WTRM 207 BEGINNING WASTEWATER TREATMENT OPERATIONS



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WTRM 207 Beginning Wastewater Treatment Operations

by

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Remixed for Gavilan College

ZTC Grant Funding provided by the ASCCC 2025

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This text was compiled on 04/23/2026

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Detailed Licensing

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1.1.1: Understanding Fractions

Fractions are portions of whole numbers consisting of a numerator (or the top number of the fraction) and the denominator (or the bottom number of the fraction.) They are numbers that represent parts of a whole.

$$\frac{\text{Numerator}}{\text{Denominator}}$$

Figure 1.1.1.1: Fraction

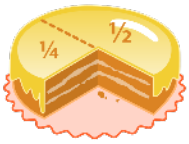


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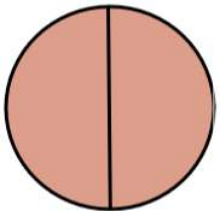


Figure 1.1.1.3: Circle with Proportions by COC OER is licensed under CC BY 4.0

Fractions are broken down into three classifications:

- Proper - $\frac{3}{4}$ - Where the numerator is smaller than the denominator
- Improper - $\frac{5}{2}$ - Where the numerator is larger than the denominator
- Mixed - $1\frac{6}{7}$ - Where a whole number precedes the fraction

Exercise 1.1

Identify the following as a proper fraction, improper fraction, or mixed number. Identify the correct word.

1.	$\frac{1}{2}$	Proper	Improper	Mixed
2.	$\frac{10}{12}$	Proper	Improper	Mixed
3.	$10\frac{1}{2}$	Proper	Improper	Mixed
4.	$\frac{11}{3}$	Proper	Improper	Mixed
5.	$\frac{101}{13}$	Proper	Improper	Mixed
6.	$130\frac{10}{13}$	Proper	Improper	Mixed
7.	$\frac{1,000}{1,111}$	Proper	Improper	Mixed
8.	$\frac{12}{7}$	Proper	Improper	Mixed
9.	$\frac{1}{7}$	Proper	Improper	Mixed
10.	$13\frac{1}{7}$	Proper	Improper	Mixed

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1.1.2: Reducing Fractions

Fractions can be reduced (expressed) in their lowest terms. This simply means that the fractions can no longer be divided by any other number.

In proper fractions, if the numerator and denominator can be divided by the same number, the fraction can be reduced.

Example: $\frac{2}{4} = \frac{1}{2}$

In the example above, this is accomplished by dividing the numerator and denominator by the number 2. Two fourths and one half represent the same number. They are just expressed differently. One half is a reduced form of two fourths.

Example: $\frac{2}{4} \div \frac{2}{2} = \frac{1}{2}$

At times a fraction can be divided multiple times in order to reduce it.

Example: $\frac{8}{12} \div \frac{2}{2} = \frac{4}{6} \div \frac{2}{2} = \frac{2}{3}$

This can also be performed in one step as follows. Both solutions provide the same answer.

Example: $\frac{8}{12} \div \frac{4}{4} = \frac{2}{3}$

In reducing improper fractions the denominator is divided into the numerator to create a mixed number. The remainder is written as a fraction.

Example:

$$\frac{8}{3} \rightarrow 3\overline{)\,8} \;\; \begin{array}{r} 2 \\ \\ -6 \\ \hline 2 \end{array} \;\; = 2\frac{2}{3}$$

Remember: The resulting mixed number may also need to be reduced further.

Example:

$$\frac{18}{4} \rightarrow 4\overline{)\,18} \;\; \begin{array}{r} 4 \\ \\ -16 \\ \hline 2 \end{array} \;\; = 4\frac{2}{4} = 4\frac{2}{4} \div \frac{2}{2} = 4\frac{1}{2}$$

Exercise 1.2

Reduce the following fractions to their lowest terms.

1. $\frac{7}{2}$
2. $\frac{10}{4}$
3. $\frac{18}{4}$
4. $\frac{20}{4}$
5. $\frac{6}{5}$
6. $\frac{100}{3}$
7. $\frac{39}{6}$
8. $1\frac{8}{12}$
9. $2\frac{9}{4}$
10. $\frac{4}{3}$

11. $\frac{14}{3}$
12. $\frac{140}{200}$
13. $\frac{10}{20}$
14. $7\frac{30}{40}$

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1.1.3: Why Fractions

Fractions are very common in waterworks mathematics. You may not see them in their “typical” form, for example:

$$\frac{3}{4} \quad \frac{2}{3} \quad \frac{1}{5}$$

You may see them as percentages:

$$75\% \quad 66\% \quad 20\%$$

Or you may see them as words:

Three quarters two thirds one fifth

However, these examples can also be expressed as fractions. We will discuss these later in the text. By understanding fractions, you can also understand how units are used to express things in terms of fractions. For example, if you drive a car at a velocity of 55 miles per hour, this is a form of a fraction.

$$\frac{55 \text{ miles}}{\text{hour}}$$

Fifty-five miles per hour is in fact a fraction. It is just expressed in a “per unit” example. It can be read as 55 miles per one unit of hour. What if you had an example of 110 miles per 2 hours? This could be written as:

$$\frac{110 \text{ miles}}{2 \text{ hours}}$$

Similar to reducing fractions such as:

$$\frac{2}{4} = \frac{1}{2}$$

The previous example of “55 miles per 2 hours” can be reduced as below:

$$\frac{110 \text{ miles}}{2 \text{ hours}} = \frac{55 \text{ miles}}{1 \text{ hour}} \text{ or } \frac{55 \text{ miles}}{hr}$$

The concept of “units” will be discussed in more detail later in this text, but understanding the concept is important to learn the process of solving waterworks mathematics problems. Since “adding” and “subtracting” fractions is not a common process in water-related math problems we will skip directly to multiplication and division of fractions.

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1.1.4: Multiplying Fractions

Multiplying and dividing fractions is a common practice when solving water related math problems. However, the process may not appear to be the multiplication and division of fractions and is commonly referred to as “unit conversion” or unit dimensional analysis. The example below demonstrates this process and will be discussed in more detail later in this text.

$$\frac{2\text{sqft}}{1} \times \frac{3\text{ft}}{1\text{sec}} = \frac{6\text{cf}}{\text{sec}}$$

For now, ignore the “units” and focus on solving the math. “Unit Dimensional Analysis” is a section we will spend a significant amount of time covering. Just look at the above problem as a fraction multiplication problem. Yes, both 2 over 1 and 3 over 1 are simply 2 and 3, but it helps to illustrate the process by looking at them as fractions.

$$\frac{2}{1} \times \frac{3}{1} = \frac{6}{1}$$

When multiplying fractions the numerators are multiplied by each other and the denominators are multiplied by each other. In other words, the numbers are multiplied straight across. So, in the example above, 2 x 3 = 6 and 1 x 1 = 1. The resulting answer is 6 over 1 or more simply put 6. However, when “units” are introduced, you can’t just say the answer is “6”. Always remember to reduce as necessary. Look at a couple other examples below:

Example 1.1.4.1

$$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$$

Example 1.1.4.2

$$\frac{2}{3} \times \frac{4}{6} = \frac{8}{18} \div \frac{2}{2} = \frac{4}{9}$$

In the first Example **1.1.4.1**, if you multiply the numbers across as before, you would multiply 1 times 1 and then 2 x 2. The resulting answer would be 1 over 4 or one forth. In the next Example **1.1.4.2** you can do the same thing. Multiply the 2 and 4 to get 8 and then multiply the 3 and 6 to get 18. The resulting answer is 8 over 18 or eight eighteenths. However, remember to always reduce if necessary. In order to reduce you need to find a number, which will go into both 8 and 18. Since 2 will go into both of these numbers, you can reduce the answer to 4 over 9 or four ninths.

Cross canceling is also something you can do. Cross canceling is nothing more than reducing before you multiply. Look for any number that goes into both a numerator and a denominator. In the example below, 2 goes into both the 2 in the first fraction and the 6 in the second fraction.

Example 1.1.4.3

$$\frac{2}{3} \times \frac{4}{6} = \frac{\cancel{2}}{3} \times \frac{4}{\cancel{6}} = \frac{1}{3} \times \frac{4}{3} = \frac{4}{9}$$

In the Example **1.1.4.3**, when you cross cancel, you reduce the two-thirds times four sixths to one third times four thirds. Then you multiply the 1 and 4 (numerators) and the 3 times 3 (denominators) to get an answer of four ninths.

When multiplying whole numbers and fractions you must first convert the whole number into an improper fraction and then, multiply. Be sure to cross cancel if possible and reduce if necessary. Placing a whole number over a 1 is an important step not only in solving these types of fraction problems, but will also be a helpful tool later in this text.

Example 1.1.4.4

$$5 \times \frac{3}{5} = \frac{5}{1} \times \frac{3}{5} \rightarrow \frac{\cancel{5}}{1} \times \frac{3}{\cancel{5}} = \frac{3}{1} = 3$$

The same rules apply when multiplying mixed numbers. Convert to improper fractions and multiply. In order to convert mixed numbers into improper fractions you must multiply the denominator by the whole number. Then add the numerator to the product

and put that number over the denominator. Be sure to cross cancel if possible and reduce if necessary. **Note: Never leave an answer as an improper fraction.**

Example 1.1.4.5

$1\frac{1}{2} \times 2\frac{3}{4}$

$1\frac{1}{2} \rightarrow (2 \times 1) + 1 \rightarrow \frac{3}{2}$

$2\frac{3}{4} \rightarrow (4 \times 2) + 3 \rightarrow \frac{11}{4}$

$\frac{3}{2} \times \frac{11}{4} = \frac{33}{8} \rightarrow 8\overline{)\,33} = 4\frac{1}{8}$ (4, remainder -32, 1)

Exercise 1.4

Multiply the following and reduce if necessary. Remember to cross cancel if possible. If you are multiplying a whole number by a fraction, place the whole number over 1.

1. $\frac{1}{2} \times \frac{2}{4}$
2. $8 \times 3\frac{2}{5}$
3. $\frac{18}{4} \times \frac{12}{9}$
4. $1\frac{10}{9} \times 4\frac{4}{7}$
5. $5\frac{9}{3} \times 7\frac{3}{5}$
6. $\frac{21}{24} \times \frac{4}{7} \times \frac{6}{3}$
7. $\frac{1}{100} \times \frac{10}{20}$
8. $\frac{13}{33} \times \frac{13}{33}$
9. $10\frac{12}{15} \times 10\frac{12}{15}$
10. $8\frac{1}{3} \times 5\frac{3}{5}$
11. $\frac{3}{4} \times \frac{6}{9} \times \frac{10}{12} \times \frac{12}{20}$
12. $\frac{100}{200} \times \frac{10}{20}$
13. $\frac{4}{5} \times \frac{5}{4}$
14. $15 \times 7\frac{1}{5}$

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1.1.5: Dividing Fractions

When dividing fractions you invert (flip upside down) the fraction on the right side of the equation (the dividend). Then it becomes a multiplication problem. Invert and multiply!

Example 1.1.5.1

$$\frac{2}{5} \div \frac{1}{2} \rightarrow \frac{2}{5} \times \frac{2}{1} = \frac{4}{5}$$

Example 1.1.5.2

$$\frac{\frac{4}{9}}{\frac{8}{9}}$$

This example reads $\frac{4}{9}$ divided by $\frac{8}{9}$.

However, after you "invert and multiply," it becomes:

$$\frac{4}{9} \times \frac{9}{8} \rightarrow \frac{1}{1} \times \frac{1}{2} = \frac{1}{2}$$

After inverting the fraction, the same rules apply as previously mentioned when multiplying fractions. You need to change mixed numbers into improper fractions; you can cross cancel, and always remember to reduce if necessary.

Example 1.1.5.3

$$\frac{3}{8} \div \frac{12}{6} \rightarrow \frac{3}{8} \times \frac{6}{12} \rightarrow \frac{\cancel{3}}{\cancel{8}} \times \frac{\cancel{6}}{\cancel{12}} = \frac{1}{4} \times \frac{3}{4} = \frac{3}{16}$$

In the Example **1.1.5.3** above the 3 divided into itself once and into the 12 four times. Similarly, 2 divided into 6, three times and into 8, four times. Can you see a different way to cross cancel?

If the dividend is a whole number write it as a fraction before inverting. Always remember to cross cancel and reduce if necessary.

Example 1.1.5.4

$$\frac{5}{8} \div 10 \rightarrow \frac{5}{8} \div \frac{10}{1} \rightarrow \frac{5}{8} \times \frac{1}{10} \rightarrow \frac{\cancel{5}}{8} \times \frac{1}{\cancel{10}} \rightarrow \frac{1}{8} \times \frac{1}{2} = \frac{1}{16}$$

Exercise 1.5

Divide the following and reduce if necessary.

1. $\frac{1}{2} \div \frac{2}{4}$
2. $\frac{5}{22} \div 7\frac{2}{4}$
3. $\frac{6}{8} \div \frac{9}{12}$
4. $3\frac{1}{3} \div 10$
5. $5\frac{1}{4} \div 8\frac{1}{2}$
6. $\frac{8}{16} \div \frac{16}{8}$
7. $4 \div 3\frac{2}{3}$
8. $\frac{2}{5} \div 5\frac{6}{9}$
9. $\frac{9}{13} \div 9$
10. $\frac{11}{22} \div \frac{1}{2}$

11. $2\frac{9}{20} \div 5\frac{2}{5}$
12. $3\frac{1}{2} \div 9\frac{1}{2}$
13. $5 \div 25$
14. $\frac{10}{3} \div \frac{1}{6}$
15. $\frac{13}{33} \div \frac{39}{3}$
16. $100\frac{1}{2} \div 10\frac{5}{6}$

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1.2.4: Percentages

1.2.4.1: Expressing Numbers as Percentages

1.2.4.2: Word Problems

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1.2.1: The Set of Real Numbers

The set of real numbers consists of the numbers that we use in everyday life. We will define the set of real numbers more precisely, but first, let's define some other sets of numbers.

Natural Numbers: The counting numbers starting with 1: 1, 2, 3, 4, …

Whole Numbers: 0 and the counting numbers: 0, 1, 2, 3, 4, …

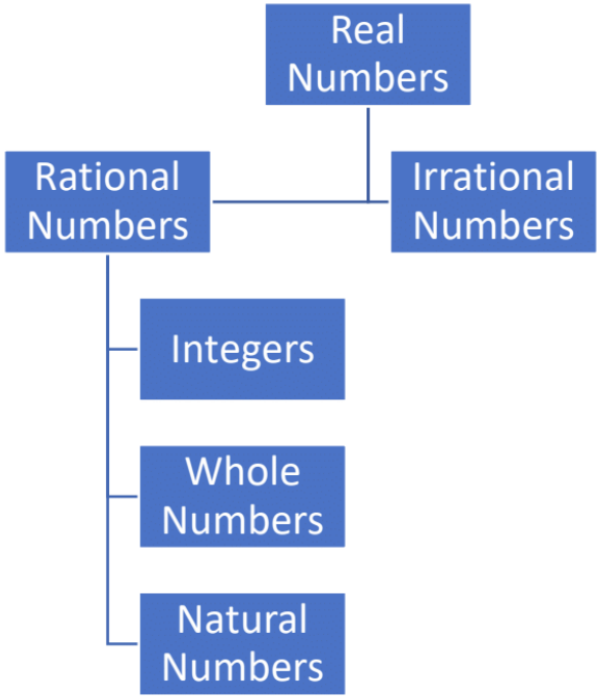
Integers: Positive and Negative Whole Numbers (includes 0); The whole numbers and their opposites: …, -4, -3, -2, -1, 0, 1, 2, 3, 4, …

Rational Numbers: A number that can be written as a fraction (integers, terminating decimals and repeating decimals)

Irrational Numbers: Numbers that cannot be written as a fraction (non-terminating decimals and non-repeating decimals)

Real Numbers: All rational and irrational numbers

Some numbers can be classified in many categories. The next diagram displays the relationship between the different sets of numbers.



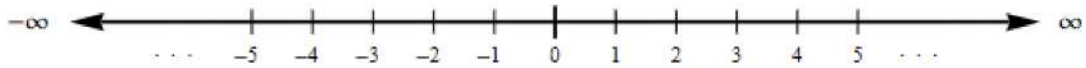
Example: Classify the following numbers

1. 2.718
2. $\sqrt{13}$
3. $\frac{24}{51}$
4. 101
5. $0.\overline{3}$
6. -5

See the video for the solutions.

The Real Number Line

We order real numbers on a number line based on their distance from 0. Positive numbers lie to the right of zero and Negative numbers lie to the left of zero. Each point on the number line corresponds to a real number.



Notice that -2 is represented by a distance of 2 units to the left of zero, the negative determines the side of zero while the 2 represents the distance from zero. Similarly, +2 is represented by a distance of 2 units to the right of zero, the positive indicates we move to the right of zero while the 2 represents the distance from zero. When writing positive numbers, it is customary not to write the "+" sign in the front.

Example: Plot the following numbers on a real number line

1. 2.718
2. $\sqrt{13}$
3. $\frac{24}{51}$
4. 101
5. $0.\overline{3}$
6. -5

See the video for a demonstration.

We determine the size of a number relative to another number using less than ((\<\)) or greater than (>) signs. Whichever number is further to the right, is larger, while a number that is further to the left is smaller.

We say "a *is less than* b" if a lies to the left of b on a real number line and we write this as: $a < b$.

We say "a *is greater than* b" if a lies to the right of b on a real number line and we write this as: $a > b$.

Examples: Use $<$ or $>$ to indicate the relationship between the stated numbers

1. 7 ____ -3
2. 5 ____ 12
3. 5.8 ____ 5.7
4. -3.2 ____ -3.1
5. -5 ____ -12

See the video for the solutions.

The Opposite of a Number and Absolute Value

Definition: The opposite of a real number, a, is $-a$.

We can think of the opposite of a real number as changing the sign of the real number.

Examples: The opposite of 5 is -5. The opposite of -7 is – (-7) = 7

Hence, -(-7) can be read as "the opposite of -7" or "the opposite of the opposite of 7" or 7.

Definition: The absolute value of a real number is its distance from zero on a real number line. The notation for the absolute value uses two vertical bars on either side of the number, hence "the absolute value of a" would be denoted as $|a|$. Since the absolute value represents a distance, its value is always positive.

Examples:

$|5|$= 5 since 5 is a distance of 5 from 0

$|-7|$=7 since -7 is a distance of 7 from 0

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1.2.2: Mathematical Operations

The Addition of Integers and Decimals

Adding Numbers with the same signs

- Add the absolute values of the numbers and assign the common sign to the result
- NOTE: When the signs are both positive, add the values

Example: $23+18$

The common sign is +, so the answer will be positive, now we add the numbers to obtain

$$23+18=41 \tag{1.2.2.1}$$

Example: $-17+(-31)$

The common sign is -, so the answer will be negative, now we add the absolute values of the numbers to obtain:

$$-17+(-31)= \tag{1.2.2.2}$$

First, calculate the sum of the absolute values:

$$|-17|+|-31|=\ 17+31=48 \tag{1.2.2.3}$$

Next, assign the result the common sign, so the final answer is: -48.

$$-17+(-31)=-48 \tag{1.2.2.4}$$

Adding Numbers with the Opposite Signs

- Take the absolute value of each number
- Subtract the smaller number from the larger number
- Assign the sign of the result based on the sign of the number with the larger absolute value
- NOTE: The sign of the larger absolute value wins. With practice, these steps will start to feel seamless.

