

Example 5.112

A 10 foot diameter ion exchange unit contains 4 feet of polystyrene media used for softening. The salt requirement for regeneration of the media is 12.6 pounds per cubic foot. How many pounds of salt are needed for regeneration of the softener?

\[
0.785(10 \text{ ft})^2(4 \text{ ft}) = 314 \text{ ft}^3
\]

\[
(314 \text{ ft}^3)(12.6 \text{lvs/ft}^3) = 3,956 \text{ lvs needed}
\]

Example 5.113

An upflow ion exchange softener measures 8 feet wide and 12 feet long. The media depth in the softener is 54-inches and has an exchange capacity of 28,000 grains per cubic foot. If the salt requirement of the media is 12 pounds per cubic foot, how many tons of salt are used to regenerate the softener?

\[
\frac{54 \text{ inches}}{12 \text{ in/ft}} = 4.5 \text{ feet}
\]

\[
(8 \text{ ft})(12 \text{ ft})(4.5 \text{ ft}) = 432 \text{ ft}^3
\]

\[
(432 \text{ ft}^3)(12 \text{lvs/ft}^3) = 5,184 \text{ lvs needed}
\]
5.16.6 Brine Regeneration

Ion exchange softeners typically are regenerated with brine (salt solution) to give better distribution of the salt onto the media surface. Brine is prepared by mixing water with rock salt. After a period of time, the salt dissolves into the water making a strong (saturated) brine solution. Saturated brine characteristics were given in Table 5.3. Each gallon of saturated brine contains about 2.6 pounds of dissolved salt. Knowing how many pounds of salt are needed for regeneration, the amount of brine solution can be calculated in gallons. The equation for calculating the gallons of saturated brine for regeneration follows along with examples.

\[
\frac{5.184 \text{ lbs salt}}{2,000 \text{ lbs/ton}} = 2.59 \text{ tons}
\]

\[
(8.34 \text{ lbs/gal})(SG)(\% \text{ solution}) = \text{ lbs salt/gallon}
\]

where \( SG \) = specific gravity of brine
\( \% \) = \% salt solution, decimal form

\[
\frac{\text{ lbs salt}}{\text{ lbs salt/gal}} = \text{ gallons saturated brine}
\]

Example 5.114

Saturated brine is prepared by adding a volume of water to a volume of rock salt in a storage tank. After the salt is dissolved, laboratory testing shows the solution has a specific gravity of 1.197 and contains 26\% slat by weight. How many pounds of salt are contained in each gallon of saturated brine solution?

\[
(8.34 \text{ lbs/gal})(1.197)(0.26) = 2.596 \text{ lbs salt/gallon}
\]
Example 5.115

The salt requirement for regeneration of an ion exchange softener is found to be 2,479 pounds. Based on the amount of salt in saturated brine from Example 59, how many gallons of saturated brine should be used for regeneration of the softener?

\[
\frac{2,479 \text{ lbs salt}}{2.596 \text{ lbs salt/gal}} = 955 \text{ gallons saturated brine}
\]

Example 5.116

A 10 foot diameter ion exchange unit contains 6 feet of polystyrene media used for softening. The salt requirement for regeneration of the media is 12.6 pounds per cubic foot. Saturated brine is used for regeneration and it contains 2.6 pounds of salt per gallon of solution. How many gallons of saturated brine are needed for regeneration of the softener?

\[
0.785(10 \text{ ft})^2(6 \text{ ft}) = 471 \text{ ft}^3
\]

\[
(471 \text{ ft}^3)(12.6 \text{ lbs/ft}^3) = 5,935 \text{ lbs salt needed}
\]

\[
\frac{5,935 \text{ lbs salt}}{2.6 \text{ lbs salt/gal}} = 2,283 \text{ gallons brine solution}
\]

Example 5.117

Saturated brine is used for regeneration of an ion exchange softener. The brine has a specific gravity of 1.197 and contains 26% salt by weight. The softener measures 8 feet wide and 12 feet long. The media depth in the softener is 54-inches and has an exchange capacity of 28,000 grains per cubic foot. If the salt
requirement of the media is 12 pounds per cubic foot, how many gallons of saturated brine are used to regenerate the softener?

\[
\frac{54 \text{ inches}}{12 \text{ in/ft}} = 4.5 \text{ feet}
\]

\[
(8 \text{ ft})(12 \text{ ft})(4.5 \text{ ft}) = 432 \text{ ft}^3
\]

\[
(432 \text{ ft}^3)(12 \text{ lbs/ft}^3) = 5184 \text{ lbs salt needed}
\]

\[
(8.34 \text{ lbs/gal})(1.197)(0.26) = 2.596 \text{ lbs salt/gallon}
\]

\[
\frac{5184 \text{ lbs salt}}{2.596 \text{ lbs salt/gal}} = 1997 \text{ gallons brine solution}
\]

5.16.7 **Brine Dilution**

Saturated brine addition to an ion exchange softener can result in incomplete regeneration of the ion exchange media. It is difficult at the high salt concentration to evenly disperse salt solution over the surface area of each sphere of exchange media. Dilute brine solution does a better job of evenly coating the media surface with salt. Saturated brine; therefore, is diluted with water to prepare a dilute brine solution before adding it to a softener. Dilute brine can be any concentration less than 26 percent, but should be dilute enough to spread evenly through the softener. It is common to make up 3 percent to 10 percent dilute brine concentrations for softener regeneration. The equation used to calculate the amount of dilute brine needed for regeneration follows along with examples. The amount of dilution water needed to make the dilute brine is found be simple subtraction.

\[
\left(\frac{\%\text{saturated}}{\%\text{dilute}}\right)\left(\text{gallons saturated}\right) = \text{gallons dilute}
\]
gallons dilute brine – gallons saturated brine = gallons dilution water

Example 5.118

Saturated brine is used to prepare dilute brine for regeneration of an ion exchange softener. The saturated brine is 26 percent by weight. You want to make a 5 percent dilute brine for regeneration. If 955 gallons of saturated brine contain the right amount of salt for regeneration, how many gallons of dilute brine must be prepared and how much dilution water is needed to make the dilute brine?

\[
\left(\frac{26\% \text{ saturated}}{5\% \text{ dilute}}\right) (955 \text{ gallons saturated}) = 4,966 \text{ gallons dilute}
\]

4,966 gallons dilute brine – 955 gallons saturated brine = 4,011 gallons dilution water

Example 5.119

A 10 foot diameter ion exchange unit contains 6 feet of polystyrene media used for softening. The salt requirement for regeneration of the media is 12.6 pounds per cubic foot. Saturated brine is used for regeneration and its concentration is known to be 26% (containing 2.6 pounds of salt per gallon). You want a 6% brine solution for softener regeneration and make it by diluting the saturated brine with water. How many gallons of dilute brine are needed for regeneration of the softener and how many gallons are dilution water will be required for the dilute brine make up?

\[
0.785(10 \text{ ft})^2 (6 \text{ ft}) = 471 \text{ ft}^3
\]

\[
(471 \text{ ft}^3)(12.6 \text{ lbs / ft}^3) = 5,935 \text{ lbs salt needed}
\]
\[
\frac{5.935 \text{ lbs salt}}{2.6 \text{ lbs salt/gal}} = 2,283 \text{ gallons saturated brine}
\]

\[
\left( \frac{26\% \text{ saturated}}{6\% \text{ dilute}} \right) \left( 2,283 \text{ gallons saturated} \right) = 9,893 \text{ gallons dilute brine}
\]

\[
9,893 \text{ gallons dilute brine} - 2,283 \text{ gallons saturated brine} = 7,610 \text{ gallons dilution water}
\]

**Example 5.120**

Dilute brine is used for regeneration of an ion exchange softener. The saturated brine has a specific gravity of 1.197 and contains 26% salt by weight. Ten percent (10%) dilute brine is needed for regeneration of the softener. The softener measures 8 feet wide and 12 feet long. The media depth in the softener is 65-inches and has an exchange capacity of 28,000 grains per cubic foot. The salt requirement of the media is 12.6 pounds per cubic foot. Based on the information given, find how many gallons of dilute brine are used to regenerate the softener and how many gallons of dilution water are needed for brine make up?

\[
\frac{65 \text{ inches}}{12 \text{ in/ft}} = 5.42 \text{ feet}
\]

\[
(8 \text{ ft})(12 \text{ ft})(5.42 \text{ ft}) = 520.3 \text{ ft}^3
\]

\[
(520.3 \text{ ft}^3)(12.6 \text{ lbs/ft}^3) = 6,556 \text{ lbs salt needed}
\]

\[
(8.34 \text{ lbs/gal})(1.197)(0.26) = 2.596 \text{ lbs salt/gallon}
\]

\[
\frac{6,556 \text{ lbs salt}}{2.596 \text{ lbs salt/gal}} = 2,525 \text{ gallons saturated brine}
\]
\[ \left( \frac{26\%\text{ saturated}}{10\%\text{ dilute}} \right) \left( 2,525 \text{ gallons saturated} \right) = 6,565 \text{ gallons dilute brine} \]

\[ 6,565 \text{ gallons dilute brine} - 2,525 \text{ gallons saturated brine} = 4,040 \text{ gallons dilution water} \]

**Example 5.121**

*This sample problem is set up to use calculations like the previous examples and demonstrates a more complex ion exchange problem dealing with multiple calculations. Take each step carefully, since information you find will be used for the next calculation. Refer to the previous examples as you need.*

A 280 gpm ion exchange plant is operating two ion exchange softeners in parallel (one half of the flow goes to each softener). Each softener is 7 feet in diameter and has 4.5 feet of polystyrene resin media. The exchange capacity of the media is 28,000 grains per cubic foot. The salt requirement for regeneration of the media is 12.3 pounds per cubic foot. Raw water hardness was found to be 26.3 gpg and you want the finished water hardness to be 110 mg/L. Saturated brine has a specific gravity of 1.1972 and contains 26% salt by weight. The spent chlorides following regeneration of each softener contain 240,000 mg/L as chloride and the discharge permit limits chloride waste discharge to the stream at 250 mg/L. About 4,200 gallons of spent brine are produced during regeneration of each softener. Calculate the information listed below.

1. The hardness capacity of the media,
2. The gallons softened per softener run cycle,
3. The percent bypass used for each softener,
4. The length of each softener run cycle in hours,
5. The amount of salt needed for regeneration of the media,
6. The gallons of saturated brine needed for regeneration.
7. The gallons of 8% dilute brine,

8. The gallons of dilution water needed for dilute brine make-up, and

9. The gallons of dilution water for stream discharge of spent chlorides.

**Hardness Capacity**

\[
0.785(7 \text{ ft})^2(4.5 \text{ ft}) = 173.1 \text{ ft}^3
\]

\[
(173.1 \text{ ft}^3)(28,000 \text{ gr/ ft}^3) = 4,846,800 \text{ grains}
\]

**Gallons Softened Per Cycle**

\[
\frac{4,846,800 \text{ grains}}{26.3 \text{ gpg}} = 184,289 \text{ gallons softened}
\]

**Percent Bypass**

\[
(26.3 \text{ gpg})(17.1) = 450 \text{ mg/ L, RH}
\]

\[
\frac{110 \text{ mg/ L, FH}}{450 \text{ mg/ L, RH}} \times 100 = 24.4\% \text{ bypass}
\]

**Length of Softener Run Cycle**

\[
\frac{280 \text{ gpm}}{2 \text{ units}} = 140 \text{ gpm each unit}
\]

\[
(140 \text{ gpm})(0.244) = 34 \text{ gpm bypass}
\]

\[
140 \text{ gpm} - 34 \text{ gpm bypass} = 106 \text{ gpm softened}
\]
\[
\frac{184,289 \text{ gallons softened}}{106 \text{ gpm}} = \frac{1,739 \text{ min}}{60 \text{ min/hr}} = 29 \text{ hours}
\]

**Salt Required**

\[
(173.1 \text{ ft}^3)(12.3 \text{ lbs/ft}^3) = 2,129 \text{ lbs salt}
\]

**Gallons Saturated Brine**

\[
(8.34 \text{ lbs/gal})(1.1972)(0.26) = 2.6 \text{ lbs salt/gallon}
\]

\[
\frac{2,129 \text{ lbs salt}}{2.6 \text{ lbs/gal}} = 819 \text{ gallons saturated brine}
\]

**Gallons Dilute Brine**

\[
\left(\frac{26\%}{8\%}\right)(819 \text{ gal saturated brine}) = 2,662 \text{ gal dilute brine}
\]

**Gallons Dilution Water**

\[
2,662 \text{ gal dilute} - 819 \text{ gal saturated} = 1,843 \text{ gal dilution water}
\]

### 5.16.8 Gallons Dilution Water for Stream Discharge

This problem has not yet been introduced, but is similar to dilution of the saturated brine. You should be prepared to calculate dilution water for discharge to a receiving stream as it is presented to you.

\[
\left(\frac{240,000 \text{ mg/L}}{250 \text{ mg/L}}\right)(4,200 \text{ gal spent brine}) = 4,032,000 \text{ gallons combined flow}
\]
Chapter Six
6.0 Primary Treatment – Typical Wastewater Problems

6.1 Flow Conversions

GPM to GPD

To convert gallons per minute (gpm) to gallons per day (gpd), multiply by 1,440 (the number of minutes in a day).

\[ 20 \text{ gpm} \times 1440 \text{ min/day} = 28,800 \text{ gpd} \]

GPD to MGD

To convert gallons per day to million gallons per day (mgd), move the decimal point six places to the left (this is the same as dividing by one million).

**Example 1**

\[ \frac{188,000 \text{ gpd}}{1,000,000} = 0.188 \text{ mgd} \]

GPM to MGD

To convert gallons per minute to million gallons per day, multiply by 1,440 minutes per day (converting to gpd) and then divide by one million (or move the decimal point six places to the left).

**Example 2**

\[ 16 \text{ gpm} \times 1,440 \text{ min/day} = 23,040 \text{ gpd} \]

\[ \frac{23,040 \text{ gpd}}{1,000,000} = 0.023040 \text{ mgd} \]
Another way to convert gpm to mgd is to use a conversion factor. 1 mgd = 694.4 gpm/mgd as shown below. Converting 16 gpm to mgd is done by dividing by 694.4 gpm/mgd.

\[
\frac{1,000,000 \text{ gpd}}{1,440 \text{ min/day}} = 694.4 \text{ gpm/mgd}
\]

\[
\frac{16 \text{ gpm}}{694.4 \text{ gpm/mgd}} = 0.023040 \text{ mgd}
\]

**MGD to GPD**

To convert mgd to gpd, multiply by 1,000,000.

**Example 3**

\[0.25 \text{ mgd} \times 1,000,000 = 250,000 \text{ gpd}\]

**MGD to GPM**

To convert mgd to gpm, multiply by 1,000,000 and then divide by 1,440 minutes per day, or simply multiply by 694.4gpm/mgd.

**Example 4**

\[
\frac{(0.25 \text{ mgd})(1,000,000)}{1,440 \text{ min/day}} = 173.6 \text{ gpm}
\]

or

\[
(0.25 \text{ mgd})(1,000,000) = 250,000 \text{ gpd}
\]

\[
\frac{250,000 \text{ gpd}}{1,440 \text{ min/day}} = 173.6 \text{ gpm}
\]

or

\[
(0.25 \text{ mgd})(694.4 \text{ gpm/mgd}) = 173.6 \text{ gpm}
\]
6.2 Detention Time

Equation

\[
Detention \ time, \ hrs = \frac{\left( \text{Tank volume, gal} \right)\left(24\text{hrs/day}\right)}{\left(\text{Flow, gpd}\right)}
\]

An easy way to visualize and use this equation is in a Davidson Pie Chart shown below.

6.2.1 Calculating Detention Time

To determine detention time in hours when the flow and tank volumes are known, cover the Detention Time portion of the pie chart as shown below. What is left uncovered is the correct equation.
Example 1
A rectangular basin 12 feet long and 9 feet wide is 6 feet deep. It treats a flow of 90,000 gallons per day. Determine the basin detention time in hours.

Equation

\[ Detention\ time,\ hrs = \frac{\text{Tank volume, gal}}{\text{Flow, gpd}} \times \frac{24\ hrs}{\text{day}} \]

Steps to solve the problem.

1. Determine tank volume in gallons.

\[ V = \text{length} \times \text{width} \times \text{depth} \]
\[ V = (12\ feet) \times (9\ feet) \times (6\ feet) \]
\[ V = 648\ ft^3 \]

2. To convert from cubic feet to gallons multiply by 7.48 gal/ft³.

\[ (648\ ft^3) \times (7.48\ gal/\ ft^3) = 4,847\ gallons \]

3. Calculate the resulting detention time in hours using the equation stated above.

\[ Detention\ time,\ hrs = \frac{(4,847\ gal)(24\ hrs/\ day)}{90,000\ gpd} = 1.29\ hrs \]

\[ 1.29,\ hrs = \frac{116,328}{90,000\ gpd} \]

NOTE: To convert hours to minutes, multiply the decimal by 60 minutes per hour.

EXAMPLE \[ (.29\ hrs)(60\ minutes/hr) = 17\ minutes \]
6.3 Calculating Flow

If you know what the tank volume and detention times are and want to calculate the flow, cover the flow section of the pie chart to set up the correct equation as shown below.

\[
\text{Flow, gpd} = \frac{(\text{Tank volume, gal}) (24 \text{ hrs/day})}{\text{Detention time, hrs}}
\]

**Example 1**

Determine the required flow in gpd for a setting basin that is 20 feet long, 10 feet wide, and 6 feet deep with a detention time of 3 hours.

Steps to solve the problem.