Example: $21+(-13)$

First, calculate the absolute value of each number:

$$|21|=21 \text{ and } |-13|=13 \tag{1.2.2.5}$$

Next, subtract the smaller number from the larger number:

$$21-13=8 \tag{1.2.2.6}$$

Next, assign the sign of the number whose absolute value was greater, in this case, the sign of 21 is the sign of the final answer (positive), hence

$$21+(-13)=8 \tag{1.2.2.7}$$

Scientific calculator keystrokes:

Example: $28+(-54)$

First, calculate the absolute value of each number:

$|28|=28$ and $|-54|=54$

Next, subtract the smaller number from the larger number:

$$54-28=26 \tag{1.2.2.8}$$

Next, assign the sign of the number whose absolute value was greater, in this case, the sign of -54 *is the sign of the final answer (negative), hence*

$$28+(-54)=-26 \tag{1.2.2.9}$$

Short-cut: Now that we have gone through the formal process for adding integers, let's get the general idea of the process:

- If the signs are the same, combine the numbers and keep the sign
- If the signs are different, disregarding the signs, subtract the smaller number from the larger number, then keep the sign of the larger number

Example: $13+(-29)$

Since 29 is larger than 13, we subtract 13 from 29 to get 16, and use the sign of 29 which is negative: -16

Example: $-28+(-54)$

Since the signs are the same, the answer will have the same sign (negative), now combine the numbers 28 + 54 = 82, so the final answer is -82

Similarly with decimal numbers:

Example: $-2.34+(-5.4)=$

Since the signs are the same, we add the numbers: 2.34 + 5.4 = 7.74 and keep the common sign (negative) to get – 7.74

Subtraction of Integers and Decimals

When subtracting an integer or decimal, we add the opposite of the number following the subtraction.

Example: $15-7=$

In this case, we can perform regular subtraction, however, we can also apply the subtraction rule of adding the opposite to obtain:

$$15+(-7)=8 \tag{1.2.2.10}$$

since 15 is larger than 7, we subtract and keep the sign of the larger number which is positive

Example: $3-12=$

Remembering to add the opposite of 12, we get

$$3+(-12)=-9 \tag{1.2.2.11}$$

Since the signs are different and 12 is larger than 3, we subtract $12-3$ to get 9, but use the sign of 12 which is negative to obtain -9

Likewise with decimal values:

Example: $8.23-(-1.2)=$

We first add the opposite of -1.2: $8.23+1.2=$

Next, we combine the numbers since they have same signs to obtain:

$$8.23-(-1.2)=8.23+1.2=9.43 \tag{1.2.2.12}$$

Multiplication and Division of Integers and Decimals

To multiply or divide integers and decimals, we use multiply the numbers and use the following rules for the sign:

- If two numbers have the same signs, the result is positive
- If two numbers have different (opposite) signs, the result is negative

Examples:

1. $(3)(-7)=\ -21$
2. $(-15)(-10)=150$
3. $(-5.2)(2)=-10.4$
4. $(2)(7)=14$
5. $(-25)\div(-5)=5$
6. $(-12.8)\div(4)=-3.2$
7. $(250)\div(-10)=-25$

8. $(48) \div (6) = 8$

Addition, Subtraction, Multiplication, and Division of Integers and Decimals using a Scientific Calculator

There are many types of scientific calculators available in the retail market, on our personal computers, and even on our personal devices such as cell phones and tablets. As a result, let's first distinguish between two types of scientific calculators: A Display calculator and a non-display calculator. Some examples of display calculators are: TI30XIIS, TI-36X Pro, TI-30XS Multiview, and the Casio fx-350ES PLUS. Some examples of non-display calculators are TI-30Xa, most cell phone calculators, and most calculators on personal computers.

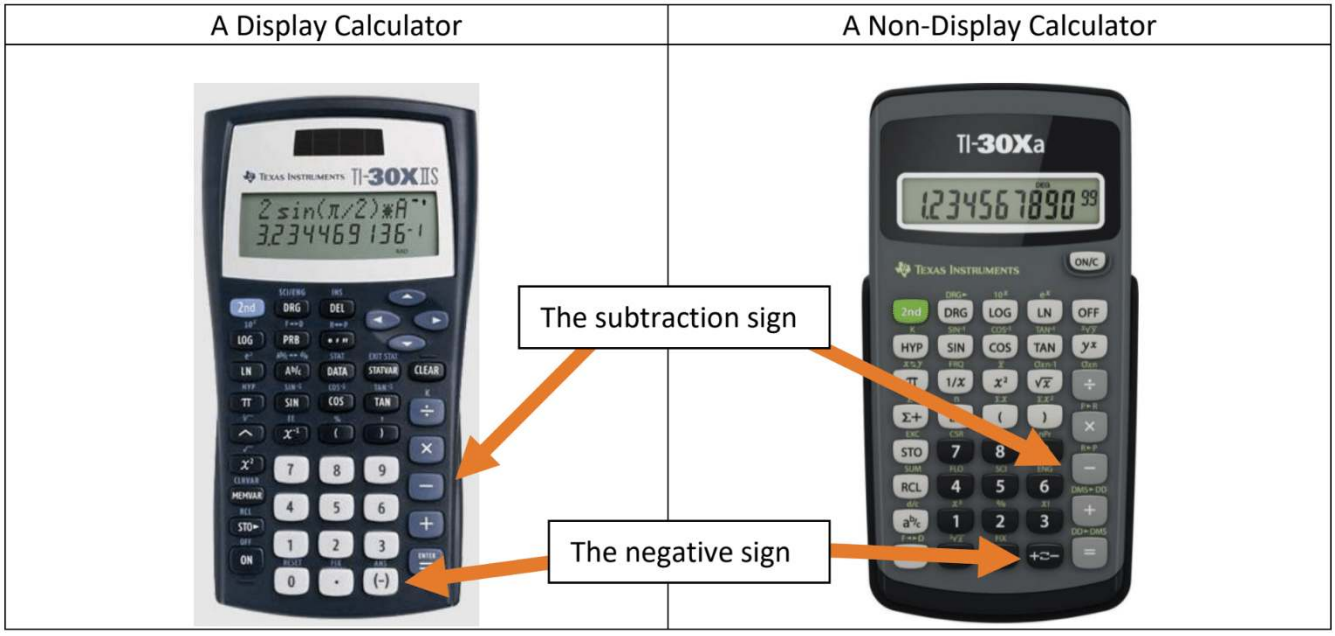
For our purposes, we will determine if a calculator is a "Display" calculator or a "non-display" calculator by doing the following:

Type 2 + 3 on your calculator.

- If your screen displays the entire expression 2 + 3, then you have a "Display" calculator.
- If you screen displays only the 3 after typing 2 + 3, then you have a "non-display" calculator.

On Display calculators, we can usually enter the problem as it is written. On a non-display calculator, we usually must enter the problem in reverse order of operations (see Unit 2 for more information).

Let's revisit some of our earlier examples and calculate them on the scientific calculator. For negative numbers, be sure to use the negative symbol, (-), which is generally at the bottom of the keyboard on a TI calculator and not the subtraction symbol, -, which is usually on the right side of the keyboard. Each calculator is different, so you may have to experiment with your calculator to determine the process.



To compute -17+(-31) use the following sequence of keystrokes to obtain -48:

Display Calculator:	Non-display Calculator:
(-) 17 + (-) 31 ENTER	17 (-) + 31 (-)=
Type the negative sign before the number	Type the negative number after the sign

To compute 8.23-(-1.2)= use the following sequence of keystrokes to obtain 9.43:

Display Calculator	Non-display Calculator:
8.23 - (-) 1.2 ENTER	8.23 - 1.2 (-) =
Use the subtraction key, then type the negative sign before the number	Use the subtraction key then type the negative sign after the number

To compute (-15)(-10) = use the following sequence of keystrokes to obtain 150:

Display Calculator	Non-display Calculator:
(-)15 X (-)10 ENTER	15 (-) X 10 (-) =
Type the negative sign before the number	Type the negative sign after the number

To compute (250)÷(-10) = use the following sequence of keystrokes to obtain -25:

Display Calculator	Non-display Calculator:
250÷(-)10 ENTER	250÷10(-) =
Type the negative sign before the number	Type the negative sign after the number

Fractions

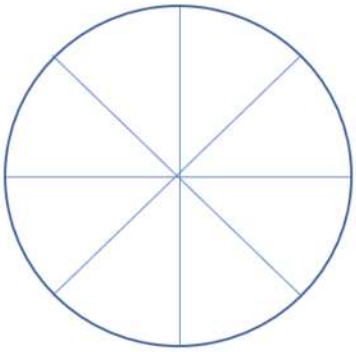
Fractions are real numbers that indicate a portion of a whole. A fraction consists of a numerator and denominator. The denominator represents the number of equal parts of an object and the numerator represents a portion of those equal parts. For example, if pipe is separated into 4 equal parts, ¼ would represent 1 out of 4 of the parts, 2/4 would represent 2 out of the 4 parts, ¾ would represent 3 out of the 4 parts, and 4/4 = 1 would represent all 4 parts or the whole pipe. Likewise, 0/4 would represent 0 of the 4 parts or nothing, hence 0/4 = 0.

The rectangle below is divided into two equal parts. Hence 1 of the pieces out of the 2 pieces would represent 1/2.



The circle shown below is divided into 8 equal parts. 1 part would represent 1/8. 2 parts would represent 2/8 which would reduce to ¼ for a couple of reasons:

1. if we were to shade 2 of the 8 pieces, that would also represent 1 of 4 equal pieces and
2. 2/8 can be reduced by dividing both the numerator (2) and the denominator (8) by the same number, which in this case would be 2, hence: $\frac{2}{8} = \frac{2\div2}{8\div2} = \frac{1}{4}$



The "bar" in a fraction also represents division, so ¼ would also mean $1 \div 4$. This can be interpreted as a whole divided into 4 equal parts or 1 of 4 equal parts.

Fractions have many applications. Fractions can also be used to represent units such as miles per hour or $\frac{miles}{hour}$. Fractions can also be used to denote ratios and proportions; we will see the use of fractions in these applications in a later unit.

Multiplying and Dividing Fractions

To multiply fractions:

Multiply the numerators and multiply the denominators.

To simplify, reduce by dividing like factors (numbers that divide into other numbers).

Examples:

1. $\frac{2}{3} \cdot \frac{5}{7}$

a. Multiply the numerators and multiply the denominators.

$$\frac{2}{3} \cdot \frac{5}{7} = \frac{10}{21}$$

Since 10 and 21 do not have any common factors, this is the simplified or reduced answer.

2. $\frac{22}{63} \cdot \frac{9}{24}$

a. Multiply the numerators and multiply the denominators.

$$\frac{22}{63} \cdot \frac{9}{24} = \frac{108}{1512}$$

b. Simplify by reducing the fraction (divide the numerator and denominator by the same number(s))

$$\frac{108}{1512} = \frac{108 \div 12}{1512 \div 12} = \frac{9}{126} = \frac{9 \div 9}{126 \div 9} = \frac{1}{14}$$

Another option for this problem is to reduce before multiplying:

$$\frac{12}{63} \cdot \frac{9}{24}$$

a. Reduce the numerators and denominators by dividing each by the same number

$$\frac{12 \div 12}{63 \div 9} \cdot \frac{9 \div 9}{24 \div 12} = \frac{1}{7} \cdot \frac{1}{2}$$

b. Multiply the numerators and denominators (multiply straight across)

$$\frac{1}{7} \cdot \frac{1}{2} = \frac{1}{14}$$

3. $\frac{24}{72} \cdot \frac{18}{30}$

Since the numbers in the fractions are large, let's reduce first, then multiply.

Determine numbers that divide into both the numerator and denominator:

9 divides into 18 and 72; 6 divides into 24 and 30 OR 6 divides into 18 and 30; 24 divides into 24 and 72

$$\frac{24}{72} \cdot \frac{18}{31} = \frac{24 \div 6}{72 \div 9} \cdot \frac{18 \div 9}{30 \div 6} = \frac{4}{8} \cdot \frac{2}{5} = \frac{4 \div 4}{8 \div 4} \cdot \frac{2}{5} = \frac{1}{2} \cdot \frac{2}{5} = \frac{1}{2 \div 2} \cdot \frac{2 \div 2}{5} = \frac{1}{5}$$

OR

$$\frac{24}{72} \cdot \frac{18}{31} = \frac{24 \div 24}{72 \div 24} \cdot \frac{18 \div 6}{30 \div 6} = \frac{1}{3} \cdot \frac{3}{5} = \frac{1}{3 \div 3} \cdot \frac{3 \div 3}{5} = \frac{1}{5}$$

To divide fractions: Invert the second fraction and change the operation to multiplication and continue as described above.

Example: $\frac{3}{5} \div \frac{9}{10}$

$$\frac{3}{5} \div \frac{9}{10} = \frac{3}{5} \cdot \frac{10}{9} = \frac{30}{45} = \frac{2}{3}$$

Example: $\frac{15}{7} \div \frac{25}{21}$

$$\frac{15}{7} \div \frac{25}{21} = \frac{15}{7} \cdot \frac{21}{25} = \frac{3}{1} \cdot \frac{3}{5} = \frac{9}{5}$$

Adding and Subtracting Fractions

With like denominators

To add or subtract fractions, the fractions must have the same denominator:

Step 1: Verify that the fractions are like fractions (fractions with the same denominator).

Step 2: Add or subtract the numerators and keep the same denominator.

Examples:

1. $\frac{2}{7} + \frac{3}{7} = \frac{2+3}{7} = \frac{5}{7}$
2. $\frac{14}{17} - \frac{5}{17} = \frac{14-5}{17} = \frac{9}{17}$

With unlike Denominators

Step 1: Rewrite the unlike fractions (fractions with different denominators) as like fractions (fractions with the same denominator) with the least common multiple as their new denominator. This new denominator is called the least common denominator (LCD).

To determine the least common denominator (LCD), find the smallest common multiple of the denominators, in other words, find the smallest number that both denominators divide into

Rewrite the unlike fractions as like fractions by multiplying the numerator and denominator of each fraction by the number that makes the denominator of each the least common denominator.

Step 2: Add or subtract the numerators and keep the common denominator.

Examples:

1. $\frac{2}{3} + \frac{1}{9} =$

First find the smallest number that both 3 and 9 will divide into, in this case it will be 9, so 9 is the LCD.

So, we need to multiply the first fraction by 3/3 to create a 9 in the denominator:

$$\frac{3}{3} \cdot \frac{2}{3} + \frac{1}{9} = \frac{6}{9} + \frac{1}{9} = \frac{7}{9}$$

2. $\frac{3}{7} + \frac{1}{4} =$

The least common denominator = 28 (since 28 is the smallest number that can be divided by both 7 and 4)

Next, multiply the numerator and denominator of 3/7 by 4/4 to create a denominator of 28 and multiply the numerator and denominator of ¼ by 7/7 to create a denominator of 28, finally add the numerators and keep the common denominator.

$$\frac{4}{4} \cdot \frac{3}{7} + \frac{1}{4} \cdot \frac{7}{7} = \frac{12}{28} + \frac{7}{28} = \frac{19}{28}$$

NOTE: We add, subtract, multiply, and divide negative fractions similar to how we added, subtracted, multiplied and divided negative numbers in Section ___.

Percents

A percent is defined to be an amount based on 100. If we divide the word into two words, we have “per” and “cent”. Per means divide by and cent means 100, hence divide by 100 or out of 100.

Example: 54% means 54 out of 100

We will use percentages to calculate values in Unit ____.

Converting between different types of numbers (fractions, decimals, and percentages)

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

To convert from a decimal to a fraction, determine the place of the last digit after the decimal, write the fraction as all the digits after the decimal over the last place of the decimal.

Example: 0.547 represents 547 thousandths since the last digit after the decimal is in the thousandths place, we have 547/1000.

To convert from a fraction to a percent

Option 1: Convert the fraction to a decimal, then convert the decimal to a percent

Option 2: Use a proportion to write the fraction with a denominator of 100, then using the definition of a percent, the percent will be based on the numerator of the fraction with a denominator of 100. We will explore this option more in Unit ___ when we learn about proportions.

To convert from a decimal to a percent, multiply the decimal by 100 or move the decimal place two units to the right.

To convert from a percent to a decimal, divide the percent number by 100 or move the decimal place two units to the left.

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SECTION OVERVIEW

1.2.3: Decimals

1.2.3.1: Understanding Decimals

1.2.3.2: Multiplying and Dividing Decimals

1.2.3.3: Rounding

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1.2.3.1: Understanding Decimals

Numbers written with decimals is another way of expressing fractions. However, decimals have a distinct differentiation with fractions in that decimals are based on 10. In that, one decimal place to the right of the whole number indicates *tenths*, two decimal places to the right of the whole number indicates *hundredths*, three decimal places to the right of the whole number indicates *thousandths*, etc.

Example 1.2.3.1.1

0.1 = tenths place

1.01 = hundredths place

0.001 = thousandths place

1.01 = ten thousandths place

1.

Decimals can easily be written as fractions by using the number to the right of the decimal point as the numerator and then using a 10, 100, 1,000, 10,000, etc. as the denominator. Determining which "base-ten" number to use as the denominator is determined by the number of digits there are to the right of the decimal point.

Example 1.2.3.1.2

$0.1 \rightarrow \frac{1}{10}$ 1 tenth

$0.01 \rightarrow \frac{1}{100}$ 1 hundredth

$0.001 \rightarrow \frac{1}{1,000}$ 1 thousandth

$0.0001 \rightarrow \frac{1}{10,000}$ 1 ten-thousandth

Exercise 2.1

Write the following decimals as fractions and reduce if necessary.

1. 0.2 =
2. 0.103 =
3. 0.13 =
4. 0.02 =
5. 0.1234 =
6. 0.0023 =
7. 0.0101 =
8. 0.1010 =
9. 0.020 =
10. 0.0202 =
11. 0.1000 =
12. 0.4500 =

Exercise 2.1.1

Write the following expressions as decimals and fractions.

		Decimal	Fraction
1.	7 tenths		
2.	1,000 ten-thousandths		
3.	475 thousandths		
4.	32 hundredths		
5.	12 thousandths		
6.	2,345 ten-thousandths		
7.	3 hundredths		
8.	10 thousandths		
9.	132 ten-thousandths		
10.	4,002 ten-thousandths		

Digits to the left of the decimal indicate a whole number. Whenever there is a whole number with a decimal fraction the expression is pronounced using “and.”

Example:

12.3 = Twelve and three tenths = $\mathbf{12\frac{3}{10}}$

100.07 = One hundred and seven hundredths = $\mathbf{100\frac{7}{100}}$

3,005.023 = Three thousand five and twenty-three thousandths = $\mathbf{3,005\frac{23}{1,000}}$

Exercise 2.1.2

Write the following expressions as a decimal and a fraction. Remember to reduce if necessary.

		Decimal	Fraction
1.	Two and five hundredths		
2.	Thirteen and two hundred thousandths		
3.	One thousand three and two ten-thousandths		
4.	Fifty-five and fifty hundredths		
5.	One and fourteen hundredth		
6.	Eleven thousand four and twelve thousandths		
7.	Ten and two tenths		
8.	Four hundred one and four ten-thousandths		
9.	Five thousand two hundred eight and one thousand ten-thousandths		

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1.2.3.2: Multiplying and Dividing Decimals

Multiplying and dividing decimals is simple enough if you use a calculator. When multiplying decimals, there is no certain order you need to type the numbers in your calculator.

Example 1.2.3.2.1

0.255 × 0.23 = 0.05865

25 × 35 = 875

100.5 × 12.75 = 1,281.375

Exercise 2.2

Multiply the following problems

1. $\begin{array}{r} 5 \\ \times 0.35 \\ \hline \end{array}$
2. $\begin{array}{r} 65 \\ \times 0.2 \\ \hline \end{array}$
3. $\begin{array}{r} 0.515 \\ \times 0.15 \\ \hline \end{array}$
4. $\begin{array}{r} 20.54 \\ \times 5.01 \\ \hline \end{array}$
5. $\begin{array}{r} 0.002 \\ \times 1.07 \\ \hline \end{array}$
6. $\begin{array}{r} 0.9 \\ \times 0.8 \\ \hline \end{array}$
7. $\begin{array}{r} 8.5 \\ \times 0.2 \\ \hline \end{array}$
8. $\begin{array}{r} 52 \\ \times 0.11 \\ \hline \end{array}$
9. $\begin{array}{r} 0.4 \\ \times 0.04 \\ \hline \end{array}$
10. $\begin{array}{r} 4.23 \\ \times 2 \\ \hline \end{array}$
11. $\begin{array}{r} 0.2 \\ \times 0.45 \\ \hline \end{array}$
12. $\begin{array}{r} 2.68 \\ \times 0.298 \\ \hline \end{array}$

When dividing decimals, the denominator (or the divisor) is divided into the numerator (or the dividend). The resultant answer is termed the quotient. In the example below, 25 is divided into 125. On your calculator, you would type in the 125 first and then the 25. It is read as 125 divided by 25.

Example 1.2.3.2.2

$$\frac{125}{25} = 5$$
$$\frac{1.25}{25} = 0.05$$
$$\frac{1.25}{0.25} = 5$$

Exercise 2.2.1

Divide the following problems.

1. $0.6 \div 5 =$
2. $28 \div 7 =$

3. $14 \div 20 =$
4. $0.54 \div 12 =$
5. $75 \div 40 =$
6. $1.44 \div 12 =$
7. $0.48 \div 2.4 =$
8. $156 \div 0.78 =$

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1.2.3.3: Rounding

Rounding is another important process to understand and properly use mathematics. As we discussed in Section 2.1, decimal places can be carried out to the ten-thousandths place and further if needed. However, there is a practical rule to follow and in waterworks mathematics we seldom carry decimal places much further than the hundredths place, unless we are working in the area of water quality. The rule to follow is to "round" the decimal to the furthest decimal place in the question. Look at the examples below.

Example 1.2.3.3.1

2 × 2 = 4	Since both numbers you are multiplying are whole numbers, then you would leave the answer as a whole number.
2.0 × 2.0 = 4.0	Now, upon first glance, the answers may look like they are the same. After all, doesn't 4 and 4.0 equal the same number? The short answer is yes. However, 4.0 is actually more accurate than 4. Why? Because 4.0 is rounded to the tenths place and is saying the value is no more than 4 and 0 tenths. When we "round" the first answer "4" can be 4.1, 4.2, 4.3, or 4.4. We don't know, since the whole numbers are expressed as whole numbers and not round to the nearest tenth. Since both numbers being multiplied are rounded to the nearest tenth, then we round the answer to the nearest tenth.
2.0 × 2 = 4.0	This answer is also rounded to the nearest tenth since one of the numbers being multiplied is rounded to the nearest tenth. However, the second example is still the most accurate.

Why?

Now let's look at how we round. The rule is simple. If the preceding number you are rounding to is </=4 (0, 1, 2, 3, or 4) you round down, which is to say you round to the preceding number. If the number is >/= 5 (5, 6, 7, 8, or 9), then you round up, which is to say the preceding number goes up by one. See the examples below.

Example 1.2.3.3.2

Round to the nearest whole number

1.2 = 1

1.24 = 1

1.25 = 1

Since we are rounding to the whole number, we look at the tenths place or the number to the right of the place we are rounding to. In these examples the number is 2, which is </= 4.

Round to the nearest tenths place

1.2 = 1.2

1.24 = 1.2

1.27 = 1.3

We now need to look at the hundredths place or the number to the right of the tenths place. Since there is no hundredths place in the first example, the number stays at 1.2. In the second example you would round down since the preceding number is </= 4 and in the third example, you would round up since the preceding number is >/= 5.

Exercise 2.3

Round the following numbers

Round to the nearest whole number.

1. 29.05
2. 135.9
3. 0.4

Round to the nearest tenth place.

4. 20.045
5. 0.98
6. 200.03

Round to the nearest hundredth place.

7. 1.234
8. 0.976
9. 345.095

Round to the nearest thousandth place.

10. 3
11. 1,367.0982
12. 0.9855

Did any of the questions above give you difficulty? Let's look at number 5. The question said to round to the nearest tenth place. Therefore, we need to look at the preceding number or the hundredths place. The number was 0.98, so we need to look at the 8. Since 8 is >/= 5 we must round the number in the tenths place up. However, in this case the number to be rounded up is a 9. Look at the example below:

0.98 the 9 becomes 10, but since it is a 0.9, it becomes 1.0

What about number 10? In this question, you need to round a whole number (3) to the thousandth place. Therefore, you need to add zeros until you get to the thousandths place. See below:

3 = 3.000

In this text we will typically round to the nearest whole number, tenths, or hundredths places.

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SECTION OVERVIEW

1.2.4: Percentages

1.2.4.1: Expressing Numbers as Percentages

1.2.4.2: Word Problems

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1.2.4.1: Expressing Numbers as Percentages

Percentages and decimals are commonly used in waterworks mathematics. Whether you are working with financial budgets, chemical percent concentrations, or water quality results, decimals and percentages are used often. Therefore, knowing how to convert to percentages from decimals is important and vice versa.

When expressing numbers as a percent they need to be whole numbers or decimals. Therefore, fractions must be converted first. Percent (%) simply means per hundred. Understanding that percent means per hundred indicates that 2 decimal places are involved.

When a number needs to be converted to a percent you multiply the number by 100 and put a percent sign (%) at the end.

Example 1.2.4.1.1

The number 1 written as a percent is

$1 \times 100 = 100\%$

The number 5 written as a percent is

$5 \times 100 = 500\%$

When a decimal is written as a percent do the same thing.

$1.4 \times 100 = 40\%$

Note that the decimal moves two places to the right.

When a percent is written as a decimal, you simply divide the number by 100. Dividing by 100 moves the decimal two places to the left.

Example 1.2.4.1.2

If 100% is to be written as a number, divide by 100.

$$100\% \div 100 = 1$$

$$8.25\% \div 100 = 0.0825$$

$$2,500\% \div 100 = 25$$

Exercise 3.1

Convert the following numbers to percentages and percentages to numbers (round all numbers to the nearest hundredth place.

1. 1 =
2. 30 =
3. 0.5 =
4. 0.75 =
5. 1.02 =
6. 35.5 =
7. 0.004 =
8. 5.005 =
9. 102% =
10. 2.3% =
11. 0.45% =
12. 1,570% =
13. 8% =
14. 0.9% =
15. 65% =
16. 12.5% =

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1.2.4.2: Word Problems

Word problems tend to give people some difficulty. Especially in problems where there is a lot of information that is not needed to solve the actual problem. However, most of the problems we deal with involve words.

> How much money did I pay in taxes last year?
>
> How many pounds of chemical do I need to add to this water supply?
>
> How many gallons of water were sold last month?
>
> What is the flow rate of water through that pipeline?
>
> What is the area of the filter bed?

Yes, the questions posed above do not have any information to be able to solve for the answer, but these are some very common questions water operators are asked to solve. In word problems, there is always an underlying question that must be answered. Narrowing down the problem to the question you are trying to solve is an important step. Another important step is being able to pull out the information (numbers) in the question to help you solve for the answer.

In word problems with percentages, there are a couple of things you should take note of. The word “is” should be treated as an equal (=) sign and the word “of” as a multiplication (x) sign. You must also remember to convert the percent to a decimal prior to solving.

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SECTION OVERVIEW

1.3: Powers, Roots, Order of Operations, and Evaluating Expressions

1.3.1: Powers and Roots

1.3.2: Order of Operations

1.3.3: Evaluating Expressions

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1.3.1: Powers and Roots

As we learned in Unit 1, we can use the following operations on real numbers: addition, subtraction, multiplication, division, and absolute value. In addition to these operations, we can also apply powers and roots.

Powers

Powers are as the notation for multiplying a number by itself multiple times. Another name for a power is an exponent. The power or exponent is denoted as a superscript.

$$a^n = \underbrace{(a \cdot a \cdot a \cdot \cdots \cdot a)}_{n \text{ times}} \tag{1.3.1.1}$$

In this notation, the a is called the "**base**" and the n is called the **power** (or **exponent**).

Examples:

1. $5^3 = 5 \cdot 5 \cdot 5 = 125$
2. $(-2)^4 = (-2)(-2)(-2)(-2) = 16$
3. $(2.3)^2 = (2.3)(2.3) = 5.29$
4. $(2/3)^5 = 2/3 \cdot 2/3 \cdot 2/3 \cdot 2/3 \cdot 2/3 = 32/243$

Roots

Roots are obtained by "undoing" a power. There are many types of roots, we will look at square roots, cube roots, and fourth roots.

- The square root of a number, a, is b if $b^2 = a$
- The cube root of a number, a, is b if $b^3 = a$
- The fourth root of a number, a, is b if $b^4 = a$
- We can generalize this to say the nth root of a number, a, is b if $b^n = a$

We use a radical symbol to represent the operation of a root: $\sqrt{}$

- Square root symbol: $\sqrt{}$
- Cube root symbol: $\sqrt[3]{}$
- Fourth root symbol: $\sqrt[4]{}$
- nth root symbol: $\sqrt[n]{}$

The number under a radical symbol is called the **radicand**.

Examples:

1. The square root of 9 is denoted as $\sqrt{9}$, since $3 \wedge 2 = 9, \ then \ \sqrt{9} = 3$.
2. $\sqrt{49}$, since $7^2 = 49, \ then \ \sqrt{49} = 7$.
3. The cube root of 8 is denoted as $\sqrt{}$, since $2^3 = 8, \ then \ \sqrt{8} = 2$.
4. $\sqrt{1.44} = 1.2$ since $(1.2)^2 = 1.44$
5. $\sqrt{\frac{36}{121}} = 6/11$ since$\left(\frac{6}{11}\right)^2 = 36/121$

To compute a root:

- On a scientific display calculator, type the radical symbol first, then the radicand followed by enter.

Example: $\sqrt{1.44}$ the keystrokes would be $\sqrt{}$ 1.44 *Enter*

- On a non-display calculator, type the radicand first, then the radical symbol (do not press =)

Example: $\sqrt{1.44}$ the keystrokes would be 1.44 $\sqrt{}$

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1.3.2: Order of Operations

The order of operations represents a mathematical agreement of the order in which calculations should be performed. The order is Grouping Symbols, Exponents, Multiplication and Division as they appear left to right, and Addition and Subtraction as they appear left to right. Traditionally, we use PEMDAS as the acronym to remember the order of operations using Parentheses, Exponents, Multiplication, Division, Addition, and Subtraction. To allow us to perform operations on more problems, let's consider Grouping Symbols as the first order since it would encompass parentheses, brackets, roots, absolute values, and fraction bars. So, let's learn the acronym GEMDAS, one way to remember the letters is to remember GEMDAS: Greater Education Makes Doctors and Scholars or Good (Environment) Efforts Minimizes Diseased Animals Swimming

Grouping **S**ymbols-**E**xponents-**M**ultiplication/**D**ivision-**A**ddition/**S**ubtraction

GEMDAS

Example 1.3.2.1

Simplify $5-3(4-6\div(-2))$.

Solution

In this problem, we start with the inner most grouping symbol which would be the parentheses around the -2, however, there is no operation with this set of parentheses, so we move to the other set of parentheses: $(4-6\div(-2))$. Within this set of parentheses, the division must occur before the subtraction, so we computer $6\div(-2)=-3$, so the parentheses would be

$$(4-(-3))$$

Next, we can recall that we subtract integers by adding the opposite, so $(4-(-3))=4+3=7$ continuing, we now have

$$5-3(4-6\div(-2))=5-3(7)$$

Next, we perform the multiplication before the subtraction to obtain:

$$5-21=-15$$

Example 1.3.2.2

Simplify $2+3\cdot\sqrt{21-5}-8+4^2$.

Solution

In this problem, we start with the radical since it is a grouping symbol:

$$\sqrt{21-5}=\sqrt{16}=4$$

So now we have:

$$2+3\cdot4-8+4^2$$

Next, we apply the power or exponent:

$$4^2=16$$

So, we now have:

$$2+3\cdot4-8+16$$

Next, we perform multiplication:

$$3\cdot4=12$$

So, we now have:

$$2+12-8+16$$

Finally, we perform addition and subtraction as it appears left to right to obtain:

$$2+12-8+16=14-8+16=6+16=22$$

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1.3.3: Evaluating Expressions

In the Water Industry, we use many formulas to make calculations. As a result, we need to know how to evaluate expressions, that is, substitute known values for variables, and simplify the expression using the order of operations.

Example 1.3.3.1

If $x = 4$ and $y = 3$ evaluate $3xy^2 + 2\sqrt{x}$.

Solution

First, substitute the given values for x and y:

$$3(4)(3)^2 + 2\sqrt{4}$$

Next, perform order of operations to simplify:

$$3\,(4)\,(3)^2 + 2\sqrt{4} = 3\,(4)\,(9) + 2\,(2) = 108 + 4 = 112$$

Example 1.3.3.2

If $a = 9$ *and* $b = 7$, evaluate $\frac{2\sqrt{a}+3}{b-5}$.

Solution

First, substitute the given values for a and b:

$\frac{2\sqrt{9}+3}{7-5}$

Next, simplify using order of operations:

$\frac{2\cdot 3+3}{7-5} = \frac{6+3}{7-5} = \frac{9}{2}$

Recall from Unit 1, we could convert this fraction to a decimal to obtain 4.5, however, the general rule of thumb is to use decimals only when you start with decimals, or the directions states to use decimals.

Example 1.3.3.3

A water plant has a rectangular basin with a base that is in the shape of a square with sides of length x and the height of the basin is y. As a result, the volume is calculated using the following expression: x^2y. If the length of the base of the basin is 50 feet and the height of the basin is 20 feet, calculate the volume of the basin.

Solution

First, we substitute the values for x and y: $x^2y = (50\ feet)^2 \cdot (20\ feet)$

Next, we simplify the expression using order of operations to obtain:

$$\left(2500\ ft^2\right)(20\ ft) = 50,000\ ft^3 \qquad (1.3.3.1)$$

Example 1.3.3.4

To estimate the extra water a town needs to store for emergencies, we must multiply the population by 45 gallons, then add 42,000 gallons to account for what the fire fighters would need in case of a fire, and then multiply the result by a safety factor of 1.8.

a. Write an expression for calculating the amount of extra water a town needs to store in case of an emergency.

b. Use the expression to calculate the amount of extra water a town needs to store in case of an emergency if the population of the town is 48,000.

Solution

a. We begin by converting the English to math:

Multiply the population, let's call the population P, by 45 gallons: $45P$

Then add 42,000 gallons: $45P + 42,000$

Then multiply by 1.8: $1.8(45P + 42,000)$

Hence, the amount of extra water needed is $1.8(45P + 42,000)$

b. If the population is 48,000, we will replace P in the above expression with 48,000 to obtain: $1.8\,(45 \cdot 48,000 + 42,000) = 1.8\,(2,160,000 + 42,000) = 1.8\,(2,202,000) = 3,963,600$

Hence, the town needs to reserve 3,963,600 gallons of water in case of an emergency.

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SECTION OVERVIEW

1.4: Solving Equations and Formulas

1.4.1: Addition, Subtraction, Multiplication, and Division Properties of Equality

1.4.2: Solving a Formula for a Variable (Rewriting a Formula)

1.4.3: Solving Quadratic Equations of the Form- $(x-a)^2=c$

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1.4.1: Addition, Subtraction, Multiplication, and Division Properties of Equality

The addition, subtraction, multiplication, and division properties of equality allow us to add, subtract, multiply, or divide the same value on both sides of an equation, this guarantees the equation remains true (note, we cannot divide by zero).

Concept: We know this to be a true statement: $5 = 5$

The statement will remain true if we perform the same operation on both sides of the equation.

- Add 4 on both sides of the equation to obtain:

$$5 + 4 = 5 + 4$$
$$9 = 9$$

- Subtract 10 on both sides of the original equation to obtain:

$$5 - 10 = 5 - 10$$
$$-5 = -5$$

- Multiply by 2 on both sides of the original equation to obtain:

$$5 \cdot 2 = 5 \cdot 2$$
$$10 = 10$$

- Divide by 15 on both sides of the original equation to obtain:

$$\frac{5}{15} = \frac{5}{15}$$
$$\frac{1}{3} = \frac{1}{3}$$

We use the Addition, Subtraction, Multiplication, and Division Properties of Equality to solve equations for a specified variable or unknown.

Process for Solving a Basic Linear Equation in One-Variable

- Isolate the variable by "undoing" the operation on the variable, that is, applying the opposite operation on both sides of the equation using the Properties of Equality

Example 1.4.1.1

Solve for x: $x + 2 = 9$

Solution

Since 2 is being added to x, to isolate the x, we need to "undo" the addition of 2, the opposite of adding 2 is subtracting 2, so using the Subtraction Property of Equality, let's subtract 2 on both sides of the equation to obtain:

$$x + 2 - 2 = 9 - 2 \tag{1.4.1.1}$$

$$x = 7 \tag{1.4.1.2}$$

Example 1.4.1.2

Solve for x: $x - 7 = 13$

Solution

Since 7 is being subtracted from x, to isolate the x, we need to "undo" the subtraction of 7, the opposite of subtracting 7 is adding 7, so using the Addition Property of Equality, let's add 7 on both sides of the equation to obtain:

$$x - 7 + 7 = 13 + 7 \tag{1.4.1.3}$$

$$x = 20 \tag{1.4.1.4}$$

Example 1.4.1.3

Solve for x: $3x = 12$

Solution

Since x is being multiplied by 3, to isolate the x, we need to "undo" the multiplication by 3, the opposite of multiplying by 3 is dividing by 3, so using the Division Property of Equality, let's divide by 3 on both sides of the equation to obtain:

$$\frac{3x}{3} = \frac{12}{3} \tag{1.4.1.5}$$

$$x = \frac{12}{3} = 4 \tag{1.4.1.6}$$

Example 1.4.1.4

Solve for x: $\frac{x}{8} = 2$

Solution

Since x is being divided by 8, to isolate the x, we need to "undo" the division by 8. The opposite of dividing by 8 is multiplying by 8, so using the Multiplication Property of Equality, let's multiply by 8 on both sides of the equation to obtain:

$$\frac{x}{8} \cdot 8 = 2 \cdot 8 \tag{1.4.1.7}$$

$$\frac{x}{8} \cdot \frac{8}{1} = 2 \cdot 8 \tag{1.4.1.8}$$

$$x = 16 \tag{1.4.1.9}$$

Example 1.4.1.5

Solve for x: $\frac{1}{2}x = 5$

Solution

We can approach this problem in a couple of different ways,

Option 1: Read the problem as x is being multiplied by ½, hence we can divide both sides by ½ to isolate the variable, x.

$$\frac{\frac{1}{2}x}{\left(\frac{1}{2}\right)} = \frac{5}{\left(\frac{1}{2}\right)} \tag{1.4.1.10}$$

$$x = \frac{5}{\left(\frac{1}{2}\right)} = \frac{5}{1} \cdot \frac{2}{1} = \frac{10}{1} = 10 \tag{1.4.1.11}$$

Option 2: Rewrite the problem or think of the problem as being read as x is being divided by 2 since ½ x *is equivalent to* $\frac{x}{2}$, so we can multiply both sides of the equation by 2 to isolate x:

$$\frac{1}{2}x = 5 \tag{1.4.1.12}$$

$$\frac{x}{2} = 5 \tag{1.4.1.13}$$

$$\frac{x}{2} \cdot 2 = 5 \cdot 2 \tag{1.4.1.14}$$

$$x = 10 \tag{1.4.1.15}$$

Similarly, if we have a fraction times a variable, let's say x, then we can multiply both sides of the equation by the reciprocal of the fraction (flip the fraction such that the numerator becomes the denominator, and the denominator becomes the numerator):

Example 1.4.1.6

Solve for x: $\frac{2}{3}x = 7$

Solution

$$\frac{2}{3}x = 7 \tag{1.4.1.16}$$

$$\frac{3}{2} \cdot \frac{2}{3}x = \frac{3}{2} \cdot 7 \tag{1.4.1.17}$$

$$x = \frac{3}{2} \cdot \frac{7}{1} = \frac{21}{2} \tag{1.4.1.18}$$

Process for solving a linear equation in one variable with multiple operations

When solving a linear equation with multiple operations, we reverse the order of operations because we are "undoing" the original operations.