1. Determine tank volume in gallons.

\[
V = (\text{length})(\text{width})(\text{depth})
\]

\[
V = (20 \text{ feet})(10 \text{ feet})(6 \text{ feet})
\]

\[
V = 1,200 \text{ ft}^3
\]

2. To convert from cubic feet to gallons, multiply by 7.48 gal/ft\(^3\).

\[
(1,200 \text{ ft}^3)(7.48 \text{ gal/ft}^3) = 8,976 \text{ gallons}
\]
3. Calculate the resulting flow rate in gpd using the detention time and the equation stated above.

\[
Flow, \text{ gpd} = \frac{\left(\text{Tank volume, gal}\right)(24\text{hrs/day})}{\left(\text{Detention time, hrs}\right)}
\]

\[
Flow, \text{ gpd} = \frac{(8,976 \text{gal})(24\text{hrs/day})}{(3\text{hrs})}
\]

\[
71,808, \text{gpd} = \frac{215,424}{(3\text{hrs})}
\]

### 6.4 Calculating Tank Volume

This same technique could be used to determine tank volume if you knew the detention time and flow. Cover the portion of the pie chart that is unknown to set up the correct equations as shown below.
Example 1
Find the tank volume in gallons if a treatment plant is operating at a flow rate of 60,000 gpd and the detention in the settling basin is 4.2 hrs.

\[
\left( \text{Tank volume, gal} \right) = \frac{\left( \text{Detention time, hrs} \right)(\text{Flow, gpd})}{(24\text{hrs/day})}
\]

\[
\left( \text{Tank volume, gal} \right) = \frac{(4.2\text{hrs})(60,000\text{gpd})}{(24\text{hrs/day})} = 10,500\text{gal}
\]

6.5 Surface Overflow Rate

The faster the water leaves a sedimentation tank, or clarifier, the more turbulence is created and the more suspended solids are carried out with the effluent water. Overflow rate—the speed at which water leaves the sedimentation tank—is controlled by an increase or decrease in flow rate to the tank.

The surface overflow rate is a measurement of the amount of water leaving a sedimentation tank per square foot of tank surface area. The treatment plant operator must be able to determine the surface overflow rate that produces the best-quality effluent leaving the tank. High velocities can and will result in increased suspended solids and turbidity in the effluent water. This is due in part to settled solids being picked up with the high velocity and carried back into the water stream that exits the tank. High horizontal velocities also prevent suspended solids from settling and carry them through the tank with the water flow.

Surface overflow rate is expressed as the gallons per day of flow up and over each square foot of tank surface (gpd/ft²). Calculations of surface overflow rate are made using the equation below.

\[
\text{Surface overflow rate, gpd / ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]
Notice that the depth of the sedimentation tank is not a consideration in the calculation of surface overflow rate. Figure 6.3 A& B depicts a surface overflow for both rectangular and circular tanks.

**Example 1**

The flow to a treatment plant is 1.2 mgd. If the sedimentation tank is 70 feet long 15 feet wide, and 7 feet deep, what is the surface overflow rate in gpd/ft$^2$?

\[
1.2 \text{mgd} = 1,200,000 \text{gpd} \quad \text{(move decimal right 6 places)}
\]

\[
\text{Surface area, ft}^2 = (\text{length})(\text{width}) = (70 \text{ ft})(15 \text{ ft}) = 1,050 \text{ ft}^2
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{1,200,000 \text{gpd}}{1,050 \text{ft}^2} = 1,143 \text{gpd/ft}^2
\]
**Example 2**

A circular sedimentation basin with a 55-ft. diameter receives a flow of 2,075,000 gpd. What is the surface overflow rate in gpd/ft$^2$?

\[
Surface \ area, \ ft^2 = 0.785d^2 = 0.785(55 \text{ ft})(55 \text{ ft}) = 2,375 \text{ ft}^2
\]

\[
Surface \ overflow \ rate, \ gpd/ft^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
Surface \ overflow \ rate, \ gpd/ft^2 = \frac{2,075,000 \text{ gpd}}{2,375 \text{ ft}^2} = 873.7 \text{ gpd/ft}^2
\]

In the previous two examples, the surface overflow rate was the unknown factor. However, *any one* of three factors (surface overflow rate, water flow rate, or surface area) might be unknown. If the other two factors are known, the same mathematical setup can be used to solve for the unknown value.

**Example 3**

A 20-foot diameter tank has a surface overflow area of 896.4 gpd/ft$^2$. What is the daily flow to the tank?

\[
Surface \ area, \ ft^2 = 0.785d^2 = 0.785(20 \text{ ft})(20 \text{ ft}) = 314 \text{ ft}^2
\]

\[
Surface \ overflow \ rate, \ gpd/ft^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
896.4 \text{ gpd/ft}^2 = \frac{\text{flow, gpd}}{314 \text{ ft}^2}
\]

\[
(896.4 \text{ gpd/ft}^2)(314 \text{ ft}^2) = \text{flow, gpd} = 281,470 \text{ gpd}
\]
Example 4

A sedimentation tank receives a flow of 5.4 mgd. If the surface overflow rate is 689 gpd/ft², what is the surface area of the sedimentation tank?

\[
\text{Surface overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{Tank surface area, ft}^2}
\]

\[
689 \text{ gpd/ft}^2 = \frac{5,400,000 \text{ gpd}}{\text{Tank surface area, ft}^2}
\]

\[
\text{Tank surface area, ft}^2 = \frac{5,400,000 \text{ gpd}}{689 \text{ gpd/ft}^2} = 7,837.4 \text{ ft}^2
\]

6.6 Weir Overflow Rate

The faster the water leaves a sedimentation tank, or clarifier, the more turbulence is created and the more suspended solids are carried out with the effluent water. Overflow rate, the speed at which water leaves the sedimentation tank, is controlled by an increase or decrease in flow rate to the tank.

The weir overflow rate is a measurement of the amount of water leaving a sedimentation tank per linear foot of weir length. In simple terms, weir overflow rate is an expression indicating the velocity at which water travels upward in the tank to reach the effluent weirs. High velocities can and will result in increased suspended solids and turbidity in the effluent water. This is due to settled solids being picked up with the high velocity and carried back into the water stream that exits the tank.

In most cases, weirs have two equal sides, which double the weir length per running foot of weir. The treatment plant operator must be able to determine the weir overflow rate that produces the best-quality effluent leaving the tank. Weir overflow is expressed as the gallons per day flow up and over each linear
foot of tank weir. Calculations of weir overflow rate are made using the equation given below.

\[
\text{Weir overflow rate, gpd} / \text{ft}^2 = \frac{\text{flow, gpd}}{\text{weir length, ft}}
\]

Notice that the depth of the sedimentation tank is not a consideration in the calculation of the weir overflow rate. Figure 6.4A, B, & C depicts weir overflow for both rectangular and circular tanks.
**Example 1**

A rectangular sedimentation tank is 40 feet wide, 100 feet long and 14 feet deep. The tank has four (4) finger type weirs extending 24 feet into the tank from the effluent wall (see Figure 6.4 A). If the flow to the tank is 2,500 gpm, find the weir overflow rate for sedimentation.

1. Find the total weir length remembering that each weir has two sides.

\[ 4 \text{ weirs} \times 24 \text{ feet} \times 2 \text{ sides} = 192 \text{ feet total weir length} \]

2. Convert the flow rate in gpm to gpd. (We will assume the tank is operated 24 hours per day.

\[ (2,500 \text{ gpm})(1,440 \text{ min/day}) = 3,600,000 \text{ gpd} \]

3. Calculate the weir overflow rate using the equation given.

\[ \text{Weir overflow rate, gpd/ft}^2 = \frac{\text{flow, gpd}}{\text{weir length, ft}} \]

\[ 18,759 \text{ gpd/ft} = \frac{3,600,000 \text{ gpd}}{192 \text{ ft}} \]

**Example 2**

Using the same sedimentation tank in Example 6.4 A above, assume the effluent wall has three rectangular openings in the wall that serve as the effluent weirs. If each opening is 4 feet wide, calculate the weir overflow rate for the tank.

1. Find the total length of weir for the tank.

\[ 3 \text{ weirs} \times 4 \text{ feet length} = 12 \text{ feet total weir length} \]
2. Calculate the weir overflow rate based on the flow rate found in Example 5.37.

\[
\text{Weir overflow rate, gpd/ft}^2 = \frac{3,600,000 \text{ gpd}}{12 \text{ ft}} = 300,000 \text{ gpd/ft}
\]

One should be able to see how the proper weir length becomes necessary for sedimentation. The 300,000 gpd/ft weir overflow rate is more than 15 times greater than typical design standards. This overflow rate likely would produce a very high exit velocity and would result in significant solids carryover from the tank.

**Example 3**

A circular tank with a diameter of 40 feet has a peripheral weir (near the outside wall or around the periphery) placed 2 feet inside the tank wall (see Figure 6.4 B). If the flow rate through the tank is 2,200,000 gpd, find the weir overflow rate for the tank.

1. Find the diameter of the peripheral weir. Since it is 2 feet inside the tank wall, we must use two times that dimension to find the weir diameter.

\[
40 \text{ feet} - (2)(2 \text{ feet}) = 36 \text{ feet} \quad \text{weir diameter}
\]

2. Find the weir length using the equation for circumference of a circle \(C = \pi d\).

\[
C = \pi d = (3.14)(36 \text{ ft}) = 113.1 \text{ ft} \quad \text{weir length}
\]

3. Calculate the weir overflow rate using the equation given.

\[
\text{Weir overflow rate, gpd/ft}^2 = \frac{2,200,000 \text{ gpd}}{113.1 \text{ ft}} = 19,452 \text{ gpd/ft}
\]
Example 4

A circular clarifier has a diameter of 52 feet. The clarifier has radial launders that each measure 16-inches wide and 19 feet long (see Figure 6.4 C). If the clarifier is treating 2.5 mgd, what is the weir overflow rate?

1. Find the total length of weir. (Remember these weirs have 2 sides.)

\[ 8 \text{ weirs} \times 19 \text{ feet} \times 2 \text{ sides} = 304 \text{ ft total weir length} \]

2. Calculate the weir overflow rate using the flow rate provided. Remember to convert the flow rate in mgd to gpd.

\[ \text{Weir overflow rate, gpd/ft} = \frac{2,500,000 \text{ gpd}}{304 \text{ ft}} = 8,224 \text{ gpd/ft} \]

6.7 Pumping Rates

The rate of flow produced by a pump is expressed as the volume of water pumped of water pumped during a given period of time. The mathematical equation used for pumping rate problems can usually be determined from a verbal statement of the problem.

VERBAL: What is the pumping rate in “gallons per minute”?

MATH: \[ X = \text{pumping rate, gallons per Minute} \]

VERBAL: What is the pumping rate in “gallons per hour”?

MATH: \[ X = \text{pumping rate, gallons per hour} \]

The number of gallons pumped during a period can be determined either by a flow meter or by measuring the number of gallons pumped into or out of a tank.
Example 1

The totalizer of the meter on the discharge side of your pump reads in hundreds of gallons. If the totalizer shows a reading of 10800 at 1:00 p.m. and 31200 at 1:30 p.m., what is the pumping rate expressed in gallons per minute?

The problem asks for pumping rate in gallons per minute (gpm), so the mathematical setup is as shown below.

\[
\text{pumping rate} = \frac{\text{gallons}}{\text{Minute}}
\]

To solve the problem, fill in the blanks (number of gallons and number of minutes) in the equation. The total gallons pumped are determined from the totalizer readings.

\[
\text{31,200 gal} - \text{10,800 gal} = 20,400 \text{ gal}
\]

The volume was pumped between 1:00 p.m. and 1:30 p.m., for a total of 30 minutes. From this information calculate the gpm pumping rate.

\[
\text{pumping rate} = \frac{20,400 \text{ gallons}}{30 \text{ Minutes}} = 680 \text{ gpm}
\]

Instead of using totalizer readings to calculate the average pumping rate for a period of a few minutes or hours (as in Example 1), you can read the instantaneous pumping rate or flow rate - the flow rate or pumping rate at one particular moment - directly from many flow meters. Other flow meters require that you perform calculations to determine the instantaneous flow rate as illustrated in the example that follows.
**Example 2**

The venturi meter on the discharge side of your pump has a throat diameter of 4 inches. The head differential between the high-pressure tap and the low-pressure tap is 1.5 ft. Use the nomograph shown in Figure 6.5 A, to determine the pumping rate in gallons per minute.

To determine the gallon per minute pumping rate, first determine the cubic feet per second pumping rate from the nomograph. Then convert the flow rate to gallons per minute.

Draw a line on the nomograph from 4 inches on the diameter of throat section scale to 1.5 feet on the head differential scale. The point where the line crosses the middle scale indicates the approximate flow rate of 0.85 ft³/sec. Now convert the cubic-feet-per-second pumping rate to gallons per minute.
FIGURE 6.5 A - Flow Rate Nomograph for Venturi Meter

\[(0.85 \text{ ft}^3/\text{s})(7.48 \text{ gal/ft}^3)(60 \text{ s/min}) = 81.48 \text{ gpm pumping rate}\]

Note: In an actual water system environment, correction factors may be needed in the use of this nomograph. Hydraulics chapter 7 deals with this subject.
When there is no meter on the discharge side of the pump, you can determine the pumping rate by measuring the number of gallons pumped into or out of a tank during a given time period. Let’s look at three examples of determining total gallons pumped demonstrated by Figure 6.5 B.

In the first example (Figure 6.5 B1), the pump is discharging into an empty tank with the outlet valve to the tank closed. The total gallons pumped during the given time are the number gallons in the tank at the end of the pumping test.

Since it is not always possible or practical to pump into an empty tank, the pumping test is sometimes conducted by pumping into a tank that already contains water(Figure 6.5 B2). The outlet valve is closed and the total gallons pumped (shaded area) during the given time is determined from the rise in water level.

In Figure 6.5 B3, the pump is located on the outlet side of the tank. To conduct a pumping test, the inlet valve of the tank is shut off. When the pump is turned on, the total gallons pumped (shaded area) during the given time is determined from the drop in water level.
**Example 3**

During a 15 minute pumping test, 15,820 gallons were pumped into an empty rectangular tank (Figure 6.5 C). What is the pumping rate in gallons per minute?

The problem asks for the pumping rate in gallons per minute, so the mathematical setup below is used.

\[
pumping\ rate = \frac{\text{gallons}}{\text{Minute}}
\]
Fill in the information given and perform the calculations to complete the problem.

\[
pumping \ rate = \frac{15,820 \text{ gallons}}{15 \text{ minutes}} = 1,055 \text{ gpm}
\]

\[1.5 \text{ meters deep} \]
\[8 \text{ meters long} \]
\[6 \text{ meters wide} \]

**FIGURE 6.5 D - Schematic for Example 4**

**Example 4**

An empty rectangular tank (Figure 6.5 D) 8 meters long and 6 meters wide can hold water to a depth of 1.5 meters. If this tank is filled by a pump in 55 minutes, what is the pumping rate in gallons per minute (gpm)?

In this example, the entire tank was filled during the 55-minute pumping test. Therefore the total volume pumped is equal to the capacity of tank in gallons.

\[Volume = (area \ of \ rectangle)(depth)\]

\[72m^3 = (8 \text{ meters})(6 \text{ meters})(1.5 \text{ meters})\]

Convert this volume to gallons. Assume one cubic meter is 264.2 gallons. This conversion factor is shown below.

\[
\left(\frac{m^3}{1}\right) \left(\frac{1,000L}{m^3}\right) \left(\frac{gal}{3.785L}\right) = 264.2 \text{ gal/m}^3
\]
\[
(72m^3)(264.2\text{ gal/m}^3) = 19,022.4\text{ gal}
\]

Then use the total volume pumped and the time period of the pumping test (55 minutes) to calculate the pumping rate.

\[
pumping \ rate = \frac{\text{gallons}}{\text{Minute}}
\]

\[
pumping \ rate = \frac{19,022.4\text{ gal}}{55\text{ min}} = 346\text{ gpm}
\]

**Example 5**

A tank 40 feet in diameter is filled with water to a depth of 3 feet (Figure 6.5E). To conduct a pumping test, the outlet valve to the tank is closed and the pump is allowed to discharge into the tank. After 75 minutes the water level rose 5.25 feet. What is the pumping rate in gallons per minute?

In this problem, the total volume pumped is represented by the cross-hatched area on the diagram (tank diameter = 40 feet and water depth = 2.25 feet).

Calculate the volume pumped in cubic feet.

\[
Volume = 0.785(d)^2(depth)
\]

\[
0.785(40\text{ ft})^2(2.25\text{ ft}) = 2,826\text{ ft}^3
\]
Now convert the cubic foot volume to gallons.

\[
(2.826 \text{ ft}^3)(7.48 \text{ gal/ft}^3) = 21.138 \text{ gal}
\]

The pumping test was conducted over a period of 75 minutes. Using the volume pumped (in gallons) and the time (in minutes) it took to pump the total volume, calculate the pumping rate in gallons per minute.

\[
\frac{21.138 \text{ gallons}}{75 \text{ minutes}} = 281.8 \text{ gpm}
\]

**Example 6**

A one (1.0) hour pumping test is run on a pump located on the outlet side of a tank (Figure 6.7 F). The inlet valve is closed and the pump is started. At the end of the test, the water level in the tank has dropped 1 meter. If the tank water depth before pumping was 2 meters, what is the pumping rate in gallons per minute?

The total volume pumped is represented by the crosshatched area on the Diagram. (Notice that information pertaining to the water depth before pumping is not needed in solving this problem. The drop in the water level is the essential depth information.)
Calculate the total volume pumped in cubic meters and convert to gallons.

\[
(15\text{m})(9\text{m})(1\text{m}) = 135\text{m}^3
\]

\[
(135\text{m}^3)(264.2\text{gal/m}^3) = 35,667\text{gal}
\]

Convert one (1.0) hour to minutes.

\[
(1\text{hr})(60\text{min/hr}) = 60\text{min}
\]

Now determine the pumping rate.

\[
\frac{35,667\text{gal}}{60\text{min}} = 594.5\text{gpm}
\]

Quite often lift stations have an influent flow that is different from the effluent flow. Under these operations, a lift station can either be filling (increasing water level) or draining (decreasing water level). Typical wet well operations are a good example of such operations. If the influent rate is more than the high service pumping rate, the wet well level will rise. If the high service flow rate if greater than the influent rate, the wet well level will fall. The trick to solving these problems is to find the difference in flow rate - either flow into or flow out of the wet well - based on the flow rates given. The examples that follow show the calculations needed to solve these types of problems.

**Example 7**

A wet well has a water depth of 8 feet at 8:00 am. The wet well measures 30 feet wide and 55 feet long. The lift station is receiving wastewater at a rate of 1.2 mgd at the same time a 350 gpm high service pump is moving wastewater to the collection system. Find whether the wet well level is rising or falling and then find out how long it will take (in hours) for the wet well level to reach 12 feet.
First, find the difference in flow rates. This will help you determine if the wet well level is rising or falling.

\[
(1.2 \text{ mgd})(694.4 \text{ gpm/mgd}) = 833 \text{ gpm in}
\]

\[
833 \text{ gpm} - 350 \text{ gpm} = 483 \text{ gpm excess going in}
\]

Based on the calculations, more flow is going into the wet well than is being pumped out, so the wet well level is rising.

Next, calculate the volume of water (gallons) being added to the wet well.

\[
12 \text{ ft} - 8 \text{ ft} = 4 \text{ ft added}
\]

\[
(4 \text{ ft})(30 \text{ ft})(55 \text{ ft}) = 6,600 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 49,368 \text{ gallons}
\]

Finally, calculate the detention time needed to raise the wet well level 4 feet. (The detention time is based on the excess flow into the wet well.)

\[
\frac{49,368 \text{ gallons}}{483 \text{ gpm}} = \frac{102 \text{ min}}{60 \text{ min/hr}} = 1.7 \text{ hours}
\]

**Example 8**

A treatment plant is producing 500 gpm during its operation. During this time, the wet well level is found to be 16 feet. A 900 gpm high service pump is operating to pump water to the collection system. Based on plant experience, the wet well level cannot go below 3.5 feet of the high service pumps lose suction. If the wet well diameter is 30 feet, how long can the plant maintain the current operations before the high service pump loses suction?
First, find the difference in pumping rates.

\[ 900 \text{ gpm out} - 500 \text{ gpm in} = 400 \text{ gpm excess out} \]

Next find the volume of water (gallons) that can be pumped from the wet well before it falls to the 3.5 ft level.

\[ 16 \text{ ft} - 3.5 \text{ ft} = 12.5 \text{ ft pumped out} \]

\[ (12.5 \text{ ft})(30 \text{ ft})^2(0.785) = 8,831.25 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 66,058 \text{ gallons} \]

Finally, find the detention time to pump down the wet well based on the excess flow rate being pumped out.

\[ \frac{66,058 \text{ gallons}}{400 \text{ gpm}} = \frac{165 \text{ min}}{60 \text{ min/hr}} = 2.75 \text{ hours} \]

### 6.8 Pump Horsepower and Efficiency

Pumps are machines that are used to lift water from one elevation to another elevation and thus deliver water under pressure. Pump horsepower is the energy necessary to lift water the height required and is known as water horsepower. Horsepower calculations are made using the conversion factors and equations given below.

1 Horsepower = 746 watts of power

1 Horsepower = 0.746 kilowatts of power

\[ \text{water horsepower (whp)} = \frac{(\text{flow, gpm})(\text{head, ft})}{3,960} \]
**Example 1**

A pump must pump 1,500 gallons per minute against a total head of 30 feet. What water horsepower is required to do the work?

\[ whp = \frac{(1,500 \text{ gpm})(30 \text{ ft})}{3,960} = 11.4 \]

Note: Dividing by 3,960 in the equation is derived by converting gallons per minute to foot pounds per minute and then dividing by 33,000 foot pounds per minute to calculate horsepower. This gives a new conversion factor 3,960.

The previous sample problem does not take into account that a motor, driven by electric current, is required drive a pump to do the work. Neither the pump nor motor are 100 percent efficient due to friction and slippage. Not all the power supplied by the motor to the pump (brake horsepower) is used to lift the water (water horsepower). Not all electric current driving the motor (motor horsepower) is used to make the pump work.

Pumps usually are between 50% and 85% efficient and electric motors are generally between 80% and 95% efficient. These efficiency ratings are provided in manufacturer’s information. Losses in electric current, couplings, bearings, and friction all contribute to loss of efficiency in pump-motor systems. Therefore, the water horsepower needed to deliver flow must be increased (brake horsepower) to drive the pump, which must be increased (motor horsepower) to compensate for the overall losses in the pump system. This is illustrated in Figure 6.6A.

![FIGURE 6.6A - Illustration of Pump and Motor Efficiencies](Image)
6.8.1 Pump and Efficiency Equations

\[
\text{brake horsepower (bhp)} = \frac{(\text{flow, gpm})(\text{head, ft})}{(3.960)(\text{pump eff,} \%, \text{motor eff,} \%)}
\]

\[
\text{motor horsepower (mhp)} = \frac{(\text{flow, gpm})(\text{head, ft})}{(3.960)(\text{pump eff,} \%, \text{motor eff,} \%)}
\]

\[
\text{pump efficiency,} \% = \frac{\text{whp}}{\text{bhp}} \times 100
\]

\[
\text{motor efficiency,} \% = \frac{\text{bhp}}{\text{mhp}} \times 100
\]

\[
\text{overall efficiency,} \% = \frac{\text{whp}}{\text{mhp}} \times 100
\]

**Example 1**

In the previous sample, a pump must provide 1,500 gallons per minute against a total head of 30 feet. Water horsepower required to deliver the water was calculated to be 11.4 whp. Water horsepower does not take into account pump and motor efficiencies. Suppose that the motor efficiency is 85 percent and the pump efficiency is 90 percent. What would the overall horsepower requirement be?

**Equation**

\[
\text{Overall horsepower} = \frac{\text{whp}}{(\text{pump eff,} \%)(\text{motor eff,} \%)}
\]

\[
14.0 \text{hp} = \frac{11.4 \text{whp}}{(0.90)(0.85)}
\]
Example 2

If 11 Kilowatts (kW) of power are supplied to a motor, and the brake horsepower is known to be 13 bhp, what is the efficiency of the motor?

1 Horsepower = 0.746 kilowatts power

1. Convert kilowatts to horsepower.

\[
14.75\text{whp} = \frac{11\text{kW}}{0.746\text{kW/hp}}
\]

2. Calculate the percentage efficiency of the motor.

\[
\text{motor efficiency,}\% = \frac{bhp}{mhp} \times 100
\]

\[
88.1\% = \text{motor efficiency} = \frac{13\text{bhp}}{14.75\text{mhp}} \times 100
\]

6.8.2 Pumping Costs

If the motor horsepower needed for a pumping job is 22 mhp, and the cost for power is $0.08 per kilowatt-hour (kwh), what is the cost of operating the motor for two hours?

1. Convert horsepower to kilowatts.

\[
kW = (mhp)\times(0.746\text{kW/hp})
\]

\[
16.4kW = (22mhp)\times(0.746\text{kW/hp})
\]

2. Multiply kilowatts by time.

\[
(16.4kW)(2\text{hrs}) = 32.8\text{kwh}
\]

3. Multiply kilowatt-hours by the cost per kwh.
\[(32.8 \text{kwh})(0.08/\text{kwh}) = 2.62\]

Total cost for two hours operating time is $2.62.

### 6.9 Chemical Dosing

**Equation**  
Chemical Feed in pounds per day (lbs/day)  

\[
\text{chemical feed (lbs/day)} = (\text{flow, mgd})(\text{dose, mg/L})(8.34 \text{lbs/gal})
\]

An easy way to visualize and use this equation is in a Davidson Pie Chart seen below.

#### 6.9.1 Chemical Feed

To find the Chemical Feed, in lbs/day, cover the Chemical Feed portion of the pie chart as seen below. What is left uncovered represents the correct equation.

\[
\text{Chemical Feed in pounds per day is equal to }
(\text{Flow, mgd})(\text{Dose, mg/L})(8.34 \text{lbs/gal})
\]
Example 1

Determine the chlorinator setting in pounds per day if you have a flow of 200 gpm and your target chlorine dose is 2.0 mg/L.

1. Convert the flow from gpm to mgd.
   Multiply flow in gpm by 1,440 (the number of minutes in a day) to convert to gallons per day (gpd).

   \[
   200 \text{ gpm} \times 1,440 \text{ min/day} = 288,000 \text{ gpd}
   \]

   Move the decimal point six places to the left to convert to millions gallons per day (mgd), or divide the flow in gpm by 694.4 gpm/mgd to convert directly to mgd.

   \[
   \frac{200 \text{ gpm}}{694.4 \text{ gpm/mgd}} = 0.288 \text{ mgd}
   \]

2. Use the equation for chemical feed to determine the chlorinator setting in pounds per day.

   \[
   \text{Chemical Feed, lbs/day} = (\text{Flow, mgd})(\text{Dose, mg/L})(8.34 \text{ lbs/gal})
   \]

   \[
   \text{Chemical Feed, lbs/day} = (0.288 \text{ mgd})(2.0 \text{ mg/L})(8.34 \text{ lbs/gal})
   \]

   \[
   \text{Chemical Feed, lbs/day} = 4.8 \text{ lbs/day}
   \]
6.9.2 Calculating Dose

If you know what the chemical feed and flow are and want to calculate the dose, cover the dose section of the pie chart to set up the correct equation as shown below.

![Diagram of pie chart]

\[ Dose, \text{mg} / L = \frac{\text{Chemical feed, lbs/day}}{(\text{Flow, mgd})(8.34\text{lbs/gal})} \]

**Example 1**

A 0.52 mgd system is feeding chlorine at a rate of 12 lbs/day. What will be the resulting chlorine dose?

\[ Dose, \text{mg} / L = \frac{12\text{lbs/day}}{(0.52\text{mgd})(8.34\text{lbs/gal})} \]

\[ 2.76\text{mg} / L = \frac{12\text{lbs/day}}{4.34} \]
6.9.3 Calculating Flow

If you know what the chemical feed and dose rates are, and want to calculate the flow, cover the flow section of the pie chart set up the correct equation as shown below.

\[
Flow, mgd = \frac{Chemical \ feed, lbs / day}{(Dose, mg / L)(8.34 lbs / gal)}
\]

**Example 1**

A treatment plant is feeding 24 lbs/day of alum at a dose of 45 mg/L. What is the flow rate used for the treatment?

\[
Flow, mgd = \frac{24 lbs / day}{(45 mg / L)(8.34 lbs / gal)}
\]

\[
0.0639 mgd = \frac{24 lbs / day}{375.3}
\]
6.10 Chlorine Demand

Chlorine demand is defined as the amount of chlorine used up in the reaction following disinfection based on the dosage applied and the residual that remains after a period of time. The equation for chlorine demand is shown below. A more complete chlorine demand definition is given in Appendix A.

\[ \text{chlorine demand} = \text{dosage} - \text{residual} \]

It is important to note that the residual chlorine needed to calculate these types of problems is the total chlorine residual, not the free chlorine residual. Using the free chlorine residual to find chlorine demand will result in an error because it ignores the combined chlorine residual in solution.

Example 1

What is the chlorine demand in milligrams per liter if the chlorine dose is 3.2 mg/L and the chlorine residual is 0.3 mg/L?

Equation

\[ \text{Chlorine demand, mg/L} = \text{Dose, mg/L} - \text{residual, mg/L} \]

1. Calculate the chlorine demand.

\[ \text{Chlorine demand, mg/L} = 3.2 \text{mg/L} - 0.3 \text{mg/L} = 2.9 \text{mg/L} \]

The chlorine dosage is equal to the chlorine demand plus the residual. This new equation is found by rearranging the initial equation given earlier.

Equation

\[ \text{Dose, mg/L} = \text{Chlorine demand, mg/L} + \text{residual, mg/L} \]

The chlorine residual is equal to the chlorine dosage minus the chlorine demand. This equation also is a rearrangement of the initial equation.

Equation

\[ \text{residual, mg/L} = \text{dose, mg/L} - \text{chlorine demand, mg/L} \]
Chapter 7 Calculating Solids

7.1 Biochemical Oxygen Demand Removal, Suspended Solids Removal and Efficiency.

The BOD and SS removal efficiency gives the operator an indication of the efficiency of the clarifier. The removal of the solids may be affected by a number of factors including flow, age and type of solids and weather factors.

The desired removal efficiencies are listed below:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>20 – 35%</td>
</tr>
<tr>
<td>SS</td>
<td>50 – 65%</td>
</tr>
<tr>
<td>Settleable Solids</td>
<td>90 – 95%</td>
</tr>
<tr>
<td>Total Solids</td>
<td>10 – 15%</td>
</tr>
</tbody>
</table>

7.1.1 Solids Removal (BOD and SS)

BOD and SS removal for a process is calculated by subtracting the concentration in mg/l leaving the process from the concentration in mg/l entering the process. The difference is used in the dosage or pounds formula.

\[
\text{IN} - \text{OUT} = \text{REMOVAL}
\]

\[
\begin{align*}
\text{IN} & = 251 \text{ mg/l} \\
\text{OUT} & = 136 \text{ mg/l} \\
\end{align*}
\]

\[
\begin{align*}
\text{REMOVAL} & = 151 \text{ mg/l} \\
\text{BOD, removed} & = 115 \text{ mg/l}
\end{align*}
\]
7.1.2 Percent Removal

To calculate the percent removal or removal efficiency of the previous example the formula is:

\[
\frac{\text{IN} - \text{OUT}}{\text{IN}} \times 100\%
\]

<table>
<thead>
<tr>
<th>Influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS, mg/l</td>
<td>SS, mg/l</td>
</tr>
<tr>
<td>251 mg/l</td>
<td>136 mg/l</td>
</tr>
</tbody>
</table>

Removed:

\[
\frac{251 \text{ mg/l} - 136 \text{ mg/l}}{251 \text{ mg/l}} \times 100\% = 45.8\% 
\]

7.1.3 Pounds of Solids Removed

Example 1

If 200 mg/l of SS enters a primary clarifier and 100 mg/l of SS leaves the clarifier with a flow to the secondary clarifier of 2 MGD. How many pounds of SS are removed by the primary clarifier?

\[
\text{Lb Removed} = \text{MGD} \times 8.34 \text{lb/gal} \times \frac{\text{mg/l Removed}}{1000}
\]

\[
\text{Lb Removed} = 2 \text{ MGD} \times 8.34 \text{ lb/gal} \times (200 - 125)
\]

\[
= 1251 \text{ lbs SS removed}
\]
7.2 Population Equivalent

The population equivalent does not reflect the actual population because of commercial and industrial contribution to the waste stream.

On average a person contributes 0.2 pound suspended solids (SS) per day and is read as 0.2 lbs SS/capita, and each person contributes 0.167 pound of bio-chemical oxygen demand (BOD) which is read as 0.167 lbs BOD/capita.

If the suspended solids or bio-chemical oxygen demand entering the plant is given in pounds, the population equivalent is calculated by dividing this number by 0.2 for SS or 0.167 for BOD.

**Example 1**

What is the population equivalent if 500 lbs of SS are reaching the plant each day?

\[
\frac{500 \text{ lbs}}{0.2 \text{ lbs/cap}} = 2,500 \text{ population}
\]

**Example 2**

What is the population equivalent of 700 lbs. of BOD are reaching the plant each day?

\[
\frac{700 \text{ lbs}}{0.167 \text{ lbs/cap}} = 4,192 \text{ population}
\]

When the SS or BOD are given as a concentration and the flow to the plant is known, the chemical dose or pounds formula is used to calculate the pounds of SS or BOD before dividing by .2 (SS) or .167(BOD) for the population equivalent.

**Example 3**

The flow to a plant is 2 MGD and the SS is 200 and the BOD is 150. Calculate the population equivalent.
BOD: \[ \text{PE} = \frac{2 \text{MGD} \times 8.34 \text{ LB/GAL} \times 150 \text{mg/l}}{0.167 \text{ lb BOD/DAY capita}} = 14,982 \text{ population} \]

SS: \[ \text{PE} = \frac{2 \text{MGD} \times 8.34 \text{ LB/GAL} \times 200 \text{mg/l}}{0.2 \text{ lb SS/day/capita}} = 16,680 \text{ population} \]

### 7.3 Bio-Chemical Oxygen Demand (BOD)

The formula for BOD is: \[ \text{Initial DO(mg/L)} - \text{Final DO(mg/L)} \]
\[ \frac{\text{Percent Sample}}{\text{Initial DO(mg/L)} - \text{Final DO(mg/L)}} \]

- Initial DO is the dissolved oxygen taken at the beginning of the test.
- Final DO is the dissolved oxygen taken at the end of the test (usually 5 days).
- % sample is the denominator of the formula and is the volume of sample used divided by the volume of a BOD sample bottle which is 300 ml. The % sample is always expressed as a decimal. That is, if 30 ml of sample is used the denominator would be:

\[ \frac{30 \text{ ml}}{300 \text{ ml}} = 0.1 \]

- The numerator (IDO-FDO) is known as depletion. Another way of expressing the formula is depletion divide by % sample.
- The target and most accurate result is when depletion (IDO-FDO) is 50 %. That means if the initial dissolved oxygen is 10 mg/l the most accurate result is the final dissolved oxygen is closest to 5 mg/l.

**Example:** What is the BOD if initial dissolved oxygen is 8 mg/L and final dissolved oxygen is 4 mg/l? 150 ml of sample was used.

\[ \text{BOD} = \frac{\text{initial DO(mg/l)} - \text{Final DO(mg/l)}}{\text{Percent Sample (Decimal)}} \]

\[ \frac{8 \text{ mg/l} - 4 \text{ mg/l}}{150 \text{mg/300ml}} = 8 \text{mg/l BOD} \]
7.4 Weighted Average

The weighted average formula is a method of giving larger numbers in the calculation more influence and smaller numbers less influence in the answer.

Example 1  Calculate the Dissolved oxygen (DO) of the stream below the plant effluent based on the following information:

Stream flow (Qs) = 10MGD  
Plant Effluent Flow (Qp) = 2 MGD  
DO Stream Above (Cs) = 8 mg/l  
DO Plant Effluent (Cp) = 6 mg/l

\[
\frac{Q_s \times C_s + Q_p \times C_p}{Q_s + Q_p} = \frac{(10 \text{MGD} \times 8 \text{mg/l}) + (2 \text{MGD} \times 6 \text{mg/l})}{10 \text{MGD} + 2 \text{MGD}} = 7.6 \text{mg/L}
\]

Because the stream flow is more significant than the flow of the plant effluent, the answer is closer to the DO of the stream than the DO of the plant effluent.

7.5 Hydraulic Loading

The hydraulic loading is the flow to a tank or pond usually expressed as gallons per day divided by the surface area of the tank or pond expressed as square feet.

\[
\text{Flow (gpd)} = \frac{\text{Flow (gpd)}}{\text{Tank Surface Area (ft}^2\text{)}}
\]

Example  If the flow to a clarifier is 500,000 gallons per day, and the rectangular clarifier has surface dimensions of 80 feet by 40 feet, what is the hydraulic loading?
Flow (gpd)
Tank Surface area (ft²)

500,000 gpd
80 ft x 40 ft = 156.25 gal/day/ft²

7.6 Organic Loading

For trickling filters: BOD (lbs/day) or BOD (lbs/day)
Volume (1000 ft³) Acre ft.

Ponds: BOD (lbs/day)
Acre ft.

Rotating Biological Contactors (RBCs)

Soluble BOD (lbs/day)
Area (1000 ft³)

The numerator is the dosage or pounds formula where the mg/l is the concentration of BOD applied to the filter. The denominator is the volume expressed as 1000 cubic feet (total volume in cubic feet divided by 1,000). The alternate denominator is acre ft and is the volume in cubic feet divided by 43,560. This is because the surface area as square feet is converted to acres by dividing by 43,560 because there are 43,560 square feet in one acre, and the third dimension remains as feet.