Example:

1. Solve for x: $2x + 5 = 15$

Order of operations state to perform multiplication, then addition, so when solving, we will reverse this order so we will "undo" the addition first, then we will "undo" the multiplication

$$2x + 5 = 15$$

Step 1: "Undo the addition by 5" by subtracting 5 on both sides of the equation

$$2x + 5 - 5 = 15 - 5$$

$$2x = 10$$

Step 2: "Undo the multiplication by 2" by dividing by 2 on both sides of the equation

$$\frac{2x}{2} = \frac{10}{2}$$

$$x = 5$$

We can check our answer by substituting the value for x into the original equation and verifying that the equation is true: \ (2\left(5\right)+5=10+5=15 \, ✔\)

2. Solve for x: $\frac{2}{3}x + \frac{1}{5} = \frac{2}{7}$

$$\frac{2}{3}x + \frac{1}{5} = \frac{2}{7}$$

Step 1: Subtract $\frac{1}{5}$ on both sides of the equation

$$\frac{2}{3}x + \frac{1}{5} - \frac{1}{5} = \frac{2}{7} - \frac{1}{5}$$

$$\frac{2}{3}x = \frac{2}{7} - \frac{1}{5}$$

Step 2: Find an LCD to subtract the fractions on the right side:

$$\frac{2}{3}x = \frac{2}{7} \cdot \frac{5}{5} - \frac{1}{5} \cdot \frac{7}{7}$$

$$\frac{2}{3}x = \frac{10}{35} - \frac{7}{35}$$

$$\frac{2}{3}x = \frac{3}{35}$$

Step 3: Multiply both sides of the equation by the reciprocal of $\frac{2}{3}$ which would be $\frac{3}{2}$:

$$\frac{3}{2} \cdot \frac{2}{3} x = \frac{3}{2} \cdot \frac{3}{35}$$

$$x = \frac{9}{70}$$

Process for solving linear equations with parenthesis

When an equation contains parentheses, we can clear the parentheses using the distributive property.

Distributive Property: $a(b+c) = ab + ac$

Examples

1. Solve for m: $5(m+3) - 2(7-m) = 12$

Step 1: Apply the distributive property to clear the parentheses:

$$5m + 5(3) - 2(7) - 2(-m) = 12$$

$$5m + 15 - 14 + 2m = 12$$

Step 2: Combine like terms

$$5m + 2m + 15 - 14 + 1 = 12$$

$$7m + 1 = 12$$

Step 3: Isolate the variable by subtracting 1 on both sides, then dividing both sides by 7

$$7m + 1 - 1 = 12 - 1$$

$$7m = 11$$

$$\frac{7m}{7} = \frac{11}{7}$$

$$m = \frac{11}{7}$$

2. Solve for x: $-7(3-x) + 11 = 2(x-3)$

Step 1: Clear the parentheses by using the distributive property

$$-21 + 7x + 11 = 2x - 6$$

Step 2: Combine like terms

$$-10 + 7x = 2x - 6$$

Step 3: Isolate the variable by subtracting $2x$ on both sides of the equation and adding 10 on both sides of the equation

$$-10 + 10 + 7x - 2x = 2x - 2x - 6 + 10$$

$$5x = 4$$

Now, divide both sides by 5:

$$\frac{5x}{5} = \frac{4}{5}$$

$$x = \frac{4}{5}$$

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1.4.2: Solving a Formula for a Variable (Rewriting a Formula)

In the Water Industry, we use lots of formulas for computing area, volume, pressure, cost, and so much more. Sometimes, we need to rewrite a formula in terms of a different quantity.

When solving a formula for a particular variable, it is sometimes helpful to place a rectangle or a circle around the variable you are isolating since formulas contain many variables and we may lose our focus as to which variable we are isolating. We will proceed as we did for solving linear equations by "undoing" operations to isolate the variable.

Example 1.4.2.1

The volume of a rectangular tank is given by $V = LWH$, rewrite the formula by solving for H.

Solution

To "undo" the multiplication of H by LW, we divide both sides of the equation by LW to obtain:

$$\frac{V}{LW} = \frac{LWH}{LW} \tag{1.4.2.1}$$

$$\frac{V}{LW = H} \tag{1.4.2.2}$$

Example 1.4.2.2

The filtration rate is defined as Filtration Rate $= \frac{Flow}{Surface\ Area}$. Solve this equation for the Surface Area.

Solution

Step 1: Multiply both sides of the equation by Surface Area (to remove the Surface Area from the denominator. In other words, we cannot isolate Surface Area until it is no longer in the denominator)

$$(Filtration\ Rate) \cdot (Surface\ Area) = \frac{Flow}{Surface\ Area} \cdot (Surface\ Area) \tag{1.4.2.3}$$

$$(Filtration\ Rate) \cdot (Surface\ Area) = Flow \tag{1.4.2.4}$$

Step 2: Isolate the Surface Area by dividing both sides by Filtration Rate

$$\frac{(Filtration\ Rate) \cdot (Surface\ Area)}{(Filtration\ Rate)} = \frac{Flow}{(Filtration\ Rate)} \tag{1.4.2.5}$$

$$Surface\ Area = \frac{Flow}{Filtration\ Rate} \tag{1.4.2.6}$$

This is helpful if we need to calculate the Surface Area and we are given the flow and the filtration rate.

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1.4.3: Solving Quadratic Equations of the Form- (x-a)²=c

When solving equations of the form: $(x-a)^2=c$, we can use the square root property which states to drop the square and take the positive and negative square root of the constant, c. Mathematically, we say the following:

If $(x-a)^2=c$,

then $x-a=\pm\sqrt{c}$

next, add a on both sides of the equation to obtain

$x=a\pm\sqrt{c}$

Example 1.4.3.1

Solve $(x-5)^2=16$

Solution

To solve, we first drop the square from the left side and take the positive and negative square root of 16 to obtain

$$x-5=\pm\sqrt{16} \tag{1.4.3.1}$$

Next, we simplify the square root

$$x-5=\pm4 \tag{1.4.3.2}$$

Next, we isolate the variable, x by adding 5 on both sides of the equation:

$$x-5+5=+5\pm4 \tag{1.4.3.3}$$

Such that after simplifying, we obtain two answers

$$x=5\pm4 \tag{1.4.3.4}$$

$$x=5+4 \quad \text{and} \quad x=5-4 \tag{1.4.3.5}$$

$$x=9 \quad \text{and} \quad x=1 \tag{1.4.3.6}$$

Example 1.4.3.1

Solve $3(x+2)^2+5=80$

Solution

To solve, we must first isolate the perfect square to create the form: $(x-a)^2=c$, so we first subtract 5 on both sides of the equation, then divide both sides by 3

$$3(x+2)^2+5-5=80-5 \tag{1.4.3.7}$$

$$3(x+2)^2=75 \tag{1.4.3.8}$$

$$\frac{3(x+2)^2}{3}=\frac{75}{3} \tag{1.4.3.9}$$

$$(x+2)^2=25 \tag{1.4.3.10}$$

Next, we drop the square and take the positive and negative square root of 25 to obtain

$$x+2=\pm\sqrt{25} \tag{1.4.3.11}$$

$$x+2=\pm5 \tag{1.4.3.12}$$

Next, we isolate the x by subtracting 2 on both sides of the equation

$$x+2-2=-2\pm 5 \tag{1.4.3.13}$$

After simplifying, we obtain two answers

$$x=-2\pm 5 \tag{1.4.3.14}$$

$$x=-2+5 \quad \text{and} \quad x=-2-5 \tag{1.4.3.15}$$

$$x=3 \quad \text{and} \quad x=-7 \tag{1.4.3.16}$$

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SECTION OVERVIEW

1.5: Equations and Word Problems

1.5.1: Solving Equations

1.5.2: Ratios and Proportions

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1.5.1: Solving Equations

Equations are a vital component to solve many mathematical questions. In fact most of all water related mathematical questions would require the use of one if not several equations. An equation is a mathematical statement that both sides of an “equal sign” are in fact equal.

Example 1.5.1.1

$3+1=4$ or $5-3=4-2$

Mathematical equations involve solving for an unknown or a variable. A variable is typically represented with a letter. That “letter” is what you are trying to solve.

Example 1.5.1.2

$3+X=4$

What number must X be in order to make this equation correct?

Obviously, the answer is 1.

Now, this is a very simple example, but it will allow you to begin the process for solving more complex equations.

How did you solve the example above? Did you simply look at the equation and intuitively know that the answer was 1? Or did you use some mathematical process to solve for the variable? Let’s break it down.

Steps to solving equations;

1. Get the unknown or unknowns on one side of the equation.
2. Get the numbers on the other side of the equation.
3. Try and follow these helpful tips.
    a. If the problem is an addition problem, you will need to subtract
    b. If the problem is a subtraction problem, you will need to add
    c. If the problem is a multiplication problem, you will need to divide
    d. If the problem is a division problem, you will need to multiply

Depending on the type of problem, this will involve adding, subtracting, multiplying, or dividing. Perhaps several steps will need to be done to solve for the variable.

Since we will not be adding or subtracting in this course, we will focus on multiplication and division problems.

If the variable is next to a fraction or directly next to a number, solving for the variable will require either multiplying or dividing.

These next two examples are using multiplication and division to get the variable by itself. In order to prevent confusion, the variable of choice will be something other than an “X.”

Example 1.5.1.3

$2N=10$	What multiplied by 2 equals 10? In order to solve for “N” you will need to divide both sides of the equation by 2.
$\frac{2N}{2}=10$	By dividing the left side of the equation by 2, you isolate the variable. However, since you divided one side of the equation by a number you must do the same to the other side of the equation.
$N=\frac{10}{2}$	
$N=5$	

In this next example, a fraction of a variable will equal a number.

Example 1.5.1.4

$\frac{2}{3}N = 14$	In order to isolate the variable in this type of problem, you will need to multiply and divided. First, divide both sides of the equation by 2 and then multiply both sides of the equation by 3.
$\frac{2}{(2)3}N = \frac{14}{2}$	The two cancels out on the left side of the equation leaving N over 3 and 14 divided by 2 becomes 7.
$\frac{N}{3} = 7$	Now, multiply both sides of the equation by 3.
$\frac{(3)N}{3} = 7 \times 3$	Here, the 3 cancels out on the left and the right side of the equation becomes 21, which is the answer.
$N = 21$	

How can you prove (or show) that 21 is the correct answer in the above example.

Exercise 4.1

1. $2X = 10$
2. $3N = 15$
3. $\frac{3}{4}G = 9$
4. $4H + 2 = 10$
5. $\frac{1}{5}J + 4 = 5$
6. $13 = \frac{3}{6}K - 1$
7. $3B - 5 = 2B + 8$
8. $10C - 7 = 3C + 14$
9. $\frac{4}{3}S - 3 = 5$
10. $14 = 2F + 2$
11. $7X + 2 = 9X - 10$
12. $15 = 5 + \frac{2}{5}P$

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1.5.2: Ratios and Proportions

Solving ratios and proportions is similar to the previous two exercises. It is simply just looking at the question a little differently. Instead of looking at it as numbers we will assign UNITS (or items) to the numbers, for example, 3 valves to 6 valves or 3 hours to 5 hours. However, the real comparisons of interest will be discussed in the next section when we compare different UNITS to each other, for example, 40 hours to 1 week, or 12 inches to 1 foot.

Example 1.5.2.1

$$\frac{2}{3} = \frac{F}{9}$$

You can read this as, 2 is to 3 as F is to 9.

In order to solve the above ratio or proportion is by cross multiplying.

$$9 \times 2 = 3 \times F$$

This would equate to

$$18 = 3F$$

Then using the method as previously used in the Equation Section, you would divide both sides of the equation by 3. Three would then cancel on the right side of the equation isolating the variable and 18 divided by 3 would give you 6. Therefore, F equals 6.

$$\frac{18}{3} = \frac{3F}{3} \quad \rightarrow \quad 6 = F$$

Exercise 4.2

1. $\frac{D}{7} = \frac{27}{9}$
2. $\frac{28}{L} = \frac{32}{8}$
3. $\frac{4}{8} = \frac{J}{64}$
4. $\frac{H}{5} = \frac{28}{70}$
5. $\frac{K}{100} = \frac{1}{3}$
6. $\frac{L}{12} = \frac{12}{3}$
7. $\frac{9}{4} = \frac{K}{12}$
8. $\frac{7}{F} = \frac{5}{15}$
9. $\frac{H}{3} = \frac{20}{6}$
10. $\frac{2}{5} = \frac{Q}{35}$
11. $\frac{13}{F} = \frac{32}{64}$
12. $\frac{1}{7} = \frac{11}{J}$

Not all proportional problems are exactly as they seem. The previous problems were directly proportional and can be solved with relative ease. However, sometimes you will encounter indirectly proportional or more properly termed “inversely” proportional.

Example 1.5.2.2

It takes 3 employees to flush 8 hydrants in 6 hours. How long would it take 5 employees to do the same job?

Solution

If you attempt to solve this problem as if it were directly proportional it would look like.

$$\frac{3}{6} = \frac{5}{W} \quad \rightarrow \quad W = \frac{30}{3} \quad \rightarrow \quad W = 10$$

By this result it would take 5 employees 4 hours longer to do the same job.

Inversely proportional problems need to be solved as follows. It is the product of the values not the ratio that you need to equate.

3 employees × 6 hours = 5 employees x W hours

$$18 = 5W$$
$$W = \frac{18}{5}$$
$$W = 3.6 \text{ hours}$$

Exercise 4.2.1

1. A safety catalog sells dust masks. They are $4.50 per dozen. How much would 4 dust masks cost?
2. An operator conducted a laboratory experiment by adding 1.5 pounds of chlorine to 5 gallons of water to get a certain chlorine dosage. If the operator wanted to disinfect 1,200 gallons of water to the same dosage, how many pounds of chlorine would she need?
3. Six water utility operators were able to exercise 75 valves in one work week. If 9 operators were assigned to do the same task, how long would it take them? (Assume 34 hours equates to a work week)

In the previous problem, you ended up with a fraction (expressed as a decimal) of an hour. What would be a better way to express this answer?

1. A water utility needs to install 2,375 feet of 16” diameter pipe. The pipe costs $25.80 per foot. How much will all the pipe cost?
2. In the problem above, the pipe is manufactured in 20 foot sections. How many sections would need to be purchased?
3. A water storage tank needs to be recoated. A contractor gave an estimate that it would take 5 of his employees a total of 39 hours to complete the job. How sooner can the job be completed if 8 employees were to do the work?

In word problems with percentages, the first thing is to convert the percent to a decimal. Then, view the word “of” as a multiplication sign and the word “is” as an equals sign. Then, solve the problem

Example 1.5.2.3

10% of 100 is

10% × 100 =

0.10 × 100 = 10

Exercise 4.2.2

Solve the following percent problems.

1. 30 is 20% of what number?
2. 10 is 45% of what number?
3. 12% of is 84.
4. What percent of 75 is 225?
5. 56% of is 182.
6. 35 is what percent of 500? _____
7. 100% of 2,000 is _____
8. What percent of 40 is 10? _____

Word problems give people fits! However, most of the problems that present themselves in practical situations are in fact word problems, we just don’t always think of them that way. For example, if you are buying something from the store and you want to figure out how much the tax will be on a certain item, you probably just multiply the cost of the item by the sales tax. You can though look at this problem as a word problem.

Exercise 4.2.3

Solve the following word problems.

1. A water utility executive earned $85,000 last year and received a 22% bonus. How much was her bonus?
2. A worker can paint a fire hydrant in ½ hour. How many hydrants can she paint in 4 hours?
3. A 5 gallon jug of bottled water is labeled 60% spring water. How many gallons in the jug is spring water?
4. On a state certification treatment exam you must score at least 70% to pass. If there are 65 questions on the test how many must you get correct to pass?

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SECTION OVERVIEW

1.6: Scientific Notation, Rounding, Conversions, and Dimensional Analysis

1.6.1: Scientific Notation

1.6.2: Rounding

1.6.3: Dimensional Analysis

Thumbnail: Expansion of small numbers expressed in scientific notation (CC BY SA 3.0 Unported; Brian Brondel via Wikipedia)

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1.6.1: Scientific Notation

Scientific notation is used to make very large numbers such as 4,895,000,000 or very small numbers such as 0.0000073 easier to use. In the Water industry, we use very large numbers when referring to the volume of water in large tanks or very small numbers when referring to pollutants per gallon of water.

Scientific Notation Form:

$$\underbrace{(a\ decimal)}_{between\ 0\ and\ 10\ (not\ including\ 10)} \times 10^{power} \tag{1.6.1.1}$$

To convert from scientific notation to the actual number

- For a positive exponent on the 10, move the decimal place to the right the equivalent number of spaces as the power
- For a negative exponent on the 10, move the decimal place to the left the equivalent number of spaces as the absolute value of the power

Example 1.6.1.1

Convert the scientific notation to the actual number: 8.735×10^{7}

Solution

Since the power of 10 is positive 7, we will move the decimal place 7 units to the RIGHT to obtain: 87,350,000

Example 1.6.1.2

Convert the scientific notation to the actual number: 2.356×10^{-4}

Solution

Since the power of 10 is negative 4, we will move the decimal place 4 units to the LEFT to obtain: 0.2356

To convert a positive number to scientific notation

- Move the decimal place to the right of the first non-zero digit. This will be the decimal number portion of the scientific notation.
- If the decimal place was moved to the left, use a positive power of 10 based on the number of places the decimal was moved
- If the decimal place was moved to the right, use a negative power of 10 based on the number of places the decimal was moved

Example 1.6.1.3

Convert 567,900,000 to scientific notation.

Solution

Currently, the decimal is understood to be after the last digit since this is a whole number, so move the decimal to the left 8 places so the decimal is between 5 and 6, hence the scientific notation is 5.679×10^{8}

Example 1.6.1.4

Convert 0.00032 to scientific notation.

Solution

Move the decimal to the right 4 places so the decimal is between 3 and 2 to create a decimal number of 3.2 and the power of 10 would then be negative 4 since we moved the decimal to the right 4 places. The scientific notation would be 3.2×10^{-4}

Note

Numbers that are larger than 1 will have a positive power of 10 in scientific notation and numbers that are less than 1 (but still positive) will have a negative power of 10 in scientific notation.

Display of scientific notation on scientific calculators

To multiply and divide numbers in scientific notation, we can multiply (or divide) the decimals and multiply (or divide) the powers of 10, then simplify by rewriting into the proper scientific notation form. To do this, we will need to understand some rules of exponents.

Rule of Exponents

1. When multiplying expressions with the same base, we keep the base and add the exponents:

$$a^x \cdot a^y = a^{x+y} \tag{1.6.1.2}$$

2. When dividing expressions with the same base, we keep the base and subtract the exponents:

$$\frac{a^x}{a^y} = a^{x-y} \tag{1.6.1.3}$$

3. Negative exponents become positive exponents if we move the expression to the opposite side of a fraction:

$$a^{-x} = \frac{1}{a^x} \text{ and } \frac{1}{a^{-x}} = a^x \tag{1.6.1.4}$$

4. A non-zero expression raised to an exponent of zero is equivalent to 1:

$$a^0 = 1 \tag{1.6.1.5}$$

Example 1.6.1.5

Multiply and simplify using scientific notation: $(2.45 \times 10^6)(3.23 \times 10^{-15})$

Solution

First, we can rearrange the multiplication to obtain:

$$\left(2.45 \times 10^6\right)\left(3.23 \times 10^{-15}\right) \tag{1.6.1.6}$$

$$= (2.45)\,(3.23) \times (10^6)(10^{-15}) \tag{1.6.1.7}$$

Next, we can multiply the decimals, then multiply the powers of 10 using an exponent rule:

$$= 7.9135 \times 10^{6+(-15)} \tag{1.6.1.8}$$

$$= 7.9135 \times 10^{-9} \tag{1.6.1.9}$$

Since the decimal value of 7.9135 is between 0 and 10 (not including 10), then this is the proper scientific notation form.

Example 1.6.1.2

Multiply and simplify using scientific notation: $(8.7 \times 10^{-6})(2.5 \times 10^{12})$

Solution

First, we can rearrange the multiplication to obtain:

$$(8.7 \times 10^{-6})(2.5 \times 10^{12}) = (8.7)\,(2.5) \times (10^{-6})(10^{12}) \tag{1.6.1.10}$$

Next, we can multiply the decimals, then multiply the powers of 10 using an exponent rule:

$$= 21.75 \times 10^{-6+12} \tag{1.6.1.11}$$

$$= 21.75 \times 10^{6} \tag{1.6.1.12}$$

Since the decimal value of 21.75 is not between 0 and 10 (not including 10), we need to convert it to proper scientific notation form and simplify further

$$21.75 \times 10^{6} = \left(2.175 \times 10^{1}\right) \times 10^{6} \tag{1.6.1.13}$$

$$= 2.175 \times 10^{1+6} \tag{1.6.1.14}$$

$$= 2.175 \times 10^{7} \tag{1.6.1.15}$$

Example 1.6.1.3

Divide and simplify using scientific notation: $\frac{4.125 \times 10^{13}}{7.5 \times 10^{-2}}$

Solution

First, we divide the decimals, then divide the powers of 10 using an exponent rule:

$$\frac{4.125 \times 10^{13}}{7.5 \times 10^{-2}} = \frac{4.125}{7.5} \times \frac{10^{13}}{10^{-2}} \tag{1.6.1.16}$$

$$= 0.55 \times 10^{13-(-2)} \tag{1.6.1.17}$$

$$= 0.55 \times 10^{15} \tag{1.6.1.18}$$

Since the decimal value of 0.55 is not between 0 and 10 (not including 10), we need to convert it to proper scientific notation form and simplify further

$$0.55 \times 10^{15} = \left(5.5 \times 10^{-1}\right) \times 10^{15} \tag{1.6.1.19}$$

$$= 5.5 \times 10^{-1+15} \tag{1.6.1.20}$$

$$= 5.5 \times 10^{14} \tag{1.6.1.21}$$

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1.6.2: Rounding

We have been using decimal numbers throughout our lives, but let's take some time to formalize the language so we can learn how to round decimals appropriately.

Reading decimal numbers:

Fraction	Decimal	Name
$\frac{1}{10}$	0.1	One-tenth
$\frac{1}{100}$	0.01	One-hundredth
$\frac{1}{1000}$	0.001	One-thousandth
$\frac{1}{10000}$	0.0001	One-ten-thousandth
$\frac{1}{100000}$	0.00001	One-hundred-thousandth

The place values to the right of the decimal are given the following names:

Tenths, hundredths, thousandths, ten-thousandths, hundred-thousandths, millionths, etc.

As a result, we read 5.643 as "five and six-hundredth-forty-three- thousandths since the last digit after the decimal ends in the thousandths place.

Examples:

1. 45.6 is read as "forty-five and six tenths"
2. In the number 543.7892, the 8 is in which place value? Since the 8 is two digits after the decimal point, the place value is hundredths.
3. 0.0143 is read as "one-hundred-forty-three ten-thousandths

For rounding decimals, to round to the nearest decimal place,

1. Consider the number to the right of the desired rounding place value
    1. If the digit is less than 5 (4 or less), we truncate at the desired rounding place value, that is, we drop all the digits after the desired rounding place value
    2. If the digit is 5 or more, we round up by adding 1 to the desired rounding place value before dropping all the remaining digits to the right

Examples:

1. Round 32.784 to the nearest hundredth.Since 8 is in the hundredths place, we consider the number immediately to the right (in the thousandths place), since 4 is less than 5, we drop all the digits after the hundredths place to obtain 32.78.
2. Round 32.786 to the nearest hundredth.Since 8 is in the hundredths place, we consider the number immediately to the right (in the thousandths place), since 6 is more than 5, we add 1 to 8 (in the hundredths place, this is called rounding up) and we drop all the digits after the hundredths place to obtain 32.79.
3. Round 6.48327 to the nearest thousandth.We start by consider the value of the digit immediately after the thousandths place, which is 2, since 2 is less than 5, we drop all the digits after the thousandths place to obtain 6.483 as the rounded number to the nearest thousandth.
4. Round 6.4592 to the nearest
    1. Tenth $\Rightarrow$ Since 5 immediately follows the tenths place, we round the 4 in the tenths place up one number to 5 (by adding 1 to 4) to obtain 6.5 as the rounded number to the tenths place.
    2. Hundredth $\Rightarrow$ Since 9 immediately follows the hundredths place, we round the 5 in the hundredths place up to 6 to obtain 6.46 as the rounded number to the hundredths place.

3. Thousandth ⇒ Since 2 immediately follows the thousandths place, we round the 5 in the hundredths place up to 6 to obtain 6.46 as the rounded number to the hundredths place.

5. Round 6.4597 to the nearest thousandth (to three decimal places).Since the fourth digit is 5 or higher, we must round the third digit after the decimal up by adding 1, but if we add 1 to 9, we would get 10, so we think of 59 (the second and third places after the decimal and round it up by 1 to obtain 60, hence 6.4597 rounded to three decimal places or the nearest thousandth becomes 6.460. We must write the zero in the thousandth place in this case to show the rounding to three decimal places, without the zero on the end, the rounding would be incorrect.

Significant Figures

Significant figures are used to assure the accuracy of a calculation based on the numbers used within the calculation. When a problem doesn't specify how to round an answer or it is not implied in its context (such as money), we use significant figures.

The following digits are considered significant:

- Digits between 1-9. Example: 875 would consist of three significant figures.
- Any zeros between non-zero digits. Example: 20.07 and 5608 would both consist of four significant figures.
- The trailing zeros in a decimal number are significant

The following digits represent ambiguous cases, so the best method to determine the significant figures is to convert the number to scientific notation:

- Any zeros in numbers that do not contain a decimal point. Example: 530,000 depending on the situation, this could represent two significant figures or six significant figures, so let's convert it to scientific notation to obtain: $5.3 \ X \ 10^4$ which would now represent two significant figures. In general, if the zeros are used to locate the decimal point, they are not significant figures, whereas if the zeros are being used for accuracy, they are included as significant figures.

The following digits are not significant:

- If a number is less than 1, the zeros that occur after the decimal point but before a non-zero digit. Example: 0.0075 would consist of two significant figures

When performing calculations, the number of significant figures of the final answer is equivalent to the fewest number of significant figures provided in the calculation.

Examples:

1. State the number of significant figures in each of the following numbers
    1. 3.402 ⇒ 4 significant figures, the non-zero digits are counted since they are between 1-9 and the zero is counted since it is between two non-zero digits
    2. 0.000472 ⇒ 3 significant figures; this number is less than 1, so the zeros after the decimal point but before the non-zero digits do not count, so we only count the digits between 1-9
    3. $8.0 \ X \ 10^4$ ⇒ 2 significant figures; we consider the decimal value (not the power of 10), the trailing zero counts since it is used to show accuracy of the number
    4. 452,000 ⇒ ambiguous case, 3 to 6 significant figures depending on the context of the number
2. Round the following numbers to three significant figures
    1. 89.0146 ⇒ Since the zero after the decimal point is significant since it is between two non-zero digits, we round to the nearest tenth in this cased to obtain 89.0
    2. 0.005324 ⇒ Since this number is less than 1, the zeros immediately to the right of the decimal point are not significant, so to round to three significant figures, we round to the nearest hundred-thousandth to obtain 0.00532
    3. 872.58 ⇒ Since all the digits are significant, to round to three significant figures, we round to the nearest whole number (three digits from the left) to obtain 873.
    4. 8723.158 ⇒ Since all the digits are significant, to round to three significant figures, we round to the nearest ten (three digits from the left) to obtain 8720.
    5. 65,207 ⇒ Since all the digits are significant, to round to three significant figures, we round to the nearest hundred (three digits from the left) or 65,200.

3. Based on the given calculations, state the number of significant figures of the answer, then perform the calculation and round it based on the significant figures
    1. $(4.5)(2.33)(6.232) \Rightarrow$ Two significant figures since 4.5 has the least number of significant figures.

$$(4.5)\,(2.33)\,(6.232) = 65.34252 \text{ which rounds to } 65$$

    2. $\frac{(2.543)(3.516)}{0.01} \Rightarrow$ One significant figure since 0.01 has the least number of significant figures.

$$\frac{(2.543)(3.516)}{0.01} = \frac{8.941188}{0.01} = 894.1188 \text{ which rounds to } 900$$

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1.6.3: Dimensional Analysis

Often in the Water and Wastewater Operations, we must use the relationship between different quantities to determine the results of various calculations. In other words, we will need to perform calculations while also recognizing the changes in the measurements and dimensions to assure the measurement of the result is reasonable.

Conversions

In the Water Industry, we often convert between units of measurement such as gallons to liters or days to hours. To convert between units of measurement, we first need to know the conversion factors or equivalencies. These equivalencies are usually provided in a chart and over time, you will most likely start to learn the ones that are used often, much like we know there are 24 hours in a day or 7 days in a week or 12 feet in a yard.

When converting between units, the idea is to multiply by a form of 1. We will create a fraction that is equivalent to 1 by doing the following:

1. Set up the starting measurement as a fraction.
2. The unit we are removing is placed opposite the position of where it is currently
3. The "new" unit will be placed in the other position
4. Insert the equivalencies

Examples:

1. Convert 153 miles per hour to feet per hour. We start by writing the words into a fraction, namely, $\frac{153\ miles}{1\ hour}$. Next, since we want to convert miles to feet, we need to eliminate the miles, so we will multiply by a fraction with miles in the denominator (opposite of where the miles are currently) and since we need to replace the miles with feet, we will place the feet in the numerator (to replace the current miles), then insert the equivalencies, 5280 feet = 1 mile, hence we multiply the original measurement by $\frac{5280\ feet}{1\ mile}$

   $$\frac{153\ miles}{1\ hour} \cdot \frac{5280\ feet}{1\ mile}$$

   Next, we simplify by reducing or canceling the mile unit of measurement and multiply straight across to obtain:

   $$\frac{153\ \cancel{miles}}{1\ hour} \cdot \frac{5280\ feet}{1\ \cancel{mile}} = \frac{153}{1\ hour} \cdot \frac{5280\ feet}{1} = \frac{807,840\ feet}{1\ hour} \text{ or 807,840 feet per hour}$$

2. The Plant needs to treat every 60 gallons of water with 7 grams of chlorine. However, the chlorine is packaged in ounces. Convert the required amount from gallons/gram to gallons/ounce. We start by writing the given information as a fraction, namely, $\frac{60\ gallons}{7\ grams}$. Next, since we want to convert the grams to ounces and the grams are currently in the denominator, we create a fraction with the grams in the numerator and the ounces in the denominator (so that the grams are opposite each other) and then insert the equivalencies to obtain:

   $$\begin{aligned} &\frac{60\ gallons}{7\ grams} \cdot \frac{1\ gram}{0.03527396195\ ounces} \\ &\frac{60\ gallons}{7\ \cancel{grams}} \cdot \frac{1\ \cancel{gram}}{0.03527396195\ ounces} = \frac{60\ gallons}{0.246917734\ ounces} \\ &= \frac{60}{0.246917734} \frac{gal}{oz} = 242.9959125\ gal/oz \end{aligned} \tag{1.6.3.1}$$

To convert between metric units, we can use the same process described above or we can use a prefix table and move the decimal point based on the direction and the number of places it takes to move from one metric unit of measure to the others based on the order of the sizes of the prefixes.

Let's begin by using a mnemonic to learn the basic six prefixes along with the base unit measurement and their order on the ladder.

"King Henry Died By Drinking Chocolate Milk"

This statement can help with remembering the order of six prefixes and the base unit.

KILO	HECTO	DEKA	BASE	DECI	CENTI	MILLI

For the base, you can have any of the following units of measurement:

- Meters (length)
- Grams (weight)
- Liters (volume)
- Meters^2 (area)

To convert from one prefix to another,

1. Determine if we must move left or right
2. Determine the number of places to move on the ladder
3. Move the decimal place in the number the same number of places in the same direction as we moved on the prefix ladder.

NOTE: Mega is three units to the left of Kilo and Micro is three units to the right of Milli

Examples:

1. Convert 674.325 centimeters to dekameters

Using the ladder, to move from centi to deka, we must move LEFT 3 places, hence, we must move the decimal place 3 places to the left to obtain 0.674325 dekameters.

2. Convert 67 hectoliters to milliliters.

Using the ladder, to move from hector to milli, we must move RIGHT 5 places, hence, we must move the decimal place 5 places to the right, keeping in mind that for a whole number, the decimal is understood to be after the last digit, 67 hectoliters convert to 6,700,000 milliliters.

3. Convert 6.5 kilograms to megagrams.

Since mega is 3 places to the left of kilo, we must move the decimal place 3 places to the left so 6.5 kilograms becomes 0.0065 megagrams.

4. Convert 8765 centimeters to meters.

Remembering that the base represents meters, we need to move from centi to the base (meters) which would be LEFT by 2 places, so move the decimal two places to the left to convert 8765 centimeters to 87.65 meters.

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SECTION OVERVIEW

1.7: Ratios, Proportions, and Percentages

1.7.1: Ratios

1.7.2: Proportions

1.7.3: Percentages

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1.7.1: Ratios

A ratio is a comparison of two numerical quantities in the same units that is usually expressed as a fraction.

Examples:

1. The ratio of 2 meters to 7 meters is $\frac{2m}{7m} = \frac{2}{7}$.
2. There are 200,000 gallons of water in a rectangular basin and 400,000 gallons of water in a cylindrical basin.
    1. What is the ratio of the number of gallons of water in the rectangular basin to the cylindrical basin?

$$\frac{200,000\ gallons}{400,000\ gallons} = \frac{2}{4} = \frac{1}{2}$$

    2. What is the ratio of the number of gallons of water in the cylindrical basin to the rectangular basin?

$$\frac{400,000\ gallons}{200,000\ gallons} = \frac{4}{2} = \frac{2}{1} = 2$$

3. The price of (some chemical) recently increased from \$10.80/case to \$13.50/case. Find the ratio of the increase in price to the original price.

    The increase in price is determined by subtracting the original price from the ending price:increase in price = \$13.50-\$10.80 = \$2.70.

    The ratio of the increase in price to the original price = $\frac{\$2.70}{\$10.80} = 0.25$ or $\frac{1}{4}$

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1.7.2: Proportions

A proportion determines the relationship between two variables as it relates to the magnitude or size of the variables. A proportional relationship shows that two ratios are equivalent such that as one amount changes, another amount changes by a relative amount.

To solve proportion problems, we set up an equation such that two ratios are equivalent:

$$\frac{\text{One characteristic from one item}}{\text{A second characteristic from the same item}} = \frac{\text{the same first characteristic from a second item}}{\text{the same second characteristic from the second item}} \tag{1.7.2.1}$$

Example 1.7.2.1

Seven containers of a chemical costs \$125. If the cost of the containers is proportional, meaning the unit price does not change, determine the cost of 12 containers of the same chemical.

Solution

Let's begin by setting up the fractions like in Equation 1.7.2.1:

$$\frac{\text{Number of containers}}{\text{Cost of those containers}} = \frac{\text{Number of another set of containers}}{\text{Cost of those containers}}$$

$$\frac{7\,\text{containers}}{\$125} = \frac{12\,\text{containers}}{x}$$

To solve for x we can use one of two methods:

Method 1: Solve for x by isolating the x (using information learned in Unit 3)

Multiply both sides of the equation by x:

$$\frac{7}{125}x = 12$$

Multiply both sides of the equation by \$125:

$$7x = 12 \cdot 125$$
$$7x = 1500$$

Divide both sides of the equation by 7 containers:

$$x = \frac{1500}{7} = \$214.29$$

Method 2: Use cross multiplication: Multiply the numerator of the first fraction by the denominator of the second fraction and set it equal to the multiplication of the numerator of the second fraction by the denominator of the first fraction.

$$(7\,\text{containers}) \cdot (\$x) = (12\,\text{containers}) \cdot (\$125)$$
$$7x = 1500$$
$$x = \frac{1500}{7}$$
$$= \$214.29$$

Hence, the cost of the 12 containers is \$214.29.

Example 1.7.2.2

We want to estimate the number of fish in a pond. Suppose we capture 280 fish, tab them, and throw them back into the pond. After a couple of days, we go back to the pond and capture 420 fish, of which 28 are tagged. Estimate the number of fish in the pond.

Example 1.7.2.3

We wish to mix a solution of hypochlorite and water by dissolving 4.8 pounds of hypochlorite in 70 gallons of water. For the same concentration, how many pounds of hypochlorite should we dissolve in 20 gallons of water?

Solution

Let's begin by setting up the fractions like in Equation 1.7.2.1:

$$\frac{\text{Number of pounds of hypochlorite}}{\text{Number of gallons of water}} = \frac{\text{Number of pounds of hypochlorite}}{\text{Number of gallons of water}}$$

$$\frac{4.8\,\text{lbs}}{70\,\text{gal}} = \frac{x\,\text{lbs}}{20\,\text{gal}}$$

$$(4.8\,\text{lbs})\,(20\,\text{gal}) = (70\,\text{gal})\,(x\,\text{lbs})$$

$$96 = 70x$$

$$\frac{96}{70} = x$$

$$x = 1.4\,\text{lbs}$$

Hence, we need 1.4 pounds of hypochlorite to dissolve in 20 gallons of water to create the same concentration.

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1.7.3: Percentages

In Unit 1, we learned how to convert between fractions, decimals, and percentages. We also learned that a percent calculated

$$Percent = \frac{Part}{Whole} \cdot 100\% \tag{1.7.3.1}$$

In this unit, we will use percentages in applications. We will concentrate on the following types of calculations which can be derived by rewriting the formula above (as learned in Unit 3):

- Calculating a percent of an amount: $(percentage)\,(whole) = part$
- Determine the percent based on the part and the whole: $\frac{Part}{Whole} \cdot 100\% = Percent$
- A value is a certain percent of a number: $whole = \frac{part}{percent}$

Examples:

1. 52% of 560 is what number?