Trickling Filter Example:

Flow to a trickling filter is 2 MGD and the BOD loading to the filter is 100mg/l. The circular trickling filter is 120 feet in diameter and 12 feet deep. Give answer in lb BOD per day per 100 cubic feet and lbs per day per acre feet

BOD (lbs/day) = 2MGD x 8.34 lb/gal x 100 mg/l
Volume (1000 ft³) = (0.785x 120ft x 120ft x 12ft) /1000ft³
\[
\frac{1668 \text{ lbs}}{135.65 \text{ ft}^3} = 12.29 \text{ lbs/1000 ft}^3
\]

**BOD (lbs/day)** = \(2\text{ MGD} \times 8.34 \text{ lb/gal} \times 100 \text{ mg/l}\)

**Volume (Acre ft)** = \((0.785 \times 120 \text{ ft} \times 120 \text{ ft} \times 12 \text{ ft})/43,560 \text{ ft}^2/\text{Acre}\)

\[
\frac{1668 \text{ lbs}}{3.1 \text{ acres}} = 538 \text{ lbs/acre}
\]

**Pond Example**

A pond receives a flow of 100,000 gallons per day with a BOD concentration of 100 mg/l. The surface dimension of the rectangular pond is 400 feet by 400 feet.

\[
\text{BOD (lbs/day)} = \frac{0.1 \text{ MGD} \times 8.34 \text{ lbs/gal} \times 100 \text{ mg/l}}{(400 \text{ ft} \times 400 \text{ ft})/43,560 \text{ ft}^2/\text{acre}}
\]

\[
83.4 \text{ lbs} = 22.7 \text{ lbs/day/acre}
\]

3.67 acres

**Rotating Biological Contactors: (RBC) Example**

An RBC has a surface area of 400,000 square feet and a flow of 1 MGD. If the soluble BOD of the primary effluent is 150 mg/l, what is the organic loading on the RBC in pounds per day per 1,000 square feet?

\[
\text{Soluble BOD (lbs/day)} = \frac{1.0 \text{ MGD} \times 8.34 \text{ lbs/gal} \times 150 \text{ mg/l}}{400 \text{ one thousand ft}^2}
\]
Soluble BOD may not always be given and must be calculated. In order to calculate soluble BOD total BOD and particulate BOD must be given. If particulate BOD is not given, then it is calculated by multiplying the suspended solids (SS) by a given K-value.

**Total BOD=Particulate BOD + Soluble BOD**

**Particulate BOD= Suspended Solids x K-value**

**Example**

If total BOD is 200 mg/land SS is 15mg/l with a K-value of .4, what is the soluble BOD concentration?

\[
\text{Total BOD} = \text{Particulate BOD} + \text{Soluble BOD}
\]

\[
200 \text{ mg/l} = (125 \times 0.4) + \text{Soluble BOD}
\]

\[
200 - (125 \times 0.4) = \text{Soluble BOD}
\]

\[
200 - 50 = \text{Soluble BOD}
\]

\[
150 = \text{Soluble BOD}
\]

In the above example, the K-value assigns the portion of suspended solids that are particulate BOD. In other words, suspended solid multiplied by the K-value equals particulate BOD.
Chapter 8       Secondary Treatment

8.1 Sludge Volume Index

The sludge volume index (SVI) indicates the settle ability of the mixed liquor suspended solids (mlss) in secondary treatment. By definition, it is the volume in milliliters occupied by one gram of sludge.

\[
\text{SVI} = \frac{30 \text{ minute settled (ml)} \times 1000 \text{ mg/gr}}{\text{mlss (mg/l)}}
\]

**Example:** A 1 liter sample of mlss settles for 30 minutes. The solids settle to the 200 ml mark. The concentration of the solids in aeration is 2,000 mg/l. Calculate the SVI.

\[
\text{SVI} = \frac{30 \text{ minute settled (ml)} \times 1000 \text{ mg/gr}}{2000 \text{ mg/l mlss}}
\]

\[
= \frac{200 \text{ ml} \times 1000 \text{ ml/gr}}{2000 \text{ mg/l mlss}} = 100 \text{ ml/gr}
\]

- The 1000 factor in the numerator converts the denominator from milligrams to grams.
- The 30 minute settling results may be given as ml, percent, or as a decimal. The 1000 factor in the numerator will be 10,000 if for a percent and 1,000,000 if a decimal is used for the settling result.

\[
\text{SVI} = \frac{30 \text{ minute settled (ml)} \times 1,000}{\text{mlss}}
\]

\[
\text{SVI} = \frac{30 \text{ minute settled (%)} \times 10,000}{\text{mlss}}
\]

\[
\text{SVI} = \frac{30 \text{ minute settled (decimal)} \times 100,000}{\text{mlss}}
\]
8.2 Food to Microorganism Ratio (F/M)

The F/M ratio indicates the amount of food available to the portion of mixed liquor suspended solids available to consume the BOD material in aeration or secondary treatment.

The formula follows:

\[
\frac{\text{BOD to aeration (lbs)}}{\text{MLVSS}} \quad \text{or} \quad \frac{\text{BOD}}{\text{MLVSS}_{to}}
\]

8.3 Sludge Age

Sludge Age is the inventory of suspended solids in aeration divided by the suspended solids applied to aeration.

Formula is:

\[
\frac{\text{Suspended Solids in Aeration(lbs)}}{\text{Suspended Solids to Aeration (lbs/day)}} = \frac{\text{SS}_{in}}{\text{SS}_{to}}
\]

- A “to” or “from “in a formula indicates a flow.
- An “in” in a formula indicates a volume.
- The numerator and denominator use the dosage or pounds to derive pounds.
- The volatile portion of the mlss is usually 70% of mlss. The 70% is that portion of mixed liquor suspended solids able to consume the BOD or organic material.

Example:
Flow to an aeration tank is 3 million gallons per day with a suspended solid concentration of 100 mg/l. Aeration tank volume is 0.862 million gallons (80ft x 120ft x 12ft.). Concentration is 2,000mg/l. Calculate the sludge age.

\[
\text{SS}_{in} = \frac{0.862 \text{MG} \times 8.34 \text{lb/gal} \times 2000 \text{mg/l}}{2,502} = 14,378 \approx 5.75 \text{ days}
\]

\[
\text{SS}_{to} = \frac{3 \text{MGD} \times 8.34 \text{lb/gal} \times 100 \text{ mg/L}}{2,502} = 2,502
\]
Calculation for aeration tank volume:

\[ 80\text{ft} \times 120\text{ft} \times 12\text{ft} \times 7.48\text{gal/ft}^3 = 0.862\text{ MG} \]
\[ \frac{1,000,000\text{ gal/MG}}{ } \]

**8.4 Mean Cell Residence Time (MCRT) or Solids Residence Time (SRT)**

MCRT or SRT is the inventory of solids in secondary treatment including aeration and the secondary clarifier using the concentration of mixed solids in aeration for the aeration tank and clarifier divided by the solids removed from inventory. Solids removed from inventory include wasting and solids going over the weirs in the plant effluent. MCRT turnover is total solids inventory (aeration and clarifier) divided by solids removed from inventory (wasting and over the weirs).

The formula is as follows:

\[
\frac{(\text{Volume Aeration + Volume Clarifier})\text{MG} \times 8.34\text{lbs/gal} \times \text{aeration mlss(mg/l)}}{\left[\text{Wasting Flow(MG) x 8.34lb/gal x Wasting SS(mg/l)} + \left[\text{Plant Flow(MG) x 8.34lb/gal x Final Effluent}\right]\right]}\]

Or:

\[
(\text{VA+Vc})\text{MG} \times 8.34 \times \text{mlss}
\]
\[
\text{Wasting (lb/day) + Final effluents(lb/day)}
\]

\[
= (1 + 2)\text{MG} \times 8.34\text{lb/gal} \times 1800\text{mg/l}
\]
\[
(0.1\text{MGD} \times 8.34 \times 30,000\text{mg/l}) + (4\text{MGD} \times 8.34 \times 8\text{mg/l})
\]

\[
= 45,036\text{lbs}
\]
\[
25,020\text{lb/day} + 267 \text{lb/day}
\]

\[
= 1.78 \text{ days}
\]
8.5 Air Requirements

Aeration blower output is rated at cubic feet per minute (cfm) or standard cubic feet per minute (scfm). The “standard” means environmental factors are used.

Example:

Air required to for a secondary treatment process is 5 million cubic feet per day. Which combination of blowers listed below is used to fulfill the requirement?

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,500 cfm blower</td>
</tr>
<tr>
<td>1</td>
<td>1,200 cfm blower</td>
</tr>
<tr>
<td>1</td>
<td>1,000 cfm blower</td>
</tr>
<tr>
<td>2</td>
<td>800 cfm blowers</td>
</tr>
</tbody>
</table>

Convert 5,000,000 ft³/day to ft³/min

\[
\frac{5,000,000 \text{ ft}^3/\text{day}}{1,440 \text{ min/day}} = 3,472 \text{ ft}^3/\text{min}
\]

You need: 1 @1,500 cfm blower, 1 @1,200 cfm blower and 1 @ 800 cfm blower

- 1 pound of oxygen satisfies one pound of bio-chemical oxygen demand
- Air contains approximately 20 percent oxygen
- There is approximately 1 pound of oxygen in 60 cubic feet of air.
Chapter Nine

9.0 THE CLASSIFICATION OF MATTER

Matter is defined anything that occupies space and has weight (mass). Matter includes subatomic particles - protons and electrons - as well as the atoms that such particles form. Matter also includes everything formed by atoms - nearly everything you encounter in the world.

Matter exists in three forms - (1) solids, (2) liquids, and (3) gases. Solids, liquids, and gases may exist in pure form, may combine chemically with other elements to form compounds, or may be mixed together without chemically combining to form mixtures. More information about matter follows.

9.1 Pure Elements

As discussed previously, elements are matter built up from subatomic particles, with properties determined by the element’s nucleus (protons and neutrons) and electron shells. All of the atoms of an element have the same number of protons in their nuclei. Elements do not break down into simpler elements. There are more than 100 elements known; 92 occur naturally, and others have been produced in the laboratory. Elements important in water chemistry are listed in Table 5.4.

A few elements exist in pure form. Carbon is an example - a diamond is pure carbon in a particular arrangement. Oxygen in the air is another example of an element in its pure form. However, most elements are unstable and are usually found combined with other elements in the form of compounds.
### TABLE 5.4 - Elements Important in Water Treatment

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Element</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>Lead *</td>
<td>Pb</td>
</tr>
<tr>
<td>Antimony *</td>
<td>Sb</td>
<td>Magnesium</td>
<td>Mg</td>
</tr>
<tr>
<td>Arsenic</td>
<td>As</td>
<td>Manganese</td>
<td>Mn</td>
</tr>
<tr>
<td>Barium *</td>
<td>Ba</td>
<td>Mercury *</td>
<td>Hg</td>
</tr>
<tr>
<td>Beryllium *</td>
<td>Be</td>
<td>Nickel *</td>
<td>Ni</td>
</tr>
<tr>
<td>Boron</td>
<td>B</td>
<td>Nitrogen</td>
<td>N</td>
</tr>
<tr>
<td>Bromine</td>
<td>Br</td>
<td>Oxygen</td>
<td>O</td>
</tr>
<tr>
<td>Cadmium *</td>
<td>Cd</td>
<td>Phosphorus</td>
<td>P</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>Potassium</td>
<td>K</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>Radium *</td>
<td>Ra</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>Selenium *</td>
<td>Se</td>
</tr>
<tr>
<td>Chromium *</td>
<td>Cr</td>
<td>Silicon</td>
<td>Si</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>Silver *</td>
<td>Ag</td>
</tr>
<tr>
<td>Fluorine †</td>
<td>F</td>
<td>Sodium</td>
<td>Na</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>Strontium *</td>
<td>Sr</td>
</tr>
<tr>
<td>Iodine</td>
<td>I</td>
<td>Sulfur</td>
<td>S</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>Thallium *</td>
<td>Tl</td>
</tr>
</tbody>
</table>

* This element must be monitored according to the requirements of the Safe Drinking Water Act.
† Fluoride, an anion of the element fluorine, must be monitored according to the requirements of the Safe Drinking Water Act.

### 9.2 Compounds

Compounds are two or more elements that are “stuck” (bonded) together by a chemical reaction. A compound can be broken down into its original elements only by a reversal of the chemical reaction that formed it. The weight of the atoms of any one element in a compound is always a definite fraction (or proportion) of the weight of the entire compound.

For example, in any given weight of water, 2/18 of the weight comes from atoms of hydrogen. When atoms of two or more elements are bonded together to form a compound, the resulting particle is called a *molecule*. A molecule may be only two atoms of one or more elements bonded together; or it may be any number of atoms bonded together, and may consist of several elements. For example, when two atoms of hydrogen and one atom of oxygen combine, a molecule of water (H₂O) is formed. When one atom of carbon and two atoms of oxygen combine, a
molecule of carbon dioxide (CO₂) is formed. When two atoms of oxygen combine, a molecule of oxygen (O₂) is formed.

Other examples of compounds are:
- salt (sodium and chlorine - NaCl)
- sulfuric acid (hydrogen, sulfur, and oxygen - H₂SO₄)
- ammonia (nitrogen and hydrogen - NH₃)
- rust (iron and oxygen - Fe₂O₃)
- lime (calcium, oxygen, and hydrogen - Ca(OH)₂)
- sand (silicon and oxygen - SiO₂)

The number of compounds that can be formed by chemical reaction between elements is enormous. Well over two million compounds have been identified by chemists, and the number is still increasing. Table 5.5 lists some of the common compounds related to water treatment.
### TABLE 5.5 - Common Compounds in Water Treatment

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Compound</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Sulfate</td>
<td>Al₂(SO₄)₃</td>
<td>Hydrochloric acid</td>
<td>HCl</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>Hydrogen peroxide</td>
<td>H₂O₂</td>
</tr>
<tr>
<td>Ammonium hydroxide</td>
<td>NH₄OH</td>
<td>Magnesium bicarbonate</td>
<td>Mg(HCO₃)₂</td>
</tr>
<tr>
<td>Calcium bicarbonate</td>
<td>Ca(HCO₃)₂</td>
<td>Magnesium carbonate</td>
<td>MgCO₃</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>CaCO₃</td>
<td>Magnesium hydroxide</td>
<td>Mg(OH)₂</td>
</tr>
<tr>
<td>Calcium hydroxide</td>
<td>Ca(OH)₂</td>
<td>Manganese dioxide</td>
<td>MnO₂</td>
</tr>
<tr>
<td>Calcium hypochlorite</td>
<td>Ca(OCl)₂</td>
<td>Methane</td>
<td>CH₄</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>CaO</td>
<td>Monochloramine</td>
<td>NH₂Cl</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>Ozone</td>
<td>O₃</td>
</tr>
<tr>
<td>Carbonic acid</td>
<td>H₂CO₃</td>
<td>Potassium chloride</td>
<td>KCl</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl₂</td>
<td>Potassium permanganate</td>
<td>KMnO₄</td>
</tr>
<tr>
<td>Chlorine dioxide</td>
<td>ClO₂</td>
<td>Phosphoric acid</td>
<td>H₃PO₄</td>
</tr>
<tr>
<td>Chloroform</td>
<td>CHCl₃</td>
<td>Sodium chloride</td>
<td>NaCl</td>
</tr>
<tr>
<td>Copper sulfate</td>
<td>CuSO₄</td>
<td>Sodium fluoride</td>
<td>NaF</td>
</tr>
<tr>
<td>Ferric chloride</td>
<td>FeCl₃</td>
<td>Sodium silicofluoride</td>
<td>Na₂SiF₆</td>
</tr>
<tr>
<td>Ferric sulfate</td>
<td>Fe₂(SO₄)₃</td>
<td>Sodium hypochlorite</td>
<td>NaOCl</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>H₂S</td>
<td>Sodium carbonate</td>
<td>Na₂CO₃</td>
</tr>
<tr>
<td>Hydrofluosilic acid</td>
<td>H₂SiF₆</td>
<td>Sodium thiosulfate</td>
<td>Na₂S₂O₃</td>
</tr>
<tr>
<td>Hypochlorous acid</td>
<td>HOCl</td>
<td>Sulfuric acid</td>
<td>H₂SO₄</td>
</tr>
</tbody>
</table>

#### 9.3 Mixtures

When atoms of two or more elements, compounds, or both, are mixed together and no chemical reaction (bonding between individual particles) occurs, then the result is a *mixture*. No new compounds are formed, and the elements or compounds may be mixed in any proportion. Any mixture can be separated into its original elements or compounds by “physical” means, such as filtering, settling, or distillation. For example, a mixture of salt water can be separated into its compounds, salt and water, by the process of distillation - heating the mixture causes the water to evaporate leaving the salt behind.
Other examples of mixtures are:

- air (mostly oxygen, carbon dioxide, and nitrogen)
- glass (sand, various metals, and borax)
- steel (primarily iron and carbon)
Chapter Ten
10.0 ACIDS, BASES, AND SALTS

Inorganic compounds (compounds generally not containing carbon) can be classified into three main groups - (1) acids, (2) bases, and (3) salts. These three items are commonly used throughout chemistry, and it is important that you understand the basic features that distinguish them. The following definitions are adequate for most water treatment chemistry; however, somewhat different definitions may be used in advanced work.

10.1 Acids

An acid is any substance that releases hydrogen ions (H\(^+\)) when it is mixed into water. For example, shortly after sulfuric acid (H\(_2\)SO\(_4\)) is mixed into water, many of the H\(_2\)SO\(_4\) molecules dissociate (split into individual ions), forming hydrogen ions (H\(^+\)) and sulfate ions (SO\(_4^{2-}\)) ions. The release of H\(^+\) ions indicates that H\(_2\)SO\(_4\) is an acid.

Acids that dissociate readily are known as strong acids. Most of the molecules of a strong acid dissociate when mixed into water, releasing a large concentration of hydrogen ions. Examples of strong acids are sulfuric acid (H\(_2\)SO\(_4\)), hydrochloric acid (HCl), and nitric acid (HNO\(_3\)).