   Since "of" means multiplication, we have $(52\%)\,(560) = a\ number$, so let's convert 52% to a decimal by dividing 52 by 100 or by moving the decimal place two units to the left to obtain 0.52, hence $(52\%)\,(560) = (0.52)\,(560) = 291.2$. As a result, 52% of 560 is 291.2.

2. 32 is what percent of 420?

   In this problem, we need to calculate the percent and we have the part, which is 32, and the whole, which is 420. Hence $Percent = \frac{32}{420} \cdot 100\% = 0.076 \cdot 100\% = 7.6\%$ (using two significant figures; see Unit 5).

3. 23 is 12% of what number? Round the final answer to the nearest hundredth. (Unit 5)

   In this problem, we are given the part and the percent and need to determine the whole, so we use: $whole = \frac{part}{percent} = \frac{23}{12\%} = \frac{23}{0.12} = 191.67$

Percentages can be used in the Water Industry in many ways. Below are a few applications of percentages and ratios.

- The volatile content of raw sludge can be calculated as a rate, proportion, or a percent. Generally, we will use a percent to represent the volatile content of raw sludge by calculating the reduction of volatile matter using the following formula:

$$\text{Volatile Solids Reduction } (= \frac{(Value\ IN) - (Value\ OUT)}{(Value\ IN) - [(Value\ IN)(Value\ OUT)]} \cdot 100\% \tag{1.7.3.2}$$

   When the volatile solids reduction is between 50%-60%, it is a good or healthy anaerobic digester. Any amount less than 50% is not reducing the volatile solids enough. NOTE: The fraction portion of this formula represents the rate or proportion. By multiplying by 100% we obtain the percentage. Also, note that the Value IN and Value OUT are decimal values between 0 and 1.

   Example: The volatile content of raw sludge is 68.2% while the digester sludge is 55.6%. Calculate the volatile solids reduction and determine if the reduction is a healthy amount.

$$\text{Volatile Solids Reduction } (= \frac{(Value\ IN) - (Value\ OUT)}{(Value\ IN) - [(Value\ IN)(Value\ OUT)]} \cdot 100\% \tag{1.7.3.3}$$

$$= \frac{0.682 - 0.556}{0.682 - (0.682)\,(0.556)} \cdot 100\% \tag{1.7.3.4}$$

$$= \frac{0.126}{0.682 - 0.379} \cdot 100\% \tag{1.7.3.5}$$

$$= \frac{0.126}{0.303} \cdot 100\% \tag{1.7.3.6}$$

$$= 0.4158 \cdot 100\% = 41.6\% \tag{1.7.3.7}$$

Since 41.6% is not between 50% and 60%, this is considered to not be a good reduction of waste solids.

- The efficiency of water can be calculated using the following formula:

$$Efficiency = \frac{(Value\ IN - Value\ OUT)}{Value\ IN} \cdot 100\% \tag{1.7.3.8}$$

where the Value IN corresponds to the water received from another water system through intertie and Value OUT corresponds to water supplied to another water system through an intertie. [Intertie as defined by Merriam- Webster Dictionary, “an interconnection permitting passage of current between two or more electric utility systems” such as in a share federal-state water system.

NOTE: The fraction portion of this formula represents the rate or proportion. By multiplying by 100% we obtain the percentage.

Example: Calculate the efficiency (as a percent) of removing BOD (Biological Oxygen Demand) at a wastewater treatment plant if the influx of BOD is 215 mg per liter and the outflow is 18 mg per liter.

$$\begin{aligned}
\text{Efficiency} &= \frac{(Value\ IN - Value\ OUT)}{Value\ IN} \cdot 100\% && (1.7.3.9)\\
&= \frac{(215\frac{mg}{L} - 18\frac{mg}{L})}{215\frac{mg}{L}} \cdot 100\% && (1.7.3.10)\\
&= \frac{197\frac{mg}{L}}{215\frac{mg}{L}} \cdot 100\% && (1.7.3.11)\\
&= 0.916 \cdot 100\% && (1.7.3.12)\\
&= 91.6\% && (1.7.3.13)
\end{aligned}$$

Hence, the efficiency of removing BOD at the wastewater treatment plant is 91.6%.

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SECTION OVERVIEW

1.8: Unit Dimensional Analysis

1.8.1: Units

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1.8.1: Units

"Units" are the single most important component of many mathematical problems especially in the waterworks industry. If you are reporting a flow rate of 1,000, what does this mean? 1,000 gallons per minute? 1,000 cubic feet per second? Or, 1,000 acre feet per year? It is strongly recommended that you get in the habit of writing down the units for all the problems you are solving. Most of the problem solving in waterworks mathematics requires the conversion of units.

Cfs gpm MGD AFY

Therefore, Unit Dimensional Analysis (UDA) is the key to solving a majority of water related mathematical problems. UDA is the process of converting units of one type (e.g. gallons) to another similar type (e.g. cubic feet). Setting up your UDA problem is the most important step conversion problems. By "stacking" your units you create a visual representation of the problem where units can be canceled. This cancellation of units is very similar to cross canceling or reducing of fractions.

Example 1.8.1.1

Convert seconds to days using UDA

$$\frac{\text{sec}}{1} \times \frac{\text{min}}{\text{sec}} \times \frac{\text{hour}}{\text{min}} \times \frac{\text{day}}{\text{hour}}$$

Solution

If we break the problem up into segments you can see how the canceling of units occurs.

$$\frac{\not{\text{sec}}}{1} \times \frac{\text{min}}{\not{\text{sec}}} = \text{min}$$

In the above example, if we just do the first step you can see that canceling seconds will yield minutes as the result. By continuing the same process you can end up with the unit the question is asking.

$$\frac{\not{\text{sec}}}{1} \times \frac{\not{\text{min}}}{\not{\text{sec}}} = \frac{\not{\text{hour}}}{\not{\text{min}}} \times \frac{\text{day}}{\not{\text{hour}}} = \text{day}$$

The reason seconds is set up over a "1" is because it is the units you are wanting to convert from and remember anything over 1 is that value.

Multiple units can be converted in a single problem too. However, convert one unit at a time. A common waterworks mathematics problem is the conversion from cfs to gpm. Cubic feet needs to be converted to gallons and seconds needs to be converted to minutes.

Example 1.8.1.2

Convert cfs to gpm.

$$\frac{\text{cf}}{\text{sec}} \rightarrow \frac{\text{gal}}{\text{min}}$$

Solution

An important thing to note is that you will be converting "like" units. This means that you will be converting **cubic feet** to **gallons** which are both a measurement of volume and converting **seconds** to **minutes** which are both a measurement of time.

There are two conversion factors that need to be used to perform this conversion. You need to ask yourself…How many seconds are in a minute? How many gallons are in a cubic foot?

There are 60 seconds in every minute.

There are 7.48 gallons in every cubic foot.

$$\frac{\text{lcf}}{\text{sec}} \times \frac{60\text{sec}}{\text{min}}$$

The expression 60 sec per minute is a conversion factor that is an equality. The conversion factor is deliberately written with the 60 sec on top of the equality because it needs to cancel the unit sec from the 1 cfs.

$$\frac{1cf}{\not{sec}} \times \frac{60\ \not{sec}}{min} = \frac{60cf}{min}$$

Since the sec cancel we end up with cubic feet per minute (cfm).

Now let's look at converting cubic feet to gallons. Remember that there are 7.48 gallons in every cubic foot.

$$\frac{1cf}{sec} \times \frac{7.48gal}{cf} = \frac{1\ \not{cf}}{sec} \times \frac{7.48gal}{\not{cf}} = \frac{7.48gal}{sec}$$

If you combine both of the examples above you can see how cfs is converted to gpm.

$$\frac{1\ \not{cf}}{\not{sec}} \times \frac{60\ \not{sec}}{min} \times \frac{7.48gal}{\not{cf}} = \frac{448.8gal}{min}$$

Exercise 5.1

Solve the following problems using UDA

1. Convert 5 cfs to gpm.
2. Convert 1,500 gpm to cfs.
3. Convert 4 MGD to gpm.
4. Convert 2.5 cfs to MGD.
5. Convert 7 fps to mph.
6. A hose is flowing at a rate of 1.5 cfs. How many gallons will flow through it in one minute?
7. A well pumps 2,000 gallons per minute. How many million gallons of water will it pump in one day?
8. A water utility sold 10 million gallons of water. They need to report this in one hundred cubic feet (CCF or HCF). How many HCF is this?
9. A water utility operator is filling up a storage tank at a rate of 1,000 gallons per minute. How long will it take until the tank has 1.5 MG of water?
10. Water is moving through a pipe at a velocity if 5.75 feet per second. Express the velocity in miles per hour.
11. Last year a water utility delivered 2.35 million gallons per day. How many acre feet did they deliver in one year?
12. A water tank was being drained at a rate of 750 gallons per minute. If the tank holds 5 MG of water, how long will it take for the tank until the tank is empty? (Express your answer as Days, Hours, Minutes – ex 2 days, 3 hours, and 10 minutes)

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SECTION OVERVIEW

1.9: Geometric Shapes

In the waterworks industry geometric shapes are prevalent. For example, a pipe is a cylinder with the opening of a circle, a sedimentation basin can be a rectangle, and an aqueduct might be a trapezoid. These are a few of the shapes that we will cover in this text. It is important to understand how to work with these shapes to be able to calculate areas, volumes, perimeters, and circumferences.

We will first look at geometric shapes and how to calculate the corresponding area of these shapes. The answer when determining the area of a geometric shape should always be given in square feet (sqft or ft^2). Other units can be used such as, square meters or square inches, but these are not typically used in the waterworks industry. Remember though that the units you are given in a question (or in "real life" for that matter, may not be the units you need to calculate square feet. Therefore, you should always convert the "given units" to feet before calculating the area. The first shape we will look at is the CIRCLE. Pipes are the backbone to water distribution systems and can also be found in treatment plants. Pipe lines carry raw water to the treatment plant, transmission lines can carry water from treatment plants to storage tanks, and distribution pipe lines delivery water to customers.

1.9.1: Areas

1.9.2: Volumes

1.9.3: Circumference

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1.9.1: Areas

Circle

Area of a circle = $0.785 \times D^2$

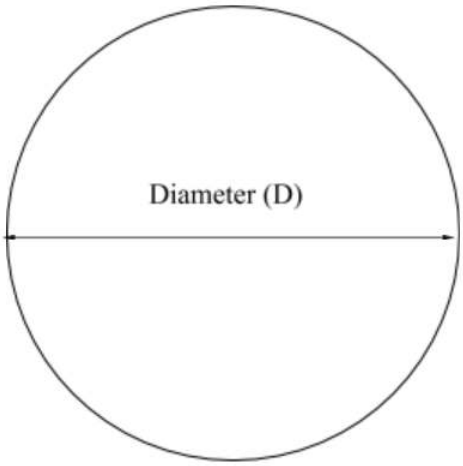


Figure 1.9.1.1: Area of a circle = $0.785 \times D^2$

Typically, you will know the diameter of a circle, for example the diameter of a pipe or a storage tank. You may have learned the following formula ($\pi \times r^2$) for calculating the area of a circle. However, in this text we will only use the previous formula. Both formulas work, but in the water industry diameters are most commonly used.

Much of the time you will be asked to calculate the area of the opening of a pipe. However, the unit given to you will typically be given in inches. There are two ways to go about solving this type of problem.

Example 1.9.1.1

What is the area of a 12” diameter pipe?

Solution

If you were to plug 12” into the formula (0.785 \times D^2\) you would end up with square inches and then you would most likely need to then convert to square feet.

So, the easiest way to solve all area problems where “feet” are not given is to convert to feet first and then plug the numbers into the formula.

A 12” diameter pipe equals a 1 foot diameter pipe.

$$\frac{12 \text{ / inches}}{1} \times \frac{1 \text{ foot}}{12 \text{ / inches}} = 1 \text{ foot}$$

By converting to feet before starting the problem you will avoid getting into units you are not familiar with.

Rectangles

Area of a rectangle = $L \times W$

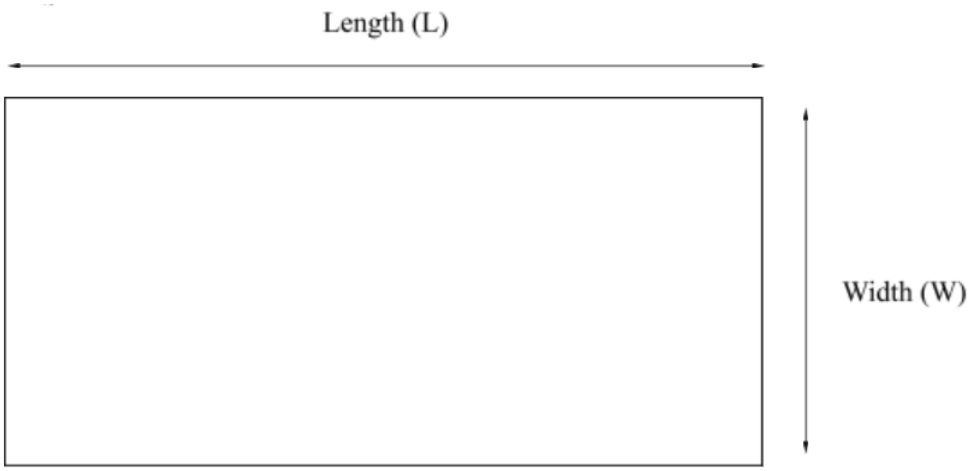


Figure 1.9.1.2: Area of a rectangle = $L \times W$

Rectangles are common shapes of storage reservoirs, sedimentation basins, and even room in an office. Calculating the area for these types of structures is simple if you know how the length and width of the structure. Remember, the area of a square is calculated the same way. These types of dimensions are typically given in feet.

Trapezoid

$$\text{Area of a trapezoid} = \frac{b1 + b2}{2} \times H$$

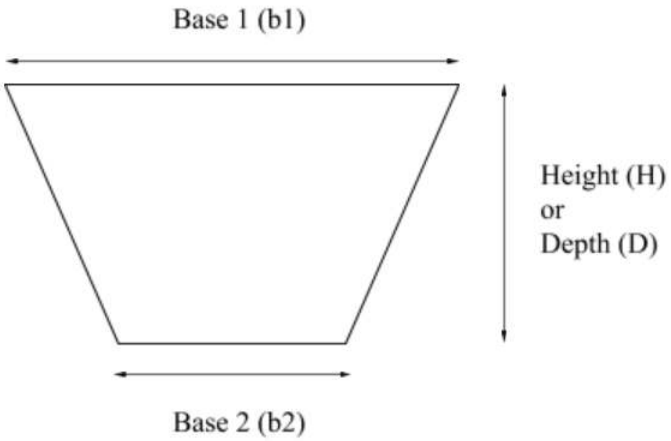


Figure 1.9.1.3: Area of a trapezoid = $\frac{b1 + b2}{2} \times H$

Trapezoids are not as common as circles, rectangles, and squares, but they are still found in the waterworks industry. Typically open channels and aqueducts are shaped like a trapezoid. In calculating the area of a trapezoid, you need to know the width across the aqueduct and the height of the water level. Now the width changes from the bottom of the trapezoid to the top. For example, the distance across the bottom of the trapezoid is a shorter distance then it is at the top of the trapezoid. The other point that needs to be addressed is the distance across the top of the trapezoid that is needed is the distance across the top of the water level. See the diagram below for an example of the base 1.

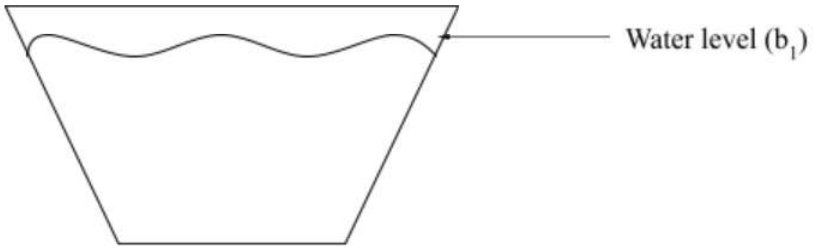


Figure 1.9.1.3: Example of the base 1

Once you know the distance across the trapezoid at the water level, then add it to the distance across the bottom of the trapezoid and divide that number by 2. Doing this finds the average distance across the trapezoid. Multiply this number by the height of the water level and you know have the area of the trapezoid.

Exercise 6.1

Calculate the following areas.

1. What is the area of a circle with a 2 foot diameter?
2. What is the area of a 36” diameter pipe?
3. What is the area of a sedimentation basin that is 30 feet wide and 10 feet deep?
4. What is the area of an aqueduct that is 5 feet across the bottom, 10 feet across the top and 7 feet deep?
5. The roof on an above ground storage tank has a 130 foot diameter. What is the area?
6. A filter is 25 feet long and 20 feet wide. What is the area?
7. A water aqueduct is 10 feet wide at the bottom and 20 feet wide at the top. If it is 20 feet deep what is the area?

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1.9.2: Volumes

Cylinder

Volume of a cylinder = $0.785 \times D^2 \times H$

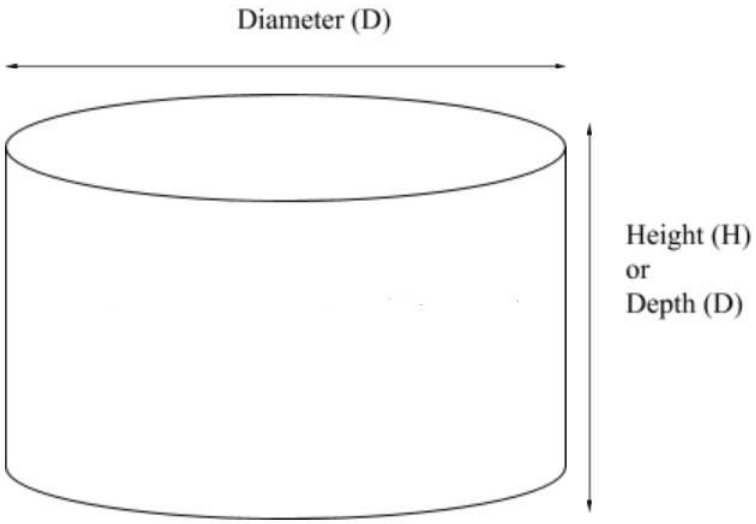


Figure 1.9.2.1: Volume of a cylinder = $0.785 \times D^2 \times H$

The volume of a cylinder uses the area formula of a circle with the addition of a third dimension. Notice that a cylinder can have either a depth or a height. They are one and the same. It all depends on your perspective. In fact all 3 dimensional structures can have a depth or a height.

Rectangle

Volume of a rectangle = $L \times W \times H$

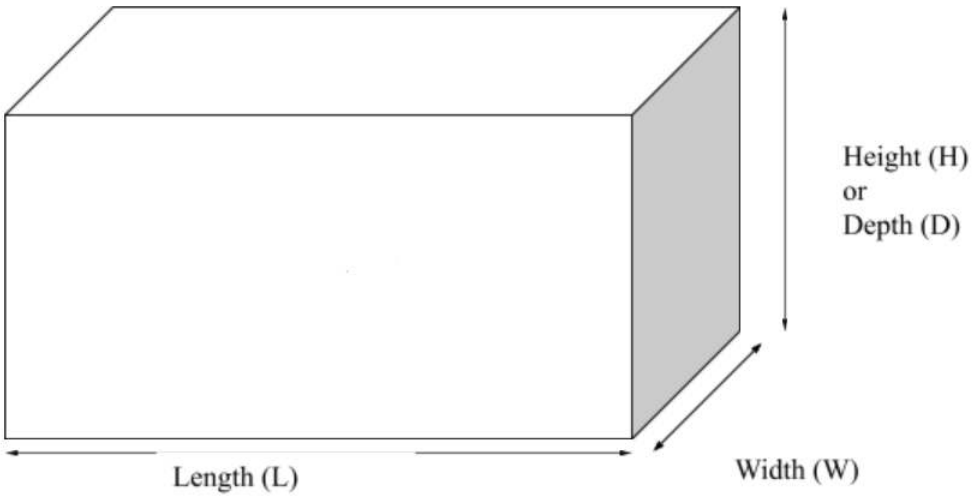


Figure 1.9.2.2: Volume of a rectangle = $L \times W \times H$

Trapezoid

Volume of a trapezoid = $\frac{b1 + b2}{2} \times H \times L$

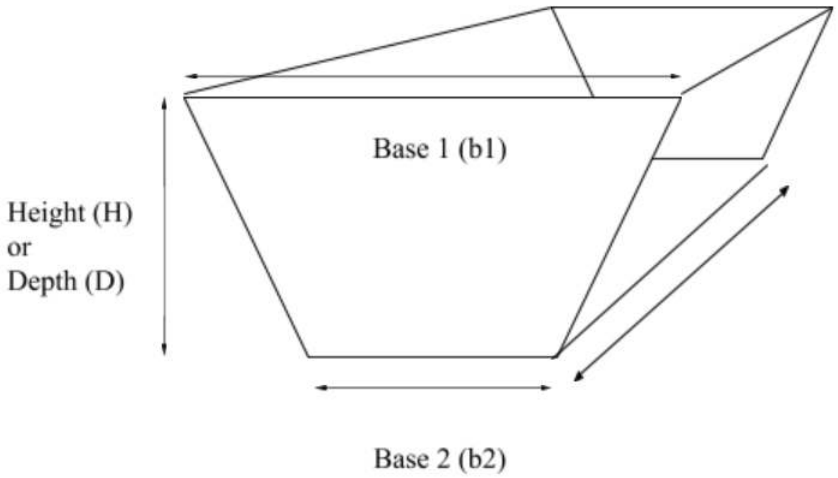


Figure **1.9.2.3**: Volume of a trapezoid = $\frac{b1 + b2}{2} \times H \times L$

There is something to keep in mind when calculating volumes. Most units in waterworks are given in “feet.” The length of pipe, the height of water tanks, the depths of aqueducts are all typically measured in feet. Therefore, calculating the volume for these geometric shapes result in cubic feet as the unit of measure. However, sometimes measurements are given in “inches” and will need to be converted to feet before solving a problem.

Exercise 6.2

Solve the following

1. What is the area of a circle with a 10 foot diameter?
2. What is the area of a circle with a 10 inch diameter?
3. What is the area of a rectangle with a depth of 10 feet and a width of 20 feet?
4. What is the area of a trapezoid that has a distance across the base of 5 feet and a distance across the top of the water level of 7 feet. The water depth is 4 feet.
5. Calculate the volume of a pipe that has a 12” diameter and is 10 feet long.
6. How many gallons of water can fit in a storage tank that is 40 feet tall and has a 90 foot diameter? (Remember one cubic foot equals 7.48 gallons)
7. A rectangular basin is 100 feet long, 40 feet wide and has a depth of 25 feet. If the water level is 3 feet from the top, how much water is in the basin?
8. A one mile long water aqueduct is 10 feet deep and is half full. The width across the water level is 7 feet and the width at the base is 5 feet. How much water is in the aqueduct? (Remember that one mile equals 5,280 feet)
9. A 75 foot tall water tank is ¾ full and has a 30 foot diameter. How many gallons of water are in it?
10. What is the capacity of a water basin that is 200 feet long, 40 feet wide, and 30 feet deep?
11. A water tank is being emptied at a rate of 1 foot per hour. If the tank has a diameter of 100 feet, how many gallons will be emptied in 4 hours?
12. A reservoir with the following dimensions (75 feet long, 20 feet wide, 10 feet deep) is 35% empty. How many gallons of water are in the reservoir?

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1.9.3: Circumference

The last geometric shape formula we will look at is the circumference of a cylinder. The circumference is the distance around a closed curve. It is the distance around the length around a circle. The importance of this formula in waterworks mathematics displays itself in questions regarding the painting or coating of a cylinder. The picture below illustrates the circumference.

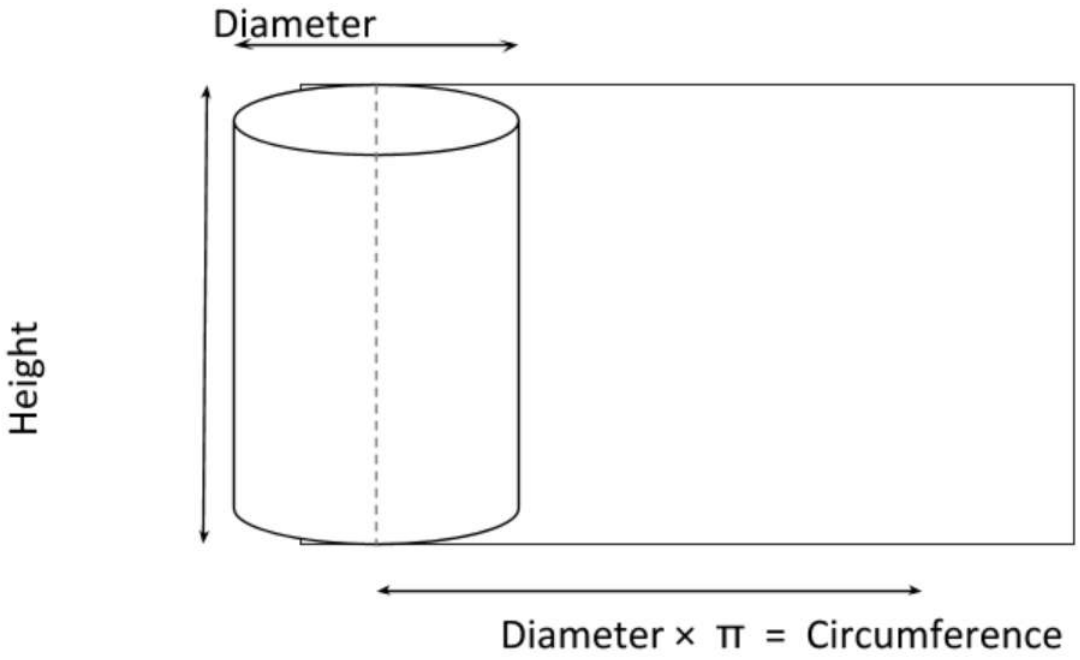


Figure 1.9.3.1: Circumference of a cylinder

If you “slice” open a cylinder and unravel it, it becomes a rectangle. The length of this rectangle is the circumference of the cylinder. In order to calculate the surface area of a cylinder, use the following formula.

$$\text{Area of a cylinder} = H \times (\text{Diameter} \times \pi)$$

Where ($\text{Diameter} \times \pi$) is the length around the cylinder.

Exercises 6.3

Solve the following

1. What is the area of the wall of a 20 ft tall tank with a 30 ft diameter?
2. What is the area of the walls of a 1,000 ft section of 24” diameter pipe?
3. You have been asked to calculate how many gallons of paint would be needed to paint a 30 ft tall tank with a 100 ft diameter. You need to paint the inside roof, floor, and walls. One gallon of paint covers approximately 200 ft2. How many gallons of paint are needed?

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SECTION OVERVIEW

1.10: Water Hydraulics

Hydraulics is a fundamental theory in waterworks mathematics. Hydraulics involves the mechanical properties of liquids. In this text we look at two different hydraulic principles, pressure and flow.

1.10.1: Pressure

1.10.2: Force

1.10.3: Flow Rate

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1.10.1: Pressure

Pressure is related to the vertical distance from the surface of water to a reference point somewhere below the water surface typically expressed in feet. For example, a water storage tank has a certain water level inside of it. The reference point below could be a water faucet a certain distance in feet below the water level. This distance in feet is the head pressure (in feet). The other common unit for pressure is POUNDS PER SQUARE INCH, (psi). You can convert back and forth between feet and pounds per square inch using one of the following conversion factors.

$$1 \text{ foot } = 0.433\text{psi} \quad \text{or} \quad 1\text{psi} = 2.31 \text{ feet}$$

To stay consistent with UDA, view the following conversion factors as

$$\frac{1 \text{ foot}}{0.433 \text{ psi}} \quad \text{or} \quad \frac{1 \text{ psi}}{2.31 \text{ feet}}$$

Remember, as with all conversion factors, these can be written as the inverse.

$$\frac{0.433\text{psi}}{1\text{foot}} \quad \text{or} \quad \frac{2.31 \text{ feet}}{1\text{psi}}$$

Example 1.10.1.1

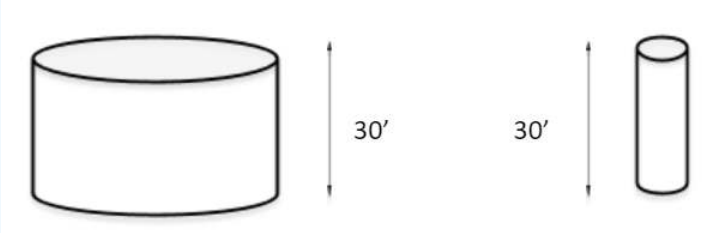


Figure 1.10.1.1

a. Assume both cylinders above are filled with water, which one has a greater pressure at the base of it?
b. What is the pressure at the base of each cylinder?

Solution

a. The answer is neither! The pressure at the base of each cylinder is the same because the height of the water is the same.
b. $\frac{30 \text{ feet}}{1} \times \frac{1\text{psi}}{2.31\text{feet}} = 12.98\text{psi}$ or (if you round) 13psi

Exercise 7.1

Calculate the following pressure problems

1. What is the pressure in psi at the bottom of a 30 foot tall tank if it is full?
2. What is the pressure in feet if the psi is 130?
3. A storage tank is 45 feet tall and half full. What is the pressure in psi?
4. A water tank sits on a 50 foot hill and is 25 feet tall. Assuming the tank is full, what is the pressure in psi at the bottom of the hill?
5. A fire hydrant was hit and water is spraying up approximately 75 feet. What is the approximate pressure in psi?

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1.10.2: Force

Pressure is the force applied over a specific area. It is the weight of water expressed as pounds divided by the area expressed as inches squared (in^2). Therefore, the resulting unit is pounds per square inch (psi). However, in the previous section we looked at pressure based on the height or elevation of a column of water and compared it against a conversion factor.

Recall the following conversion factors:

0.433 psi = 1 foot and 1 psi = 2.31 feet

Let's take a look at what 1 psi is actually saying. One (1) pound of force per square inch of surface area. Therefore, if you have one (1) pound of water and place it on one (1) square inch of area, the resulting pressure would be 1 psi.

The definition of force can be explained as the push or pull which an object can change the velocity of the object on which it is applied. If the pressure is known and the area of which the pressure is being applied, the force can be calculated. See the example below:

A pressure of 100 psi exerts how much force against an area of 1 in^2?

In this example, there is

$$\frac{100\text{lbs}}{\text{in}^2} \times \text{in}^2$$

This would equate to 100 lbs of force because the in^2 would cancel.

This says that 100 pounds of force is being exerted. Another example of calculating the force in pounds would be by calculating the entire volume of water and then converting to the water of the volume of water. Look at the example below.

If a tank with a 100 ft diameter and is 20 ft tall, what is the force at the bottom? In this example, the dimensions of the tank can be used to calculate the volume of water.

$$V = 0.785 \times (100\text{ft})2 \times 20\text{ft} \times 7.48 = 1,174,360\text{gal}$$

This volume can now be converted to pounds.

$$1,174,360 \text{ gal } \times 8.34 \text{ lbs/gal } = 9,794,162 \text{ lbs}$$

This is the force exerted.

Exercise 7.2

1. Calculate the force exerted on a 6" diameter valve with a pressure of 90 psi.
2. What is the force at the base of a 100 ft tall tower filled with water and a diameter of 10 ft?
3. A water tank is 50 feet tall and half full. If the diameter is 75 feet, what is the force exerted at the bottom?
4. A fire hydrant with a 2 ½" opening has a pressure of 130 psi. What is the corresponding force?

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1.10.3: Flow Rate

Flow is the path that a certain liquid (water) takes for a specific time. It is commonly referred to as Flow Rate. A garden hose, a water main, an aqueduct, a gutter, have flow rates. You must know the area of the vessel or container that is flowing the liquid and you must also know the velocity that the liquid is moving. Flow Rate is simply expressed as volume over time.

$$\frac{\text{Volume}}{\text{Time}}$$

The volume can be gallons, million gallons, cubic feet or any other volume unit. The time can be any time such as, seconds, minutes, hours, etc. However, when solving Flow Rate ALWAYS use the UNTIS – CUBIC FEET PER SECOND, where Q represents Flow Rate.

Expressed as

$$\text{Q} = \frac{\text{Volume}}{\text{Time}} = \frac{\text{cubic feet}}{\text{second}}$$

In order to calculate a Flow Rate, you need to know the Area of the vessel that the liquid is traveling through and the Velocity in which the liquid is traveling. The formula for Flow Rate is

$$\text{Q} = \text{A} \times \text{V}$$

Where the Area is expressed as – $0.785 \times D^2$ (for circles) - $L \times H$ (for rectangles) and $\frac{b1 + b2}{2} \times H$ (for trapezoids)

And

Where Velocity is expressed as – $\frac{\text{Distance}}{\text{Time}}$

The UNITS for AREA should always be in SQUARE FEET and the UNITS for VELOCITY should always be in FEET PER SECOND.

Therefore, the equation should look like this

$$\frac{\text{cubic}}{\text{feet}} = \frac{\text{ft}^2}{1} \times \frac{\text{ft}}{\text{second}} \quad \rightarrow \quad \frac{\text{ft} \times \text{ft} \times \text{ft}}{\text{second}} = \frac{\text{ft} \times \text{ft}}{1} \times \frac{\text{ft}}{\text{second}}$$

If you like using the “Pie Wheel” the following can be applied for Flow Rate.

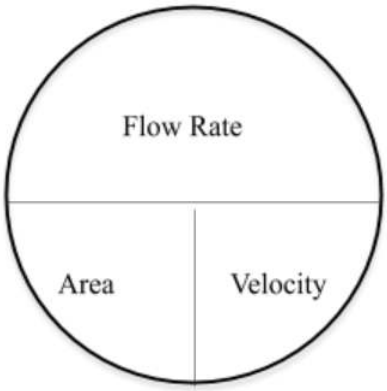


Figure **1.10.3.1**: Pie Wheel

Exercise 7.3

1. What is the pressure in pounds per square inch at the bottom of a 45 foot tall water storage tank?
2. An 80 foot tall standpipe is ¾ full. What is the pressure in psi at the bottom?
3. A 30 foot water tank has a pressure gauge installed 2 feet from the bottom of the tank. If the pressure gauge reads 11 psi, what is the level in the tank?
4. A 12” pipeline is flowing water at a velocity of 3.5 fps. What is the corresponding flow rate?

5. A 36” diameter pipe is flowing water at a velocity of 5 fps. How many gallons of water will flow through it in 2 hours?
6. An 18” pipe is flowing 1,500 gpm. What is the velocity?
7. What is the area of a box culvert that is flowing 4.5 MGD at a velocity of 2.45 fps?
8. An 8” diameter pipe is flowing water at a velocity of 7.65 fps. What is the flow rate in gallons per minute?
9. A 28 foot tall water tank is sitting on a 75 foot tall hill. What is the pressure in a home at the bottom of the hill? (Assume the pressure gauge is 3 feet from the bottom of the home and the tank is full)
10. What is the velocity through a 20” diameter pipe that flows 2.5 MGD?
11. A home that is receiving water from a water tank that is on top of a 115 foot hill has a pressure of 57 psi. What is the water level in the tank?
12. What is the area of a pipe that flows 2,550 gpm at a velocity of 5 fps?

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SECTION OVERVIEW

1.11: Chemical Dosage Analysis and Waste Water Treatment

One of the most common and useful formulas in waterworks mathematics is one in which you use to calculate the amount of chemical needed to add to water. It is commonly known as the Pound Formula. The “pound” formula, because it is a calculation for the weight of a chemical that is being added to water. Typically this chemical is chorine or a chlorine related compound. However, it can be also used to calculate alum, ferric chloride, or any other type of chemical dosage.

Wastewater has several treatment processes to help breakdown the sewage as it moves through a wastewater treatment plant. In addition to adding chemicals, bacteria and microorganisms are used to establish adequate balances during the treatment process to remove organic material and reduce ammonia.

1.11.1: The “Pound Formula”

1.11.2: Food to Microorganism Ratio

1.11.3: Mean Cell Residence Time (MCRT)

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1.11.1: The “Pound Formula”

When solving the “Pound” formula the following two formulas are used.

The first formula is used when you are calculating chemical dosage on a volume of water, for example a tank, reservoir, or pipeline.

$$\frac{\text{MG}}{1} \times \frac{8.34\text{lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{millionparts}} = \frac{\text{lbs}}{1}$$

The second formula is used when you are calculating chemical dosage on a flow rate, for example through a pipeline, in a channel, or through a treatment facility.

$$\frac{\text{MG}}{\text{D}} \times \frac{8.34\text{lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{millionparts}} = \frac{\text{lbs}}{\text{day}}$$

Note that the only difference between the two formulas is the unit for time. It is also important to note that the formula uses specific units for volume and flow…MILLION GALLONS and MILLION GALLONS PER DAY.

Therefore if you are given a volume in cubic feet, gallons, acre-feet or some other unit, you must convert to million gallons.

The same holds true for flow rates. If you are given a flow rate in cubic feet per second, gallons per minute, acre-feet per year or some other unit, you must convert to million gallons per day.

The following charts are helpful in illustrating how to use the pound formula. Look at the horizontal line as a division sign. Anything above the line is divided by anything below the line. Everything below the line (that are next to each other) would be multiplied together.

Here is an example.

Example 1.11.1.1

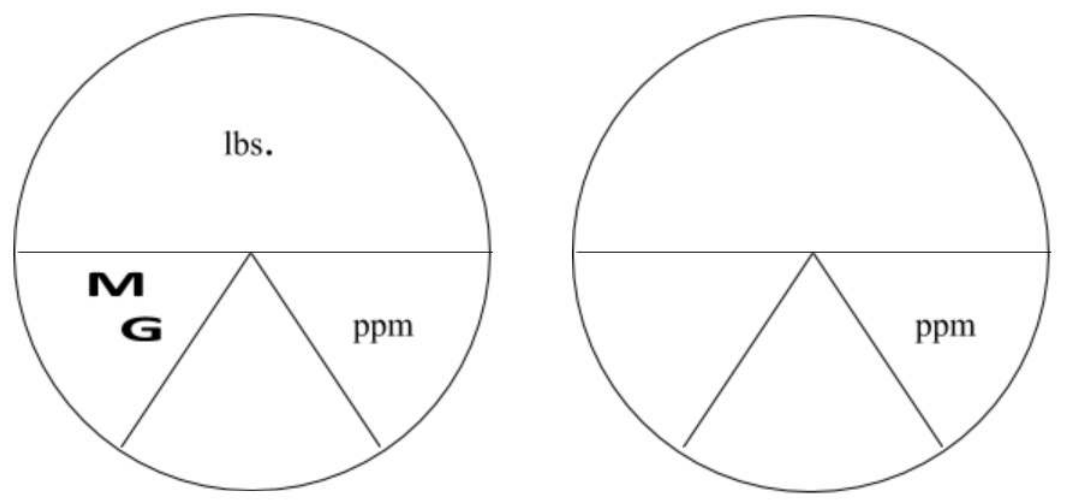


Figure 1.11.1.1

MG(D) and ppm are the two variables below the line. Therefore, they would be multiplied by each other and multiplied by 8.34 lbs./gallon. Since lbs or lbs/day are above the line then you would divide the product of the values below the line.