Acids that dissociate poorly are known as weak acids. They release very few hydrogen ions in water. Examples include carbonic acid (H\(_2\)CO\(_3\)), which is the acid found in soft drinks, and hydrogen sulfide (H\(_2\)S), the compound responsible for the rotten-egg odor found naturally in some groundwaters and certain deep surface water. The four equations that follow are examples of how acids dissociate when mixed into water.
\[ HCl \xrightarrow{H_2O} H^+ + Cl^- \]
(A strong acid, generally more than 99% of the molecules dissociate in water.)

\[ H_2SO_4 \xrightarrow{H_2O} 2H^+ + SO_4^{2-} \]
(A strong acid, generally more than 99% of the molecules dissociate in water.)

\[ H_2S \xrightarrow{H_2O} 2H^+ + S^{2-} \]
(A weak acid, generally less than 0.1% of the molecules dissociate in water.)

\[ H_2CO_3 \xrightarrow{H_2O} 2H^+ + CO_3^{2-} \]
(A weak acid, generally less than 0.1% of the molecules dissociate in water.)

Solutions that contain significant numbers of \( H^+ \) ions are called acidic. Three other features that distinguish acids from bases and salts are:

1. Acids change the color of chemical color indicators.
   - Acids turn litmus paper red.
   - Acids turn phenolphthalein colorless.
   - Acids turn methyl orange to red.

2. Acids neutralize bases, resulting in the formation of a salt and water.

3. Acids found naturally in foods give the foods a sour taste. The sour flavor of citrus fruits is caused by citric acid. *It is vital to note that tasting the acids found in laboratories and water treatment plants can be dangerous, even fatal.*

### 10.2 Bases

A base is any substance that produces hydroxide ions (OH\(^-\)) when it dissociates in water. Lime \([Ca(OH)_2]\), caustic soda \([sodium \ hydroxide, \ or \ NaOH]\), and common household ammonia \([NH_4OH]\) are familiar examples of bases. Strong bases are those that dissociate readily, releasing a large concentration of hydroxide ions \((OH^-)\). \(NaOH\) is an example of a very strong, caustic base. Weak bases, such as \(Ca(OH)_2\) and\(NH_4OH\), dissociate poorly, releasing few \(OH^-\) ions. The equations that follow are examples of how bases dissociate when mixed into water.
\[ \text{NaOH} \xrightarrow{H_2O} \text{Na}^+ + \text{OH}^- \]

(A strong based, generally more than 99% of the molecules dissociate in water.)

\[ \text{KOH} \xrightarrow{H_2O} \text{K}^+ + \text{OH}^- \]

(A strong based, generally more than 99% of the molecules dissociate in water.)

\[ \text{Ca(OH)}_2 \xrightarrow{H_2O} \text{Ca}^{2+} + 2\text{OH}^- \]

(A relatively weak base, generally less than 15% of the molecules dissociate in water.)

\[ \text{NH}_4\text{OH} \xrightarrow{H_2O} \text{NH}_4^+ + \text{OH}^- \]

(A relatively weak base, generally less than 0.5% of the molecules dissociate in water.)

Solutions that contain significant numbers of OH\(^-\) ions are called basic solutions or alkaline solutions. The term alkaline should not be confused with the term alkalinity, which has a special meaning in water treatment. Three other features that distinguish bases from acids and salts are:

1. Bases change the color of chemical color indicators.
   - Bases turn litmus paper blue.
   - Bases turn phenolphthalein red.
   - Bases turn methyl orange to yellow.

2. Bases neutralize acids, resulting in the formation of a salt and water.

3. Bases found naturally in foods give the foods a bitter taste. Baking soda and milk of magnesium both taste bitter because they contain basic compounds. It is vital to note that tasting the bases found in laboratories and water treatment plants can be dangerous, even fatal.
10.3 Salts

Salts are compounds resulting from an acid-base mixture. The process of mixing an acid with a base to form a salt is called neutralization. Calcium sulfate (CaSO₄), for example, is a salt formed by the following acid-base neutralization.

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O$$

Another example is sodium chloride (NaCl) formation from an acid-base addition.

$$HCl + NaOH \rightarrow NaCl + H_2O$$

Notice that each acid-base reaction resulted in a salt plus water. Salts generally have no effect on color indicators. When occurring naturally in foods, salts taste salty; however, like all chemicals found in the laboratory or water treatment plants, salts may be poisonous, and tasting them could be dangerous or fatal.

10.4 Aqueous pH

Solutions range from very acidic (having a high concentration of H⁺ ions) to very basic (having a high concentration of OH⁻ ions). When there are exactly as many OH⁻ ions as H⁺ ions, the solution is neutral - neither acidic nor basic - and each OH⁻ can combine with an H⁺ to form a molecule of H₂O. Pure water is neutral, and most salt solutions are neutral or very nearly so.

The pH of a solution is a measurement of how acidic or basic the solution is (Figure 12). The pH scale runs from 0 (most acidic) to 14 (most basic). The scale is a log scale, which means that each pH measurement is 10 times greater than the preceding value. For example, if [OH⁻] at pH 7 equals 10, at pH 8 [OH⁻] equals 100 and at pH 9 [OH⁻] equals 1,000. This is also true for [H⁺] in acidic solutions moving from pH 7 to pH 1. Pure water has a pH of 7, the center of the range, neither acidic nor basic.
For each treatment process, there is a pH at which the operation is most effective. If the pH of the water is too low (the water is too acidic) for an operation to be effective, its pH can be increased by the addition of a base, such as lime \([\text{Ca(OH)}_2]\). The \(\text{OH}^-\) ions released by the base will combine with some of the \(\text{H}^+\) ions of the acidic water, forming \(\text{H}_2\text{O}\) molecules and lowering the concentration of \(\text{H}^+\) ions.

Similarly, if the pH of water is too high (the water is too basic), then the pH can be lowered by the addition of acid. In water treatment, pH is often lowered by bubbling carbon dioxide (\(\text{CO}_2\)) gas through the water. The \(\text{CO}_2\) reacts with water to form carbonic acid (\(\text{H}_2\text{CO}_3\)), and the acid dissociates into \(2\text{H}^+ + \text{CO}_3^{2-}\). The \(\text{H}^+\) ions then combine with some of the \(\text{OH}^-\) ions of the basic water, forming \(\text{H}_2\text{O}\) molecules and lowering the concentrations of \(\text{OH}^-\) ions.

### 10.5 Alkalinity

When acid is added to water that has a high concentration of \(\text{OH}^-\) ions (basic water, high in pH), the \(\text{H}^+\) ions released by the acid combine with the \(\text{OH}^-\) ions in the water to form \(\text{H}_2\text{O}\). As long as the water contains \(\text{OH}^-\) ions, those ions will neutralize the added acid and the water will remain basic. In natural waters, alkalinity is measured by bicarbonate (\(\text{HCO}_3^-\)) ion concentration. Bicarbonate alkalinity maintains pH by taking on or neutralizing \(\text{H}^+\) ions:

\[
\text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{CO}_3
\]
or by giving up H\(^+\) ions:

\[
HCO_3^- \rightarrow H^+ + CO_3^{2-}
\]

These reactions maintain the pH of natural water at around pH 7. After enough acid has been added to combine with all the OH\(^-\) ions, addition of more acid will give the water a high concentration of H\(^+\) ions - the water will become acidic.

However, if acid is added to water containing carbonate (CO\(_3^{2-}\)) ions in addition to OH\(^-\) ions, then some of the H\(^+\) ions released by the acid will combine with the OH\(^-\) ions to form H\(_2\)O, and some will combine with the CO\(_3^{2-}\) ions to form HCO\(_3^-\) (bicarbonate ions). As more acid is added, the H\(^+\) ions released will combine with the HCO\(_3^-\) ions to form H\(_2\)CO\(_3\) (carbonic acid). A concentration of H\(^+\) ions will begin to accumulate (the water will become acidic) only after enough acid has been added to convert all the OH\(^+\) to H\(_2\)O and to convert all the CO\(_3^{2-}\) ions to HCO\(_3^-\) ions and then to H\(_2\)CO\(_3\).

The CO\(_3^{2-}\) ions and HCO\(_3^-\) ions in the water increase the capacity of the water to neutralize (or buffer) an acid. Alkalinity is a measurement of water’s capacity to neutralize an acid, whether the neutralization is the result of OH\(^-\), CO\(_3^{2-}\), HCO\(_3^-\), or other negative ions.

In water treatment OH\(^-\), CO\(_3^{2-}\), and HCO\(_3^-\) are the ions causing most of the alkalinity. Alkalinity caused by OH\(^-\) is called hydroxide alkalinity; if caused by CO\(_3^{2-}\) it is called carbonate alkalinity; and if caused by HCO\(_3^-\) it is called bicarbonate alkalinity. The combined effect of all three types is reported by a lab as the total alkalinity. The distribution of alkalinity in water follows the general relationship shown in Figure 12.

The experiment illustrated in Figure 13 demonstrates the relationship between alkalinity and pH. In Step 1, equal volumes of two solutions are prepared.
FIGURE 12 - Relationship of Alkalinites in Water
Solution 1 is made up by mixing a base [lime, Ca(OH)$_2$] into water. The pH of Solution 1 is 11, and the only alkalinity is provided by the hydroxyl ions (OH$^-$) released by the base. Solution 2 is made up by mixing the same base [Ca(OH)$_2$] and calcium carbonate [CaCO$_3$] into water. The pH of Solution 2 is also 11 - that is, Solution 1 and Solution 2 have the same concentration of OH$^-$ ions. However, Solution 2 has a higher alkalinity than Solution 1, because the alkalinity of Solution 2 includes carbonate ions (CO$_3^{2-}$ released by the calcium carbonate) in addition to the hydroxide ions (OH$^-$ released by the lime).
In Step 2, sulfuric acid (H\text{2}SO\text{4}) is slowly added to Solution 1 until the pH drops to 7, as indicated by the pH meter. The pH 7 means that enough H\text{+} ions have been added (released by the acid) to combine with all the OH\text{-} ions originally in the basic solution. The same volume of acid is added to Solution 2, but the pH meter still indicates a basic solution - pH greater than 7. The carbonate ions (CO\text{3}^{-2}) in Solution 2 have combined with some of the H\text{+} ions released by the acid; as a result, there are not yet enough H\text{+} ions in Solution 2 to balance the original concentration of OH\text{-} ions.

To complete the experiment in Step 3, more acid is added to Solution 2 until the pH drops to a neutral 7. The solutions had the same pH at the beginning of the experiment, and they have the same pH at the end. But Solution 2, which had the higher initial alkalinity, was capable of neutralizing a greater volume of acid than Solution 1. (Note that the pH meter readings and equations in Figure 13 indicate a slightly simpler behavior of the chemicals than actually would occur in a laboratory.)
11.0 CONVERSIONS AND EQUATIONS

11.1 Basic Water Units

One cubic foot of water weighs 62.4 pounds  
One cubic foot of water contains 7.48 gallons  
One gallon of water weighs 8.34 pounds
11.2 Frequently Used Rates and Units

1 liter of water 1,000 grams
1 ounce 28.35 grams
1 milliliter of water (cc) 1 gram
1 part per million 1 lb per million lbs
1 part per million 8.34 lbs/million gallons
1 part per million 1 milligram per liter
1 percent 10,000 parts per million
1 ounce per cubic foot 1 gram per liter
1 million gallons per day 1.55 ft³ per second
1 million gallons per day 694.4 gallons per minute
1 cubic foot per second 448.8 gallons per minute
1 psi 2.31 feet of head
1 foot of head 0.433 psi
1 gallon 8.34 lbs
1 gallon 3,785 milliliters
1 cubic foot 7.48 gallons
1 cubic foot 62.4 lbs
1 cubic foot 1,728 cubic inches
1 day 1,440 minutes
1 day 24 hours
1 day 86,400 seconds
1 mile 5,280 feet
1 acre 43,560 square feet
1 horsepower 0.746 kilowatts
1 horsepower 746 watts
1 horsepower 33,000 ft-lbs/minute
1 pound 16 ounces
1 pound 435.6 grams
1 ounce 28.35 grams
1 gram 1,000 milligrams
1 kilogram 2.205 pounds
1 kilogram 1,000 grams
1 liter 1,000 milliliters
1 liter 0.2642 gallons
1 inch 2.54 centimeters
1 inch 25.4 millimeters
1 grain 64.8 milligrams
1 meter 39.37 inches
1 meter 3.281 feet
1 square foot 144 square inches
1 grain per gallon = 17.1 mg/L
1 grain per gallon = 143 lbs/million gallons
1 mg/L = 1 mg/kg
1 kilowatt = 1.341 horsepower
1 acre-foot = 43,560 cubic feet
1 square yard = 9 square feet
1 cubic yard = 27 cubic feet
1 inch mercury column = 1.133 feet water head
1 inch mercury column = 0.489 psi water pressure
1 gallon liquid alum = 5.4 lbs dry alum
1 gallon liquid ferric chloride = 4.8 lbs dry iron

11.3 Formulas

Perimeter = \( L_1 + L_2 + L_3 + L_4 \ldots \)
Where: \( L \) = length of each side of object being measured

**Circle of Circumference**

\[ \pi D \]
Where: \( \pi = 3.1416 \)
\( D \) = Diameter of circle

**Rectangle Area**

\[ L \times W \]
Where: \( L \) = length
\( W \) = width

**Circle Area**

\[ \pi r^2 \text{ or } 0.785d^2 \]
Where: \( \pi = 3.1416 \)
\( r \) = radius
\( d \) = diameter

**Triangle Area**

\[ \frac{bh}{2} \]
Where: \( b \) = base
\( h \) = height
Rectangular Volume
\( L \times W \times D \)
Where: \( L = \) length
\( W = \) width
\( D = \) depth

Cylinder Volume
\( \pi r^2 h \) or \( 0.785d^2 h \)
Where: \( h = \) height
\( \pi = 3.1416 \)
\( r = \) radius
\( d = \) diameter

Triangular Trough Volume
\( \frac{bhl}{2} \)
Where: \( b = \) base
\( h = \) height
\( l = \) length

Cone Volume
\( \frac{\pi r^2 h}{3} \) or \( \frac{0.785d^2 h}{3} \)
Where: \( h = \) height
\( \pi = 3.1416 \)
\( r = \) radius
\( d = \) diameter

Sphere Volume
\( \frac{\pi D^3}{6} \)
Where: \( \pi = 3.1416 \)
\( D = \) Diameter

Velocity
\( V = \frac{D}{T} \)
Where: $V = $ velocity
$D = $ distance
$T = $ time

**Flow Rate**

$Q = AV$

Where: $Q = $ flow rate
$V = $ velocity
$A = $ area

**Head**

$H = \text{psi} \times 2.31$

Where: $H = $ head, in feet
\text{psi} = $ pounds per square inch

\text{psi}

$\text{psi} = \frac{H}{2.31}$

Where: \text{psi} = pounds per square inch
$H = $ head in feet

### 11.4 Conversions - English Measurements

**Linear**

<table>
<thead>
<tr>
<th>1 foot (ft)</th>
<th>12 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 yard (yd)</td>
<td>36 inches</td>
</tr>
<tr>
<td>3 feet</td>
<td></td>
</tr>
<tr>
<td>1 mile (mi)</td>
<td>5,280 feet</td>
</tr>
<tr>
<td>1,760 yards</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>feet to inches</th>
<th>multiply by 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>yards to inches</td>
<td>multiply by 36</td>
</tr>
<tr>
<td>yards to feet</td>
<td>multiply by 3</td>
</tr>
<tr>
<td>miles to feet</td>
<td>multiply by 5,280</td>
</tr>
<tr>
<td>miles to yards</td>
<td>multiply by 1,760</td>
</tr>
<tr>
<td>inches to feet</td>
<td>divide by 12</td>
</tr>
<tr>
<td>inches to yards</td>
<td>divide by 36</td>
</tr>
<tr>
<td>feet to yards</td>
<td>divide by 3</td>
</tr>
<tr>
<td>feet to miles</td>
<td>divide by 5,280</td>
</tr>
<tr>
<td>yards to miles</td>
<td>divide by 1,760</td>
</tr>
</tbody>
</table>
Area
1 square foot (ft\(^2\)) = 144 square inches
1 square yard (yd\(^2\)) = 9 square feet (ft\(^2\))
1 acre (A) = 43,560 square feet (ft\(^2\))

To Convert
sq ft to sq in multiply by 144
sq yd to sq in multiply by 1,296
sq yd to sq ft multiply by 9
sq in to sq ft divide by 144
sq ft to sq yd divide by 9
Acres to sq ft multiply by 43,560

Volume
1 cubic foot (ft\(^3\)) = 1,728 cubic inches (in\(^3\))
1 cubic yard (yd\(^3\)) = 27 cubic feet (ft\(^3\))
1 cubic foot (ft\(^3\)) = 7.48 gallons (gal)
1 Acre-foot = 43,560 cubic feet (ft\(^3\))
1 Acre-foot = 325,851 gallons

To Convert
cubic feet to cubic inches multiply by 1,728
cubic yards to cubic feet multiply by 27
cubic feet to gallons multiply by 7.48
Acre-feet to cubic feet multiply by 43,560
Acre-feet to gallons multiply by 325,851
cubic inches to cubic feet divide by 1,728
cubic feet to cubic yards divide by 27
gallons to cubic feet divide by 7.48

Weight
1 pound (lb) = 16 ounces (oz)
1 pound (lb) = 7,000 grains
1 ounce = 437.5 grains

Water
1 cubic foot = 62.4 pounds (lbs)
1 gallon = 8.34 pounds (lbs)
1 pound (lb) = 0.016 cubic feet (ft\(^3\))
1 pound (lb) = 0.1198 gallons
To Convert

ounces to pounds multiply by 0.0625

cubic feet to pounds multiply by 62.4

gallons to pounds multiply by 8.34

pounds to cubic feet divide by 0.016

pounds to gallons divide by 0.1198

### 11.5 Conversions - Metric Measurements

#### Linear

- 1 centimeter (cm) = 10 millimeters (mm)
- 1 meter (m) = 100 centimeters (cm)
- 1 kilometer (km) = 1,000 meters (m)

#### Area

- 1 square meter (m²) = 10,000 square cm (cm²)

#### Volume

- 1 milliliter (mL) = 1 cubic centimeter (cc)
- 1 cubic centimeter = 0.001 liter (L)
- 1 liter (L) = 1,000 milliliters (mL)
- 1 liter (L) = 1,000 cc
- 1 kiloliter (kL) = 1,000 liters (L)

- 1 part per million water = 1 milligram per liter (mg/L)
- 1 part per million water = 1 gram per cubic meter (g/m³)

#### Weight

- 1 milligram (mg) = 0.001 gram (gm)
- 1 gram (gm) = 1,000 milligrams (mg)
- 1 kilogram (kg) = 1,000 grams

- 1 part per million (ppm) = 1 milligram/kilogram (mg/kg)

### 11.6 English to Metric Conversions

#### Linear

- 1 inch (in) = 2.54 centimeters (cm)
- 1 inch (in) = 0.0254 meters (m)
- 1 inch (in) = 25.4 millimeters
- 1 foot (ft) = 0.3048 meters (m)
- 1 yard (yd) = 0.9144 meters (m)
- 1 mile (m) = 1.609 kilometers (km)
Area

1 sq inch  6.4516 sq centimeters
1 sq foot  0.0929 sq meters
1 sq yard  0.8361 sq meters

Volume

1 cubic inch  16.39 cubic centimeters
1 cubic inch  0.0164 liters
1 cubic foot  0.0283 cubic meters
1 cubic foot  28.32 liters
1 cubic yard  0.7645 cubic meters
1 gallon  3.785 liters
1 quart  0.946 liters
1 ounce  29.57 milliliters

Weight

1 grain  0.0648 grams
1 ounce  28.35 grams
1 pound  453.6 grams

11.7 Metric to English Conversions

Linear

1 centimeter (cm)  0.3937 inches
1 meter (m)  3.281 feet
1 meter (m)  1.0936 yards
1 kilometer (km)  0.6214 miles

Area

1 sq centimeter  0.155 sq inches
1 sq meter  10.76 sq feet
1 sq meter  1.196 sq yards

Volume

1 cubic centimeter  0.061 cubic inches
1 cubic meter  35.3 cubic feet
1 cubic meter  1.308 cubic yards
1 milliliter  0.0353 ounces
1 liter  61.025 cubic inches
1 liter  0.0353 cubic feet
1 liter  0.2642 gallons
1 liter  1.057 quarts
**Weight**

- 1 gram = 15.43 grains
- 1 gram = 0.0353 ounces
- 1 gram = 0.0022 pounds
- 1 kilogram = 2.205 pounds
- 1 milliliter = 1 gram

### 11.7 Temperature

There are two common scales for temperature, Fahrenheit (°F) and Celsius (°C) (centigrade).

Fahrenheit = (°C x 1.8) + 32°
Celsius = (°F - 32°) ÷ 1.8

<table>
<thead>
<tr>
<th>Fahrenheit</th>
<th>Celsius</th>
</tr>
</thead>
<tbody>
<tr>
<td>212°F</td>
<td>Water Boils 100°C</td>
</tr>
<tr>
<td>32°F</td>
<td>Water Freezes 0°C</td>
</tr>
</tbody>
</table>

**Example:** Convert 41°F to Celsius

\[
C = (°F - 32°) ÷ 1.8
\]
\[
C = (41 - 32) ÷ 1.8
\]
\[
C = 9 ÷ 1.8
\]
\[
C = 5°
\]

**Example:** Convert 10°C to Fahrenheit

\[
°F = (°C x 1.8) + 32°
\]
\[
°F = (10°C x 1.8) + 32°
\]
\[
°F = 18 + 32
\]
\[
°F = 50°
\]

There is another conversion method that is easier to remember. It consists of the same three steps regardless of whether you are converting from Celsius to Fahrenheit or vice versa.

**Step One:** Add 40°

**Step Two:** Multiply by 1.8 to convert to Celsius

or

**Step Two:** Divide by 1.8 to convert to Fahrenheit

**Step Three:** Subtract 40
Chapter Twelve

12.0 CHARTS AND TABLES

Pipe Area and Volume

<table>
<thead>
<tr>
<th>Inside Pipe Diameter (in.)</th>
<th>Cross Sectional Area (in²)</th>
<th>Volume Gallons per Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5”</td>
<td>1.76</td>
<td>0.908</td>
</tr>
<tr>
<td>2”</td>
<td>3.14</td>
<td>0.163</td>
</tr>
<tr>
<td>2.5”</td>
<td>4.91</td>
<td>0.254</td>
</tr>
<tr>
<td>3”</td>
<td>7.06</td>
<td>0.367</td>
</tr>
<tr>
<td>4”</td>
<td>12.96</td>
<td>0.672</td>
</tr>
<tr>
<td>6”</td>
<td>28.67</td>
<td>1.47</td>
</tr>
<tr>
<td>8”</td>
<td>50.26</td>
<td>2.61</td>
</tr>
<tr>
<td>10”</td>
<td>78.54</td>
<td>4.08</td>
</tr>
<tr>
<td>12”</td>
<td>113.10</td>
<td>5.86</td>
</tr>
<tr>
<td>16”</td>
<td>201.06</td>
<td>10.45</td>
</tr>
<tr>
<td>18”</td>
<td>254.47</td>
<td>13.20</td>
</tr>
<tr>
<td>20”</td>
<td>314.16</td>
<td>16.35</td>
</tr>
<tr>
<td>24”</td>
<td>452.39</td>
<td>23.42</td>
</tr>
</tbody>
</table>

Example 12.1

A section of a 10” water main is 1,450 feet long. What is the volume of water in that section of pipe?

Referring to the table above, we see that a 10” diameter pipe has a volume of 4.08 gallons per linear foot of pipe.

\[ 4.08 \text{ gallons/foot} \times 1,450 \text{ feet} = 5,916 \text{ gallons} \]
12.1 Circular Tank Volumes

Example 12.2

A storage tank with a diameter of 36 feet has 24 feet of water in it. What is the volume of water in gallons?

Referring to the table above, we see that a 36 ft. diameter cylinder has 7,609.85 gallons per foot of depth.

\[ 24 \text{ ft} \times 7,609.85 \text{ gals/ft} = 182,636.4 \text{ gallons} \]
**Example 12.3**

A 12 foot diameter storage tank holds 4 feet of liquid alum. How many gallons of liquid alum are in the tank?

Referring to the table above, we see that a 12 ft. diameter cylinder has 845.54 gallons per foot of depth.

\[4 \text{ ft} \times 845.54 \text{ gals/ft} = 3,382.2 \text{ gallons}\]

**Example 12.4**

A standpipe in the distribution system has a diameter of 25 feet. The water level in the standpipe is 86.4 feet. How much water does the standpipe hold at this water level?

Referring to the table above, we see that a 25 ft. diameter cylinder has 3,669.88 gallons per foot of depth.

\[86.4 \text{ ft} \times 3,669.88 \text{ gals/ft} = 317,078 \text{ gallons}\]

**Example 12.5**

A 4 foot diameter day tank holds 3.2 feet of liquid phosphate. How many gallons of chemical are left in the tank?

Referring to the table above, we see that a 4 ft. diameter cylinder has 93.95 gallons per foot of depth.

\[3.2 \text{ ft} \times 93.95 \text{ gals/ft} = 300.6 \text{ gallons}\]
12.2 **Horizontal Tank Volumes**

![Diagram of a horizontal tank with 50% filled]

**Example 12.6**

A horizontal tank 10 feet in diameter is measured to have 7 feet of water in the tank. The tank is 12 feet long. How much water is in the tank?

1. Referring to the table above for horizontal tanks we see that we need to determine the percentage of water depth to total depth.

   7 feet water in tank = 70% full
   10 foot diameter tank

2. Referring to the table we see that a horizontal tank with the water depth at 70 percent of the tank diameter will contain 73.8% of the total volume of the tank.

3. Referring to the table on the previous page we see that a tank with a diameter of 10 feet holds 587.18 gallons/ft.

   Total tank volume = 587.18 gals/ft. x 12 ft. = 7,046.16 gallons

<table>
<thead>
<tr>
<th>Percentage of water depth to total depth</th>
<th>Percentage of total volume available</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>100.00%</td>
</tr>
<tr>
<td>90%</td>
<td>94.80%</td>
</tr>
<tr>
<td>80%</td>
<td>85.80%</td>
</tr>
<tr>
<td>70%</td>
<td>73.80%</td>
</tr>
<tr>
<td>60%</td>
<td>62.60%</td>
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<tr>
<td>50%</td>
<td>50.00%</td>
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<tr>
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<td>30%</td>
<td>26.20%</td>
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<tr>
<td>20%</td>
<td>14.22%</td>
</tr>
<tr>
<td>10%</td>
<td>5.22%</td>
</tr>
</tbody>
</table>
Example 12.7

A horizontal tank 12 feet in diameter is measured to have 3.6 feet of liquid alum in the tank. The tank is 18 feet long. How much alum is in the tank?

1. Referring to the table above for horizontal tanks we see that we need to determine the percentage of water depth to total depth.

   3.6 feet alum in tank = 30% full
   12 foot diameter tank

2. Referring to the table we see that a horizontal tank with the water depth at 30 percent of the tank diameter will contain 26.2% of the total volume of the tank.

3. Referring to the table on the previous pages we see that a tank with a diameter of 12 feet holds 845.54 gallons/ft.

   Total tank volume = 845.54 gals/ft x 18 ft. = 15,219.72 gallons

   Water volume = 15,219.72 gals x 26.2% = 3,987.6 gallons
### 12.3 Pressure Conversions

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<tr>
<th>Feet</th>
<th>psi Feet</th>
<th>psi</th>
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</thead>
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<td>0.433</td>
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<tr>
<td>4.62</td>
<td>2</td>
<td>0.867</td>
</tr>
<tr>
<td>6.93</td>
<td>3</td>
<td>1.301</td>
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<tr>
<td>9.24</td>
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<td>1.734</td>
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<td>11.54</td>
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<td>2.16</td>
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<tr>
<td>13.85</td>
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<tr>
<td>16.16</td>
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<tr>
<td>18.47</td>
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<td>3.46</td>
</tr>
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<td>20.78</td>
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</tr>
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<td>69.27</td>
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<tr>
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</tr>
<tr>
<td>115.45</td>
<td>50</td>
<td>21.67</td>
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</table>

### 12.4 Temperature Conversions

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<th>Centigrade Fahrenheit</th>
<th>Centigrade</th>
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<td>32</td>
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<tr>
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<tr>
<td>57.2</td>
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### 12.5 Flow Conversions

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<th>ft³/sec</th>
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<td>1</td>
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<td>11,520</td>
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12.6 Volume Conversions

<table>
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<th>ft³</th>
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<td>1,000</td>
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</tbody>
</table>
APPENDIX A

TERMINOLOGY USED IN WATER TREATMENT

ABSORPTION. The taking up of one substance into the body of another.

ACID. (1) A substance that tends to lose a proton. (2) A substance that dissolves in water with the formation of hydrogen ions. (3) A substance containing hydrogen which may be replaced by metals to form salts.

ACIDITY. The quantitative capacity of aqueous solutions to react with hydroxyl ions. It is measured by titration with a standard solution of a base to specified end point. Usually expressed as milligrams per liter of calcium carbonate.

ACRE-FOOT. (1) A volume of water one (1) foot deep and one (1) acre in area, or 43,560 cubic feet. (2) A 43,560 cubic foot volume of trickling filter medium.

ACTIVATED CARBON. Carbon particles possessing a high adsorptive capacity.

ACTIVATED SILICA. A negatively charged colloidal particle formed by the reaction of a dilute sodium silicate solution with a dilute solution of an acidic material or other activator. Used primarily as a coagulant aid.

ACTIVE WATER. Water having corrosive qualities.

 ADSORPTION. The adherence of a gas, liquid, or dissolved material on the surface of a solid. Should not be confused with absorption.

AERATION. (1) The bringing about of intimate contact between air and a liquid by one or more of the following methods: (a) spraying the liquid in the air, (b) bubbling air through the liquid, (c) agitating the liquid to promote surface absorption of air. (2) The supplying of air to conduits, et cetera, to relieve low pressures and to replenish air entrained and removed from such confined spaces by flowing water. (3) Relief of the effects of cavitation by admitting air to the section affected.

AERATOR. A device that promotes aeration.

AEROBIC BACTERIA. Bacteria that require free elemental oxygen for their growth.
AGGLOMERATION. The coming together of dispersed suspended matter into larger flocks or particles which settle rapidly.

AIR BINDING. The clogging of a filter, pipe or pump due to the presence of entrained air.

AIR-BOUND. Obstructed, as to the free flow of water, because of air entrapped in a high point; used to describe a pipeline or pump in such condition.

AIR RELIEF VALVE. An air valve placed at the summit of a pipeline to release the air automatically and prevent the pipeline from becoming air-bound with a resultant increase of pressure.

BACKFLOW. The backing up of water through a conduit or channel in the direction opposite to normal flow.

BACKFLOW PREVENTER. A device for a water supply pipe to prevent the backflow of water into the water supply system from the connections on its outlet end.

BACKWASH. The reversal of flow through a rapid sand filter to wash clogging material out of the filtering medium and reduce conditions causing loss of head.

BACTERIA. A group universally distributed, rigid, essentially unicellular microscopic organisms lacking chlorophyll. Bacteria usually appear as spheroid, rod-like, or curved entities, but occasionally appear as sheets, chains, or branched filaments. Bacteria are usually regarded as plants.

BICARBONATE ALKALINITY. Alkalinity caused by bicarbonate ions (HCO₃⁻).

BLACK ALUM. Waterworks alum containing a small percentage of activated carbon.

BLOW DOWN. The draining off of a portion of any process flow to maintain the constituents in solution within desired concentrations. Process may be intermittent or continuous.

BLUE COPPERAS. Copper sulfate.

BLUE VITRIOL. A waterworks term for copper sulfate.
BRACKISH WATER. Water having a mineral content in the general range between fresh water and sea water. Water containing from one thousand (1,000) to ten thousand (10,000) milligrams per liter of dissolved solids.

BREAKPOINT CHLORINATION. Addition of chlorine to water until the chlorine demand has been satisfied and further additions result in a residual that is directly proportional to the amount added beyond the breakpoint.

BREAKTHROUGH CAPACITY. The capacity of an ion-exchange column at a fixed regeneration level, usually expressed as kilograins per cubic foot exchanger.

BRINE. Concentrated salt solution remaining after removal of distilled product; also, concentrated brackish saline or sea waters containing more than 36,000 milligrams per liter of total dissolved solids.

BTU. Quantity of heat required to raise one (1) pound of water one (1) degree Fahrenheit. Abbreviation for British thermal unit.

BUFFER. Any of certain combinations of chemicals used to stabilize the pH values or alkalinities of solutions at a constant level.

BUFFER SOLUTION. A solution containing two (2) or more substances which, in combination, resist any marked change in pH following addition of moderate amounts of either strong acid or base.

CAVITATION. The formation of a cavity between the downstream surface of an impeller and the water being pumped.

CHELATION. The formation of a compound soluble in water in which the resultant molecule is no longer chemically reactive. See COMPLEXATION.

CHEMICAL PRECIPITATION. (1) Precipitation induced by addition of chemicals. (2) The process of softening water by the addition of lime and soda ash as the precipitant.

CHLORAMINES. Compounds made up of organic or inorganic nitrogen and chlorine.

CHLORINATION. The application of chlorine to water, generally for the purpose of disinfection, but frequently for accomplishing other biological or chemical results.
CHLORINE. An element ordinarily existing as a greenish-yellow gas about 2.5 times as heavy as air. At atmospheric pressure and a temperature of -30.1° Fahrenheit, the gas becomes an amber liquid about 1.5 times as heavy as water. The chemical symbol of chlorine is Cl, its atomic weight is 35.457, and its molecular weight is 70.914.

CHLORINE-AMMONIA TREATMENT. The application of chlorine to water before or after the application of ammonia, to provide a persistent combined chlorine residual or to control the production of chlorinous tastes.

CHLORINE CONTACT CHAMBER. A detention basin where chlorine is diffused through the liquid. Also called chlorination chamber.

CHLORINE DEMAND. The difference between the amount of chlorine added to water or wastewater and the amount of residual chlorine remaining at the end of a specified contact period. The demand for any given water varies with the amount of chlorine applied, time of contact, and temperature of the water.

CHLORINE DIOXIDE. An orange, water soluble, unstable, extremely explosive gas, ClO₂. Used in water treatment primarily to remove tastes and odors.

CHLOROPHENOLS. Phenolic compounds reacting with chlorine to produce chlorophenols. Chlorophenols are capable of producing odors ten (10) to one thousand (1,000) times stronger than those of the unreacted phenols.

CLARIFIER. A unit of which the primary purpose is to settle out solid matter. Usually applied to sedimentation tanks or basins.

CLEARWELL. A reservoir for the storage of filtered water. Designed for sufficient capacity to prevent the necessity of frequent variations in the rate of filtration with variations in demands.

CLOSED CENTRIFUGAL PUMP. A centrifugal pump having its impeller built with the vanes enclosed within circular disks.

COAGULANT. A compound responsible for coagulation; a floc-forming agent.

COAGULANT AID. Any chemical or substance used to assist or modify coagulation.

COAGULATION. The destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of a coagulant.
COLIFORM BACTERIA. All aerobic and facultative, gram negative, no-spore forming bacilli, having a metallic green sheen, that produce gas from lactose broth within ±24 hours at 35.0°C ± 0.5°C.

DETENTION TIME. The theoretical time required to displace the contents of a tank or unit at a given rate of discharge (volume divided by rate of discharge).

DIAPHRAGM PUMP. A pump in which a flexible diaphragm, generally of rubber or equally flexible material, is the operating part. It is fastened at the edges in a vertical cylinder. When the diaphragm is raised suction is exerted, and when it is depressed the liquid is forced through a discharge valve.

DIATOMACEOUS EARTH. A fine, silica material consisting mainly of the skeletal remains of a kind of algae called diatoms.

DIFFERENTIAL PLUNGER PUMP. A reciprocating pump with a plunger so designed that it draws the liquid into the cylinder on the upward stroke but is double acting on the discharge stroke.

DIFFUSION AERATOR. An aerator that blows air under low pressure through submerged porous plates, perforated pipes, or other devices so that small air bubbles rise through the water or wastewater continuously.

DISINFECTION. The art of killing the larger portion of microorganisms in or on a substance with the probability that all pathogenic bacteria are killed by the agent used.

DISTRIBUTION SYSTEM. A system of conduits by which a water supply is distributed to consumers. The term applies particularly to the network or pipelines in the streets in a domestic water system and or to pipes and canals other than the main canal in an irrigation system.

DOMESTIC CONSUMPTION. The quantity of material applied to obtain a specific effect.

DOUBLE-SUCTION IMPELLER. An impeller with two (2) suction inlets, one on each side of the impeller.

DRAWDOWN. The magnitude of the lowering of the water surface in a well, and of the water table adjacent to the well, resulting from the withdrawal of water from the well by pumping.
DRINKING WATER STANDARDS. (1) Standards prescribed by the United States Environmental Protection Agency for the quality of drinking water supplied to interstate carriers. (2) Standards prescribed by state or local jurisdictions for the quality of drinking water supplied from surface-water, groundwater, or bottled-water sources.

DRY FEEDER. A feeder for dispensing a chemical or other fine material in the solid state to water at a rate controlled manually or automatically by the rate of flow. The constant rate may be either volumetric or gravimetric.

DYNAMIC HEAD. That head of a fluid which would produce statically by pressure of a moving fluid.

EFFECTIVE SIZE. The diameter of the size of grains in filter media in which 10 percent passes through a mesh of a given size and 90 percent is retained on the mesh. Commonly referred to as D_{10}.

FALSE FILTER BOTTOM. A type of under drain system consisting of a porous or perforated floor suspended above the true bottom of the filter. See FILTER BOTTOM.

Fecal Streptococci. A bacteria whose presence is indicative of fresh fecal contamination.

FERRIC SULFATE. A soluble iron salt, Fe_{2} (SO_{4})_{3}, formed by reaction of ferric hydroxide and sulfuric acid or by reaction of iron and hot concentrated sulfuric acid. Used as a coagulating agent.

FILTER. A device or structure for removing solid or colloidal material, usually of a type that cannot be removed by sedimentation. The liquid is passed through a filtering medium, usually a granular material but sometimes finely woven cloth, unglazed porcelain, or specially prepared paper. There are many types of filters used in water treatment.

FILTER BOTTOM. The under drain system for collecting the water that has passed through a rapid sand filter and for distributing the wash water that cleans the filtering medium.

FILTER CLOGGING. The effect occurring when fine particles fill the voids of a sand filter and retard the normal passage of liquid through the filter.

FILTER GALLERY. A gallery provided in a treatment plant for the installation of the conduits and valves and for a passageway to provide access to them.
FILTER RATE. The rate of application of material to some process involving filtration, for example, application water flow to a rapid sand filter.

FILTER RUN. The interval between the cleaning and washing operations of a rapid sand filter.

FLASH MIXER. A device for quickly dispersing chemicals uniformly throughout a liquid.
FLOC. Small gelatinous masses formed in a liquid by the reaction of a coagulant added and the suspended matter in the liquid.

FLOCCULATING TANK. A tank used for the formation of floc by the gentle agitation of liquid suspensions, with or without the aid of chemicals.

FLOCCULATION. In water treatment, the agglomeration of colloidal and finely divided suspended matter after coagulation by gentle stirring by either mechanical or hydraulic means.

FLOCCULATION AGENT. A coagulating substance which, when added to water, forms a flocculent precipitate which will entrain suspended matter and expedite sedimentation; examples are alum, ferrous sulfate, and lime.

FLOW. (1) The movement of a stream of water or other mobile substance from place to place; a stream of water; movement of silt, water, sand, or other material. (2) The fluid which is in motion.

HYDRATED LIME. Limestone that has been “burned” and treated with water under controlled conditions until the calcium oxide portion has been converted to calcium hydroxide.

HYDROLOGIC CYCLE. The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration. Also called water cycle.

HYDROXIDE ALKALINITY. Alkalinity caused by hydroxyl ions (OH⁻).

HYPOCHLORITE. Calcium, sodium, or lithium hypochlorite. Used to disinfect water.

IMPELLER. A rotating set of vanes designed to impel rotation of a mass of fluid.

INFLUENT. Water or other liquid flowing into a reservoir, basin, or treatment plant, or any unit thereof.
ION EXCHANGE. A chemical process in which ions from two (2) different molecules are exchanged.

ION-EXCHANGE TREATMENT. The use of ion-exchange materials such as resin or zeolite to remove undesirable ions from a liquid and substitute acceptable ions in place of them.

IRON BACTERIA. Bacteria that assimilate iron and excrete its compounds in their life processes.

JET PUMP. A device that pumps fluids by converting the energy of a high-pressure fluid into that of a high-velocity fluid. It consists of a nozzle that discharges a jet of fluid at high pressure into a venture tube. The fluid to be pumped enters a chamber just ahead of the venture tube where the high-velocity jet draws it into the tube.

LANGELIER’S INDEX. The hydrogen-ion concentration that water should have to be in equilibrium with its content of calcium carbonate.

LIME. Any of a family of chemicals consisting essentially of calcium hydroxide made for limestone (calcite) which is composed almost wholly of calcium carbonate or a mixture of calcium and magnesium carbonate.

LIME AND SODA-ASH PROCESS. A process for softening water by the addition of lime and soda ash to form precipitates of calcium carbonate and magnesium hydroxide.

LIME-SODA SOFTENING. A process whereby calcium and magnesium ions are precipitated from water by reaction with lime and soda ash.

LIQUID CHLORINE. Elemental chlorine placed in a liquid state by a combination of compression and refrigeration of dry, purified chlorine gas. Liquid chlorine is shipped under pressure in steel containers.

OVERFLOW RATE. One of the criteria for the design of settling tanks in treatment plants; expressed in gallons per day per square foot of surface area in the settling tank.

OZONE. Oxygen in molecular form with three (3) atoms of oxygen forming each molecule (O₃). Used for disinfection.
PARTS PER MILLION. The number of weight or volume units of a minor constituent present with each one million (1,000,000) units of the major constituent of a solution or mixture. Formerly used to express the results of most water analyses, but more recently replaced by the ratio milligrams per liter.

PATHOGENIC BACTERIA. Bacteria which may cause disease in the host organisms by their parasitic growth.

PERCOLATION. The movement or flow of water through the interstices or the pores of a soil or other porous medium.

PERIPHERAL WEIR. The outlet weir extending around the inside of the circumference of a circular settling tank, over which the effluent discharges.

PERMANENT HARDNESS. A characteristic of water usually attributed to hardness-producing metallic ions other than calcium or magnesium. See HARDNESS.

pH. The reciprocal of the logarithm of the hydrogen-ion concentration. The concentration is the weight of hydrogen ions, in grams, per liter of solution. Neutral water, for example, has a pH value of seven (7) and a hydrogen-ion concentration of $10^{-7}$ g/L.

PHENOLPHTHALEIN ALKALINITY. A measure of the hydroxides plus one half of the normal carbonates in aqueous suspension. Measured by the amount of sulfuric acid required to bring the water to a pH value of 8.3, as indicate by a change in color of phenolphthalein. It is expressed in parts per million of calcium carbonate.

PISTON PUMP. A reciprocating pump wherein the cylinder is tightly fitted with a reciprocating piston.

PLATE COUNT. Number colonies of bacteria grown on selected solid media at a given temperature and incubation period, usually expressed in number of bacteria per milliliter of sample.

POSITIVE HEAD. The energy possessed per unit weight of a fluid, due to its elevation above some datum. Also called elevation head.

POST CHLORINATION. The application of chlorine to water prior to any treatment.
POTASSIUM PERMANGANATE. A purple crystalline salt of potassium and manganese used as an oxidizing agent for tastes and odors or for manganese removal.

PRECHLORINATION. The application of chlorine to water prior to any treatment.

PRECIPITATE. To cause a soluble substance to become insoluble or to be removed from the solution phase to the solid phase – not synonymous with settling.

RECARBONATION. (1) The process of introducing carbon dioxide as a final stage in the lime-soda ash softening process in order to convert carbonates to bicarbonates and thereby stabilize the solution against precipitation of carbonates. (2) The diffusion of carbon dioxide gas through liquid to replace the carbon dioxide removed by the addition of lime.

RED WATER. Rust-colored water. Such color is usually due to the presence of precipitated ferric iron salts or to dead organisms whose life processes depended on iron and manganese.

REGENERATION. The periodic restoration of exchange capacity of ion-exchange media used in water treatment.

RESERVOIR. A pond, lake, tank, basin, or other space, either natural or created in whole or in part by the building of engineering structures, which is used for storage, regulation, and control of water. Sometimes called impoundment.

RESIDUAL CHLORINE. Chlorine remaining in water at the end of a specified contact period as combined or free chlorine.

RIPRAPH. Broken stone or boulders placed compactly or irregularly on dams, levees, dikes, or similar embankments for protection of earth surfaces against the action of waves or currents.

SALINE-WATER. Water containing dissolved salts - usually from ten thousand (10,000) to thirty-three thousand (33,000) milligrams per liter.
SALINITY. The relative concentration of salts, usually sodium chloride, in a given water. It is usually expressed in terms of the number of parts per million of chloride (Cl).

SATURATION. The condition of a liquid when it has taken into solution the maximum possible quantity of a given substance at a given temperature and pressure.

SATURATION INDEX. A numerical value obtained by calculation from a water analysis. It is intended to enable the prediction of the scale-forming or scale-dissolving tendencies of water.

SCHMUTZDECKE. A “dirty skin” or layer of flocculent material that forms on the surface of a sand filter.

SEDIMENTATION. The process of subsidence and deposition of suspended matter carried by water or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called settling. See CHEMICAL PRECIPITATION.

SEQUESTER. To form a stable, water-soluble complex. See COMPLEXATION.

SODIUM TRIPOLYPHOSPHATE. STP or STPP: sodium triphosphate; pentasodium triplyphosphate (Na$_5$P$_3$O$_{10}$). A water-soluble chelating agent for certain metals in solution.

SOFT WATER. Water having a low concentration of calcium and magnesium ions. According to United States Geological Survey criteria, soft water is water having a hardness of sixty (60) milligrams per liter or less.

SOLIDS-CONTACT CLARIFIER. A unit in which liquid passes upward through a solids blanket and discharges at or near the surface. See CLARIFIER.

SOLUTION FEEDER. A feeder for dispensing a chemical or other material in the liquid or dissolved state to water at a rate controlled manually or automatically by the quantity of flow. The constant rate is usually volumetric.

SPECIFIC GRAVITY. The ratio of the mass of a body to the mass of an equal volume of water.
STABILIZATION. The water treatment process intended to reduce the corrosive and scale forming tendencies of water.

STANDARD METHODS. Methods for the examination of water published jointly by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation.

STERILIZATION. The destruction of all living microorganisms.

SULFATE-REDUCING BACTERIA. Bacteria capable of assimilating oxygen from sulfate compounds, thereby reducing them to sulfides. See SULFUR BACTERIA.

SULFUR BACTERIA. Bacteria capable of using dissolved sulfur compounds in their growth; bacteria deriving energy from sulfur or sulfur compounds.

SUPERCHLORINATION. Chlorination wherein the doses are deliberately selected to produce free or combined residuals that will disinfect contaminated wells and distribution systems.

TEMPORARY HARDNESS. Hardness that can be removed by boiling, more properly called carbonate hardness. See CARBONATE HARDNESS.

THRESHOLD ODOR. The minimum odor of the water sample that can just be detected after successive dilution with odorless water. Also called odor threshold.

TOTAL DYNAMIC DISCHARGE HEAD. Total dynamic head plus the dynamic suction head or minus the dynamic suction lift.

TOTAL DYNAMIC HEAD. The difference between the elevation corresponding to the pressure at the discharge flange of a pump and the elevation corresponding to the vacuum or pressure at the suction flange of the pump, corrected to the same datum plane, plus the velocity head at the discharge flange of the pump, minus the velocity head at the suction flange of the pump.

UNIFORMITY COEFFICIENT. The degree of variation in the size of grains of media that constitute a granular material, divided by the effective size. Commonly referred to as $D_{60}$ divided by $D_{10}$.

VIRUS. The smallest microorganism known to man capable of producing disease in humans.
WASH WATER RATE. The rate at which wash water is applied to rapid sand filter during the washing process. Usually expressed as the rise of water in the filter in inches per minute or gallons per minute per square foot.

WASH WATER TANK. An elevated tank at a rapid sand filtration plant, in which water is pumped at a rate such that the tank will be filled between washings and set at a height such that the was water will have a pressure of about fifteen (15) pounds per square inch at the strainers.

WASH WATER TROUGH. A through or gutter used to carry away the water that has washed the sand in a rapid sand filter.

WATER. A transparent, odorless, tasteless liquid, a compound of hydrogen and oxygen, $\text{H}_2\text{O}$, freezing at thirty-two (32) degrees Fahrenheit zero (0) degrees centigrade and boiling at 212 degrees Fahrenheit or one hundred (100) degrees centigrade, which, in more or less impure state, constitutes rain, oceans, lakes, rivers, and other such bodies; it contains 11.188 percent hydrogen and 88.812 percent oxygen, by weight. It may exist as a solid, liquid, or gas and, as normally found in the lithosphere, hydrosphere, and atmosphere, may have other solid, gaseous, or liquid materials in solution or suspension.

WATER-BORNE DISEASE. A disease caused by organisms or toxic substances carried by water. The most common water-borne diseases are typhoid fever, Asiatic cholera, dysentery, and other intestinal disturbances.

WATER HAMMER. The phenomenon of oscillations in the pressure of water about its normal pressure in a closed conduit, flowing full, that results from a too-rapid acceleration or retardation flow. Momentary pressures greatly in excess of the normal static pressure may be produced in a closed conduit by this phenomenon.

WATER SUPPLY FACILITIES. The works, structures, equipment, and processes required to supply and treat water for domestic, industrial, and fire use.

WATER SUPPLY SOURCE. A stream, lake, spring, or aquifer from which a supply of water is or can be obtained.

WATER SYSTEM. Collectively, all of the property involved in the operation of a water utility, including land, water lines, pumping stations, treatment plants, and general property.
WATER TABLE. The upper surface of the zone, saturation, except where that surface is formed by an impermeable body.

WATER TOWER. A tower containing a tank in which water is stored, normally for providing local storage in a distribution system where ground-level storage would provide inadequate pressure.

WATER TREATMENT. The conditioning of water to render it acceptable for a specific use.
APPENDIX B

Summary of Water Treatment Techniques

1. Treatment of Inorganic Chemicals
   a. Contaminants
      (1) Total hardness is comprised of calcium magnesium, strontium, and to a lesser extent, heavy metals (discussed in 1 a (3) below.) Removal of total hardness is usually accomplished by softening. Softening can be by chemical precipitation as with lime softening or by ion exchange as with zeolites. Hardness is also reduced when total dissolved solids are removed (discussed in 1 a (4) below).

      (2) Alkalinity in water is mainly bicarbonate, carbonate, and, in some cases, hydroxide ions. Removal of alkalinity is usually accomplished by lime softening where alkalinity is precipitated with calcium and magnesium. Hydroxide alkalinity is frequently recarbonated with carbon dioxide. All forms of alkalinity can be removed by acid neutralization.

      (3) Noncarbonate hardness is simply the arithmetic value obtained when alkalinity is subtracted from hardness. It represents hardness for which there is no alkalinity. This is important in precipitation softening, because alkalinity is required to react with calcium and magnesium to form the calcium carbonate and magnesium hydroxide. This is also important because it represents “permanent hardness” or hardness which will not precipitate in boilers, condensers, heat exchangers, cooling towers, hot water systems, etc. Noncarbonate hardness is removed by the addition of alkalinity. Soda ash is commonly added to increase the alkalinity.

      (4) Total dissolved solids are called total non-filterable residue in Standards Methods for the Examination of Water and Wastewater. This represents all of the dissolved chemicals in water with the exception of dissolved gases. The following is a partial list of total dissolved solids: calcium, magnesium, potassium, sodium, chlorides, sulfates, nitrates, fluoride, phosphate, silica, and other light metals, heavy metals, and non-metals. Numerous organic chemicals are potential dissolved solids in water.

      (5) Hydrogen Ion Concentrations. The hydrogen ion concentration (pH) of water indicates the degree of acidity or basicity of the water. A low pH water is acidic (below 7.0), and a high pH water is basic (above 7.0.) The pH may be lowered by the addition of an acid such as hydrochloric, sulfuric, or carbonic acids. The pH may be raised by the addition of a base such as lime, caustic soda, or, in some cases, soda ash.
(6) **Other Inorganic Chemicals**

(a) **Silica** comes from various soils and weathered rocks and may be in either insoluble or soluble form. Particulate (or insoluble) silica (for example, clay) can be removed by alum or iron salt coagulation. Soluble silica may be removed by ion exchange or by lime softening in which magnesium is removed (dolomitic lime softening).

(b) **Phosphate** may be removed with alum coagulation.

(c) **Cyanide** may be removed by oxidation with chlorine.

(d) **Nitrate** may be removed by oxidation to nitrate chemical oxidizing agents.

(e) **Nitrates** may be removed by ion exchange or by biological reduction to ammonia. The ammonia formed can be removed by stripping (aeration) and chlorination which is discussed in 1 (d). Nitrate removal is quite costly and complicated and is used primarily in advanced wastewater treatment.

(f) **Fluoride** can be removed by contact with activated alumina, bone char, or synthetic hydroxyl apatite. Defluoridation is quite costly.

2. **Treatment of Organic Chemicals and Materials**

(a) **Organic chemicals** are compounds obtained from living things or things that have been alive. The simplest organic compounds known are those containing carbon and hydrogen only. These are called hydrocarbons. There are many types of derivatives of hydrocarbons. Many of them contain oxygen and nitrogen. Carbon, hydrogen, oxygen, nitrogen, and, to a lesser degree, sulfur are the main elements found in organic compounds. Many other elements are also found in organic compounds.

(b) **Synthetic organic chemicals** are manmade organic chemicals. Hundreds of thousands of these chemicals have been made by man. Detergents, plastics, paints, insecticides, pesticides, fungicides, and herbicides are among this long list of chemicals. Many of these compounds produce tastes and odors. Many are highly toxic. These materials can get into water sources. The water treatment method of removal is by use of granular activated carbon. **Parameters to test** for organic chemicals used by water treatment personnel are as follows:

(1) Total organic carbon.
(2) Chemical oxygen demand.
(3) Biochemical oxygen demand.
(4) Carbon chloroform extract.
(5) Rapid fluorometric method.

These tests are nonspecific methods which give an indication of the organics in water. Total organic carbon is the most accurate to determine total content of organic matter. Carbon chloroform extract is a good test for water treatment purposes, because it extracts and measures the neutral fraction of organics, which normally contain substances that create odors.
The treatment methods which most effectively lower the value of these parameters are granular activated carbon and chemical oxidation.

3. **Treatment of Biological Contaminants**
   (a) **Pathogenic bacteria** (disease producing bacteria) are commonly found in water sources. They can be removed by coagulation and filtration, ozone, ultraviolet radiation, high pH, and by chlorination. Chlorination is the safest, surest method. Free chlorine at lower pH’s (7-8) is most effective.
   (b) Viruses are also found in water sources. Removal methods are the same as in 3 except that higher chlorine dosages and/or longer contact periods are required. Also, water to be chlorinated should be free of turbidity (particulate matter) which can protect virus particles from chlorine. The turbidity should be below one (1) Jackson Turbidity Unit. Viruses are also believed to be destroyed by a high pH.

4. **Algae**
   Prevention of heavy growths or blooms by copper sulfate treatment is the most common method of avoiding algal problems. Several new copper containing compounds have been developed. These compounds are copper chelates, such as copper citrate, copper gluconate, and copper ethanolamine. With these compounds, copper stays in solution longer which, in some cases, results in better control of algae. These compounds are considerably more expensive than copper sulfate. Overtreatment with copper sulfate is costly and can destroy the biological balance of the water supply. Also algae can become resistant to copper. Proper control of algae requires a monitoring program in which algae is identified (at least genus level) and numbered. Knowledge of their biological and ecological characteristics (limnology) of the body of water should be known. This knowledge can be used to anticipate problems and treat them before the problem gets out-of-hand.

**Procedure B-1 How to Set Up an Algae Control Program**
1. Read the algal section in *Standard Methods for the Examination of Water and Wastewater*. Pay a university botanist to help you with your program.
2. Buy a manual or textbook on algae.
3. Buy a microscope and related equipment. Also, some sampling equipment should be purchased. Algae can be concentrated by membrane filtration or by staining through a number 200 silk bolting cloth net.
4. Start the monitoring program.
   (a) In winter, the sampling should be conducted monthly. If there is a clear ice cover on the water, or if there is a turnover, or a known input of nutrients, such as nitrates and phosphates from a waste treatment plant spill, then sampling should be increased to weekly.
   (b) In summer, the sampling frequency should be on a weekly basis unless the levels of algae start increasing rapidly. If the numbers are increasing rapidly, daily samples can be
collected to determine the rate of increase. If there is a known input of nutrients, the sampling frequency should be increased.

5. **Taste and odor** are also common contaminants affecting esthetic qualities. Removal of these contaminants is sometimes most easily accomplished by eliminating the source of the taste and/or odor as in the case of biological and industrial contaminants. An example of eliminating a biological source would be contacting the industry responsible for the contaminant to resolve the problem and/or filing a notarized complaint with the Ohio Environmental Protection Agency.

Sometimes a contaminant can be eliminated at the source by not pumping raw water during the period of contamination.

Up ground reservoirs or off stream reservoir supplies should be careful that the water they pump is of reasonably good quality.

Tastes and odors are most effectively removed by activated carbon or by chemical oxidation with ozone, potassium permanganate, chlorine dioxide, or chlorine. Coagulation and filtration are sometimes helpful in removing tastes and odors.
## Appendix C
### MAJOR CONTAMINANTS IN WATER

<table>
<thead>
<tr>
<th>SUBSTANCE</th>
<th>SOURCES</th>
<th>HEALTH RISKS</th>
<th>TREATMENT FOR REMOVAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Treatment chemicals used for coagulation.</td>
<td>Possible anorexia.</td>
<td>Controlled use of the coagulant.</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved minerals, industrial pollution, orchard runoff, glass and electronics wastes.</td>
<td>Gastrointestinal damage, cardiac damage, known carcinogen, skin damage, circulatory problems.</td>
<td>Chemical oxidation, lime softening, coagulation, iron removal processes, adsorption mediums.</td>
</tr>
<tr>
<td>Asbestos</td>
<td>Dissolved minerals, asbestos-cement pipe.</td>
<td>None proved due to ingestion, inhalation is known to cause cancer, increase risk for intestinal polyps.</td>
<td>Corrosion control in asbestos cement pipe systems. Coagulation and filtration if found in source water.</td>
</tr>
<tr>
<td>Algae</td>
<td>Natural occurrence in surface water where sunlight and food are readily available.</td>
<td>Tastes and odors, possible gastroenteritis.</td>
<td>Reservoir management practices, disinfection, copper sulfate, chlorine, chlorine dioxide, ozone, potassium permanganate, coagulation, sedimentation filtration, nutrient control, carbon or oxidation for taste and odor control.</td>
</tr>
<tr>
<td>Actinomycetes</td>
<td>Bacteria that feed on some algae species.</td>
<td>Tastes and odors.</td>
<td>Same as for algae control.</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>Dissolved minerals, carbonates, and bicarbonates of calcium and magnesium.</td>
<td>None known.</td>
<td>Lime softening, pH adjustment, chemical precipitation.</td>
</tr>
<tr>
<td>Alachlor</td>
<td>Herbicide runoff from row crops.</td>
<td>Eye, liver, kidney, or spleen problems, anemia, possible carcinogen.</td>
<td>Activated carbon adsorption.</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Naturally occurring nitrogen or nitrogen compounds, agricultural fertilizers, sewage contamination.</td>
<td>None known.</td>
<td>Aeration, chemical oxidation, disinfection, lime softening, pH adjustment.</td>
</tr>
<tr>
<td>Antimony</td>
<td>Dissolved minerals, piping materials, industrial pollution, solder, electronics components, petroleum refineries, fire retardants.</td>
<td>Decreased longevity, increased blood cholesterol, decreased blood sugar..</td>
<td>Coagulation, filtration, reverse osmosis.</td>
</tr>
<tr>
<td>Barium</td>
<td>Dissolved minerals, industrial pollution, jet fuels, drilling wastes, discharge from metal refineries.</td>
<td>Cardiovascular disease, hypertension, increased blood pressure.</td>
<td>Chemical oxidation, lime softening, coagulation, reverse osmosis, ion exchange, electrodialysis.</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Sewage contamination, human and animal feces.</td>
<td>Gastrointestinal disorders, typhoid, dysentery, cholera, Legionella, other infections and diseases.</td>
<td>Disinfection, pH adjustment, boiling, coagulation, filtration, reverse osmosis, membrane filtration.</td>
</tr>
<tr>
<td>Benzene</td>
<td>Factory discharges, leaching from gas storage tanks and landfills, natural gas additive.</td>
<td>Anemia, decrease in blood platelets, possible carcinogen.</td>
<td>Watershed protection, packed tower aeration.</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Dissolved minerals, mining runoff, discharge from metal refineries, discharge from aerospace industries, industrial pollution.</td>
<td>Bone damage, lung damage, intestinal lesions, possible carcinogen.</td>
<td>Activated alumina, coagulation, filtration, lime softening, ion exchange, reverse osmosis.</td>
</tr>
<tr>
<td>Bromate</td>
<td>Byproduct created during ozonation.</td>
<td>Probable carcinogen.</td>
<td>Controlled use of ozone for disinfection to reduce production.</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Industrial pollution, galvanized pipe waste batteries, paints.</td>
<td>Possible kidney damage, known carcinogen.</td>
<td>Chemical oxidation, lime softening, coagulation, reverse osmosis, ion exchange.</td>
</tr>
<tr>
<td>Chloramines</td>
<td>Disinfectant added for microbial control in drinking water.</td>
<td>High concentrations may have adverse affects on the blood and liver, eye and nose irritation.</td>
<td>Controlled use of chloramines for disinfection.</td>
</tr>
<tr>
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</tr>
<tr>
<td>Chlorine</td>
<td>Disinfectant added for microbial control in drinking water.</td>
<td>High concentrations may have adverse affects on the blood and liver, eye and nose irritation, stomach discomfort.</td>
<td>Controlled use of chlorine for disinfection.</td>
</tr>
<tr>
<td>Chlorine dioxide</td>
<td>Disinfectant added for microbial control in drinking water.</td>
<td>High concentrations may have adverse affects on the blood and liver, may also cause neurological effects on developing nervous systems.</td>
<td>Controlled use of chlorine dioxide for disinfection.</td>
</tr>
<tr>
<td>Chromium</td>
<td>Industrial pollution, fossil fuel combustion, discharge from steel mills.</td>
<td>Liver and kidney damage, internal bleeding, respiratory disorders, allergic dermatitis, possible carcinogen.</td>
<td>Chemical oxidation, lime softening, coagulation, reverse osmosis, ion exchange.</td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td>Human and animal feces.</td>
<td>Cryptosporidiosis, severe diarrhea, vomiting, cramps.</td>
<td>Disinfection, coagulation, filtration.</td>
</tr>
<tr>
<td>Copper</td>
<td>Copper salts for algae control, brass and copper pipe corrosion.</td>
<td>Gastrointestinal irritation, liver or kidney damage, anemia.</td>
<td>Controlled use of copper salts, corrosion control.</td>
</tr>
<tr>
<td>Chloride</td>
<td>Salt runoff, agricultural wastes, human and animal wastes.</td>
<td>Possible elevated plasma chloride levels, tastes and odors.</td>
<td>Watershed control practices, reverse osmosis, electrodialysis.</td>
</tr>
<tr>
<td>Cyanide</td>
<td>Industrial pollution, discharge from steel mills, discharge from refineries and plastic or fertilizer industries.</td>
<td>Liver, spleen, brain damage; poisoning, nerve damage, thyroid problems, fatal at high concentrations.</td>
<td>Chlorination, ion exchange, reverse osmosis.</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Naturally occurring.</td>
<td>None known, but increases dissolution of minerals and metals.</td>
<td>Aeration, lime softening.</td>
</tr>
<tr>
<td>Chlorate/Chlorite</td>
<td>Byproducts of chlorine dioxide generation.</td>
<td>Possible anemia, other health effects not completely researched, possible methemoglobinemia from chlorate. Chlorate poisoning is fatal.</td>
<td>Controlled use of chlorine dioxide, GAC.</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Treatment chemicals used for disinfection.</td>
<td>Byproduct formations are possible carcinogens, no conclusive evidence on health effects of chlorine residual in water.</td>
<td>Heat, detention time, introduction of reducing agents, sulfur dioxide, carbon adsorption, controlled use of treatment chemicals.</td>
</tr>
<tr>
<td>Chlorine dioxide</td>
<td>Treatment chemical used for disinfection, taste and odor control.</td>
<td>Headaches, nausea at high concentrations.</td>
<td>Heat, detention time, introduction of reducing agents, carbon adsorption, GAC, controlled use of treatment chemical.</td>
</tr>
<tr>
<td>Chlordane</td>
<td>Residue from banned herbicides.</td>
<td>Liver or nervous system problems, possible carcinogen.</td>
<td>Carbon adsorption, granular activated carbon, packed tower aeration.</td>
</tr>
<tr>
<td>Chloramines</td>
<td>Reaction resulting from ammonia and chlorine during disinfection.</td>
<td>Oxidation of hemoglobin, possible red blood cell damage in hemodialysis patients.</td>
<td>Same as for chlorine.</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>Discharges from chemical and agricultural chemical manufacturers.</td>
<td>Liver or kidney problems.</td>
<td>Carbon adsorption, granular activated carbon, packed tower aeration.</td>
</tr>
<tr>
<td>Color</td>
<td>Dissolved organics, colloids, dissolved metals, industrial pollution, improper waste disposal practices.</td>
<td>Possible byproduct formation when disinfected.</td>
<td>Coagulation, sedimentation, filtration, chemical oxidation, chlorine, chlorine dioxide, ozone, potassium permanganate, carbon adsorption.</td>
</tr>
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<tr>
<td>Dichlorobenzene, o-, p-</td>
<td>Discharge from industrial chemical factories.</td>
<td>Liver, kidney, spleen damage, anemia, circulatory system problems.</td>
<td>Activated carbon adsorption.</td>
</tr>
<tr>
<td>Dichloroethylenes, cis, trans, 1,1-,1,2-</td>
<td>Discharge from industrial chemical factories.</td>
<td>Liver problems, possible carcinogens.</td>
<td>Activated carbon adsorption.</td>
</tr>
<tr>
<td>Disinfection Byproducts (DBPs)</td>
<td>Reaction with certain organics during disinfection.</td>
<td>Some are poisonous at high concentrations, liver and kidney disorders, nervous system disorders, possible carcinogens.</td>
<td>Enhanced coagulation, enhanced softening, GAC, carbon adsorption, removal of organics prior to disinfection.</td>
</tr>
<tr>
<td>Epichlorohydrin</td>
<td>Treatment chemicals used for coagulation, typically polymers.</td>
<td>Possible carcinogen.</td>
<td>Controlled use of polymers for treatment.</td>
</tr>
<tr>
<td>Fluoride</td>
<td>Dissolved minerals, treatment chemicals.</td>
<td>Dental fluorosis, skeletal fluorosis, bone disease.</td>
<td>Controlled use of chemical additives, activated silica, bone char, reverse osmosis, distillation.</td>
</tr>
<tr>
<td>Giardia</td>
<td>Cyst from animal feces.</td>
<td>Giardiasis, gastroenteritis, diarrhea, vomiting, cramps.</td>
<td>Coagulation, sedimentation, filtration, disinfection, chlorine, chloramine, dioxide, chloramines, ozone, potassium permanganate, lime softening.</td>
</tr>
<tr>
<td>Haloacetic acids (HAA5)</td>
<td>Byproduct of disinfection process using chlorine-based chemicals.</td>
<td>Probable carcinogens.</td>
<td>Enhanced coagulation, enhanced softening, GAC, removal of organics prior to disinfection.</td>
</tr>
<tr>
<td>Hardness</td>
<td>Dissolved calcium and magnesium compounds.</td>
<td>Kidney stones.</td>
<td>Lime softening, ion exchange softening.</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>Bacterial decomposition, sulfur compounds, sewage contamination</td>
<td>Tastes and odors.</td>
<td>Aeration, chemical oxidation, chlorine, chloramine, dioxide, ozone, potassium permanganate, GAC.</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved minerals, biological decomposition.</td>
<td>Tastes and odors, staining.</td>
<td>Aeration and filtration, chemical oxidation, chlorine, chloramine, dioxide, ozone, potassium permanganate.</td>
</tr>
<tr>
<td>Legionella</td>
<td>Bacteria that thrive in hot water systems.</td>
<td>Legionnaire's disease, Pontiac fever.</td>
<td>Coagulation, sedimentation, filtration, lime softening, disinfection, chlorine, chloramine, dioxide, ozone, chloramines.</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Dissolved minerals.</td>
<td>None known.</td>
<td>Lime softening, ion exchange softening.</td>
</tr>
<tr>
<td>Manganese</td>
<td>Dissolved minerals, biological decomposition.</td>
<td>Tastes and odors, staining.</td>
<td>Chemical oxidation and filtration, chlorine, chloramine, dioxide, ozone, potassium permanganate, aeration at high pH.</td>
</tr>
<tr>
<td>Mercury</td>
<td>Industrial pollution, runoff from croplands and landfills, refinery and factory waste discharged.</td>
<td>Kidney damage, nervous system disorders, poisoning, death.</td>
<td>Chemical oxidation, coagulation, lime softening.</td>
</tr>
<tr>
<td>Methane</td>
<td>Bacterial decomposition, sewage contamination.</td>
<td>Tastes and odors.</td>
<td>Aeration, coagulation, sedimentation, filtration.</td>
</tr>
<tr>
<td>Nitrate/Nitrite</td>
<td>Agricultural runoff, fertilizers, human and animal feces.</td>
<td>Methemoglobinemia - reduces oxygen carrying capacity of the blood, possible carcinogen.</td>
<td>Reverse osmosis, ion exchange.</td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved minerals, mining operations, industrial pollution.</td>
<td>Heart and liver damage, gastrointestinal irritation.</td>
<td>Lime softening, ion exchange, reverse osmosis.</td>
</tr>
<tr>
<td>Organics</td>
<td>Plant and animal wastes, decomposition of vegetation, algae blooms, biological decomposition, sewage contamination.</td>
<td>Tastes and odors, possible carcinogenic byproducts when disinfected or chlorinated.</td>
<td>Carbon adsorption, chemical oxidation, coagulation, chlorine, chloramine, dioxide, ozone, potassium permanganate, reverse osmosis, membrane filtration.</td>
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</tr>
<tr>
<td>Polychlorinated biphenyls (PCBs)</td>
<td>Transformers, capacitors, improper waste practices.</td>
<td>Gastrointestinal disorders, liver damage, nervous system disorders, probable carcinogen.</td>
<td>Granular activated carbon.</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Treatment chemical used for corrosion/scaling control, bacterial decomposition.</td>
<td>Liver and kidney damage, gastrointestinal irritation.</td>
<td>Coagulation, controlled use of treatment chemicals.</td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved minerals, petroleum discharges, mining discharges.</td>
<td>Liver damage, heart damage, hair loss, nail loss, numbness in fingers or toes.</td>
<td>Coagulation, lime softening, chemical oxidation, reverse osmosis.</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Dissolved minerals and inorganic, treatment chemicals.</td>
<td>Acute diarrhea, tastes and odors.</td>
<td>Lime softening, controlled use of treatment chemicals.</td>
</tr>
<tr>
<td>Synthetic organic chemicals (SOCs)</td>
<td>Pesticide and herbicide use, agricultural runoff.</td>
<td>Nervous system disorders, heart disease, liver damage paralysis, coma, sterility, kidney disease, possible or probable carcinogens.</td>
<td>Carbon adsorption, granular activated carbon, packed tower aeration.</td>
</tr>
<tr>
<td>Total dissolved solids (TDS)</td>
<td>Dissolved minerals.</td>
<td>Tastes and odors.</td>
<td>Lime softening, coagulation, chemical oxidation, reverse osmosis, membrane filtration, electrodialysis.</td>
</tr>
<tr>
<td>Trihalomethanes (THM's)</td>
<td>Byproduct of disinfection process using chlorine-based chemicals.</td>
<td>Probable carcinogens.</td>
<td>Enhanced coagulation, enhanced softening, GAC, removal of organics prior to disinfection.</td>
</tr>
<tr>
<td>Thallium</td>
<td>Dissolved minerals, industrial pollution, leaching from ore processing, discharges from glass, electronics, and drug factories.</td>
<td>Liver, kidney, and brain damage; intestinal damage, hair loss.</td>
<td>Activated alumina, ion exchange.</td>
</tr>
<tr>
<td>Volatile organic chemicals (VOCs)</td>
<td>Industrial pollution, fossil fuels, pesticides and insecticides.</td>
<td>Anemia, liver disease, kidney disease, nervous system disorders, possible or probable carcinogens.</td>
<td>Packed tower aeration, granular activated carbon.</td>
</tr>
<tr>
<td>Zinc</td>
<td>Galvanized pipe, treatment chemicals used for corrosion control.</td>
<td>Muscle weakness, nausea, irritability.</td>
<td>Corrosion control in piping systems, controlled use of treatment chemicals for corrosion control.</td>
</tr>
</tbody>
</table>