In this class we will assume that any chemical we are using is in its pure form. In other words there is no adjustment for a lesser concentration form of a chemical. When chlorine is used, it is 100% chlorine.

In addition to drinking water treatment, wastewater treatment uses this same formula to calculate the chemical dosage needed to add certain chemicals to wastewater. Also, this formula is used to determine the amount of “waste” present in wastewater. A common way to measure the amount of organic waste is by the Biochemcial Oxygen Demand (BOD) test. Wastewater has a large amount of organic material that would put a certain demand on an aquatic system by depleting the available oxygen. The results of

the test are typically expressed as mg/L or ppm and can be used in the “pound formula.” The following questions cover both drinking water and wastewater treatment processes.

Exercises 8.1

1. How many pounds of chlorine are needed to dose 1 MG of water to 2 ppm?
2. How many pounds of chlorine are needed to dose 2,200,000 gallons of water to a concentration of 3.5 mg/L?
3. Dry Alum is added at a rate of 150 lb/day in a treatment plant operating at a rate of 16 MGD. What is the dosage in milligrams per liter?
4. How many gallons of water can be treated to a dosage of 10 ppm with 150 pounds of chlorine?
5. A wastewater treatment plant has a primary tank that can hold 2.5 MG. If the BOD test results are 450 mg/L, how many pounds of BOD are in the tank?
6. An operator added 75 pounds of chlorine to a water storage tank that has a 100 foot diameter and is 30 feet tall. The tank was only half full. What was the dosage?
7. A wastewater treatment plant treats 37,500 lbs of BOD per day. If the average daily flow is 8 MGD, what is the BOD concentration?
8. A well is flowing at a rate of 1,600 gpm and requires a dosage of 0.5 mg/L. How pounds of chlorine are needed per day?
9. An aeration tank receives a flow rate of 4,500 gpm. If the BOD concentration is 210mg/L, how many pounds of BOD are loading the aeration tank?
10. A treatment plant operates at a rated capacity of 15 MGD and maintains a constant 1.25 mg/L chlorine dosage. How many pounds of chlorine are needed per year?
11. In question 10, what is the annual budget for chlorine if the cost is $1.65 per pound?
12. A wastewater treatment plant receives an average daily flow of 9.5 MGD. If the BOD test results are 320 mg/L, how many pounds of BOD does the treatment plant receive in a single day?
13. A water tank has a 150 foot diameter and is 35 feet tall. If 200 pounds of chlorine were added to it, what is the dosage?
14. How pounds of ferric chloride are needed to treat a basin that is 120 feet long, 30 feet wide, and 15 feet deep to a dosage of 3.25 mg/L?

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1.11.2: Food to Microorganism Ratio

Wastewater treatment relies on a biological process to treat the large amounts of organic material found in sewage. Bacteria consume the organic material (measured as BOD) and thus removes it from the wastewater. BOD can be thought of as food available to the bacteria.

The amount of bacteria in the system can also be measured by a test called the Mixed Liquor Suspended Solids (MLSS). The ratio of how much food (BOD) in pounds is available to the population of microorganisms (MLSS) in pounds, is critical to the proper operation of a conventional wastewater treatment plant. This ratio is a baseline to determine how much food a single pound of organisms will eat every day.

In aerobic wastewater treatment, operators supply bacteria with air in aeration tanks, so they can breathe. Typically, there is food available in the incoming wastewater for the bacteria. Under these conditions the microorganisms thrive and actually grow their population. If operators did not periodically "waste" the excess microorganisms from the system the MLSS would become too high and alter the F/M ratio.

To calculate the Food to Microorganism ratio (F/M) we need to determine the amount of BOD in pounds, being sent to through the treatment system as well as the amount of available MLSS in pounds, in the system. The equation for F/M is:

$$F/M = \text{Pounds of BOD per day/Pounds of MLSS in tanks}$$

Typical Food to Microorganism ratios are between 0.2 and 0.5. A low F/M ratio means there are many microorganisms and a limited food supply. Conversely, a high F/M ratio means there is much more food available compared to microorganisms. Therefore, a very high or low ratio would result in a dispersed floc that will not settle well in the secondary clarifier.

Exercise 8.2

1. A wastewater treatment plant receives an average flow of 5 MGD and the influent BOD is 260 mg/L. If the MLSS test shows there are 1,800 mg/L in the aeration tank that has a volume of 1.5 MG, what is the F/M ratio?
2. The primary effluent flow of wastewater treatment plant is 3.8 MGD and has a BOD concentration of 295 mg/L. The aeration tank is 150 feet long, 10 feet wide, and 8 feet deep. What is the F/M ratio if the MLSS is found to 2,600 mg/L?
3. What is the F/M of a wastewater treatment facility with the following process control data?

   Influent Q = 4.8 MGD

   Influent BOD = 425 mg/L

   Primary Effluent BOD = 272 mg/L

   MLSS = 2,100 mg/L

   Aeration Volume = 2,890,000 gallons

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1.11.3: Mean Cell Residence Time (MCRT)

As we just learned with the F/M ratio, bacteria and microorganisms are essential to a properly functioning wastewater treatment plant. Another operational control parameter is the mean cell residence time (MCRT). This estimates how long a single bacteria or microorganism stays in the treatment process. The treatment process takes a certain amount of time to effectively remove the organic material and reduce the high amounts of ammonia. If the MCRT is to low then treatment will be insufficient. If the MCRT is too high then there is excess MLSS in the system which adds to the cost of operation.

The equation to find out the MCRT is based on how much MLSS is in the system and how much MLSS is leaving the system through wasting. There are other equations and terms very similar to MCRT such as the Solids Retention Time (SRT). Some textbooks include the pounds of solids available in the secondary clarifiers as well as the final effluent suspended solids that are leaving the system.

For this introductory class we will use the following equation:

MCRT = Lbs under aeration/Lbs per day wasted

The pounds under aeration is exactly the same as in determining the “M” in the F/M ratio. To determine the pounds wasted we need to know the flow rate of the waste activated sludge (WAS) and the concentration. Most treatment plants waste from the return activated sludge (RAS). The RAS is the microorganisms that have been settled out in a secondary clarifier. Therefore, the concentration of RAS is typically higher than MLSS.

The MCRT will depend on the type of wastewater treatment system. Extended air plants will generally have MCRTs greater than 30 days. Conventional activated sludge plants generally have MCRTs between 5 to 10 days. Biological nutrient removal plants typically operate with a MCRT between 12 and 20 days, and high rate oxygen plants between 1 and 3 days. However, it is important to note that there are plenty of case studies showing plants operating outside these ranges while still achieving optimal treatment. Each plant is different and will develop their own optimal operating range.

Exercise 8.3

1. A wastewater treatment plant has a total of 35,000 lbs of MLSS and has 2,900 lbs/day leaving the system. What is the MCRT in days?
2. What is the MCRT of a wastewater treatment facility with the following parameters?

   Influent flow = 10.5 MGD

   Primary Effluent BOD = 285 mg/L

   Aeration Volume = 5 MG

   MLSS = 2,280 mg/L

   WAS Q = 115 gpm

   WAS Conc. = 8,110 mg/L
3. An aeration tank has a volume of 375,000 gallons. The MLSS test results show there is 2,860 mg/L in the aeration tank. If a total of 2,100 lbs/day are wasted from the system, what is the MCRT of the facility?

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SECTION OVERVIEW

1.12: Water Treatment Mathematics

1.12.1: Detention Time

1.12.2: Weir Overflow Rate

1.12.3: Filtration Rate

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1.12.1: Detention Time

Detention Time is the amount of time it takes for a molecule of water to travel a certain distance. In a sedimentation basin it is the time it takes for a particle to travel across the basin. Water treatment operators calculate detention times for settling basins, flocculation basins, or rapid mixing chambers. The term “Contact Time” can also be applied using this formula. Contact Time is not to be confused with CT (Concentration Time). Contact Time is best described as the time a certain chemical is in contact with water. For instance, if you add chlorine to a water supply you can ask yourself “how long is it in contact with the water before a customer drinks the water?” For reference, Detention Times are commonly expressed in hours. However, as you will see when solving for Detention Time the resulting answer will not be in hours and will have to be converted.

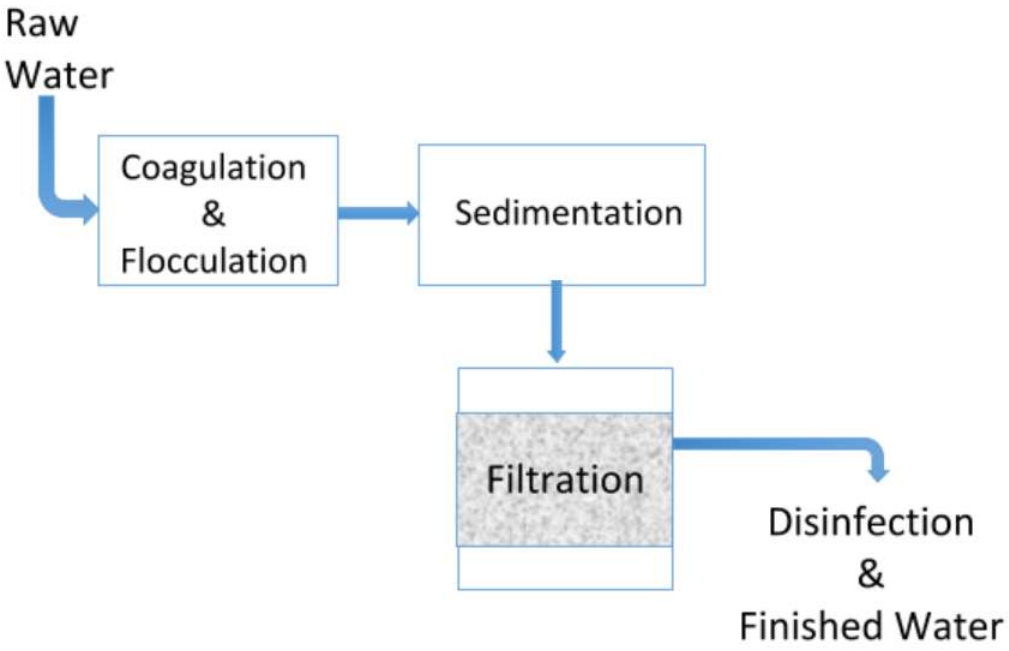


Figure 1.12.1.1: Treatment Process Example

The following formula is used for calculating detention times.

$$Dt = \frac{\text{Volume}}{\text{Flow}}$$

The “Pie Wheel” for Detention Time looks like this.

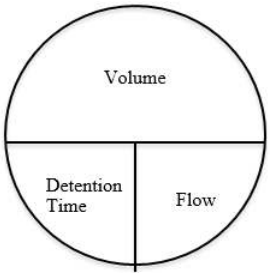


Figure 1.12.1.2: Pie Wheel

“Units” are extremely important with this formula. There are three variables in this formula; Detention Time, Flow, and Volume. Here are some examples for each.

Detention Time – seconds, minutes, hours, days

Flow – cubic feet per second, gallons per minute, million gallons per day

Volume – cubic feet, gallons, million gallons

Take note at the above examples. If the units are similar (matching) then dividing volume by flow will yield a time (Detention Time). However, simply dividing a volume by a flow will not result in a time. For example, if you divide gallons by cubic feet per second there is no resulting answer. This is because “gallons” and “cubic feet” will not cancel each other.

When solving for Detention Time, the units for Volume and Flow must match. Solving for Detention Time is not the only variable to solve for with this formula. If Detention Time and Volume are given then you will be solving for Flow. Similarly, if Detention Time and Flow are given then you will be solving for Volume. In all of these examples, the units must be similar in order to cancel out and yield your answer.

Using the “unit” examples above, list all possible matches of units in order to cancel and yield an answer.

Volume	Flow	Detention Time

Remember, using the above examples will not provide any answer in HOURS. Always remember to convert your answer to the units specified in the question.

Exercise 9.1

1. What is the detention time in minutes of a 400,000 gallon sedimentation basin with an average flow rate of 5,000 gpm?An 80 foot tall standpipe is ¾ full. What is the pressure in psi at the bottom?
2. What is the detention time in hours through a 100,000 gallon reservoir with a flow rate of 750 gpm?A 12” pipeline is flowing water at a velocity of 3.5 fps. What is the corresponding flow rate?
3. It has been determined that a basin has a detention time of 2 hours and 10 minutes. If the flow through the basin is 2.67 cfs, what is the volume of the basin in gallons?An 18” pipe is flowing 1,500 gpm. What is the velocity?
4. What is the flow rate (in gpm) through a 40 foot wide, 10 foot deep, 50 foot long basin if the detention time is 1 hour and 55 minutes?ng 4.5 MGD at a velocity of 2.45 fps?
5. A 25 foot tall reservoir with a 120 foot diameter has a detention time of 3 hours and 22 minutes. What is the daily flow (in MGD) through the reservoir?A 28 foot tall water tank is sitting on a 75 foot tall hill. What is the pressure in a home at the bottom of the hill? (Assume the pressure gauge is 3 feet from the bottom of the home and the tank is full)
6. A 75 foot long, 30 foot wide, and 20 foot deep basin has a flow of 2.25 MGD. What is the detention time? (Express as hours, minutes, seconds – ex. 5 hours, 3 minutes, and 2 seconds)A home that is receiving water from a water tank that is on top of a 115 foot hill has a pressure of 57 psi. What is the water level in the tank?
7. A series of tracer studies determined that the detention time through a 2,350,000 gallon basin is 2 hours and 12 minutes. What is the daily flow (in MGD)?
8. If a flow of 4.45 cfs is moving through 2 miles of 36” diameter pipe, what is the detention time?
9. A treatment plant has a daily flow of 30 MG. There are two 200,000 gallon sedimentation basins. What is the detention time through the plant.
10. What is the volume of a reservoir that has a detention time of 29 minutes and a flow of 5.4 cfs?

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1.12.2: Weir Overflow Rate

Another calculation is one that measures the flow of water over a structure called a “weir.” A weir is an obstruction used to raise the level of flow and evenly disperse it. It allows the measurement of flow to be easily calculated. In a treatment plant process weirs are commonly used to “skim off” the flow of water from the sedimentation process before the water travels to the filters. Weir overflow rates are typically expressed as gallons per minute per foot of weir. They can also be expressed as million gallons per day per foot of weir.

The important thing with this formula is that you determine the actual length of the weir and express it using the flow rate specified in the problem.

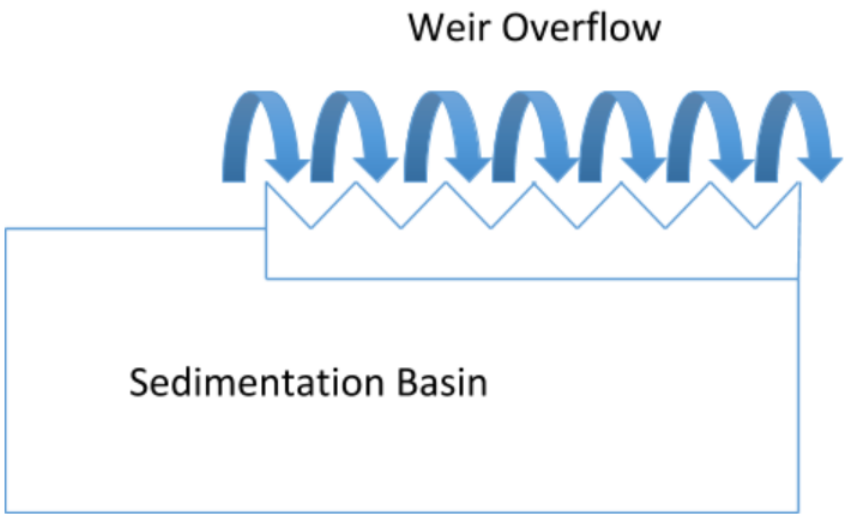


Figure **1.12.2.1**: Overflow

This formula is used:

$$\textbf{Weir Overflow Rate (gpm/ft)} = \frac{\textbf{Flow (gpm)}}{\textbf{Weir Length (ft)}}$$

Exercise 9.2

1. What is the weir overflow rate of a 100 foot long weir with a flow of 3,450 gpm?
2. A weir over flow rate is 28 gpm/ft with a flow rate of 2,300 gpm. What is the length of the weir?
3. A 75 ft weir has a daily flow 1.25 MG. What is the weir overflow rate?
4. A circular weir with a diameter of 85 feet has a weir overflow rate of 17.5 gpm/ft. What is the flow rate in MGD? (Note: you will need the formula for circumference in this problem)
5. A 8.5 MGD treatment plant has a calculated weir overflow rate of 32 gpm/ft. How long is the weir?

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1.12.3: Filtration Rate

Filtration is the last stage in the treatment process for removing particles from the water. The filtration media can vary from sand to gravel to anthracite coal to garnet or a variety of materials layered to trap the remaining suspended solids in the water. Filtration rate is the measure of how much water passes through a certain sized filter over a specific time. Typically filtration rates are expressed in gallons per minute per square foot of filter area (gpm/ft^2). It is the flow of water through the surface area of a filter.

In the picture below a filter is 5 ft by 5 ft and divided into 1 ft by 1 ft sections. This is done to demonstrate how filtration rates are expressed (in 1 ft^2 sections).

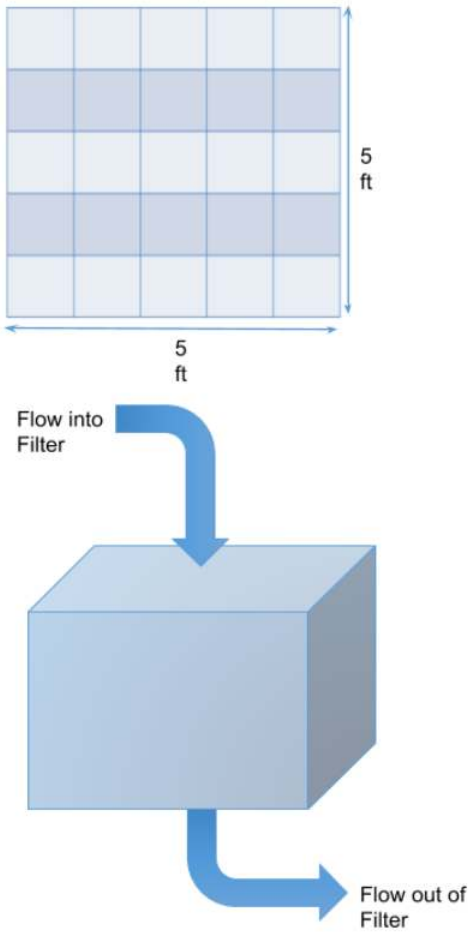


Figure **1.12.3.1**: Demonstration of how filtration rates are expressed

As flow enters a filter it travels down through the media and then out to either a finished water clear well for distribution or perhaps disinfected prior to delivery.

This is the formula used for Filtration Rates:

$$\mathbf{FR} = \frac{\mathbf{Flow}}{\mathbf{SurfaceArea}}$$

Since Filtration Rates are expressed as gpm/ft^2 then it only makes sense to convert the flow rate to gpm prior to dividing by the filter surface area. However, in this equation it is not necessary to do so prior to dividing.

The “Pie-Wheel” for Filtration Rates looks like this:

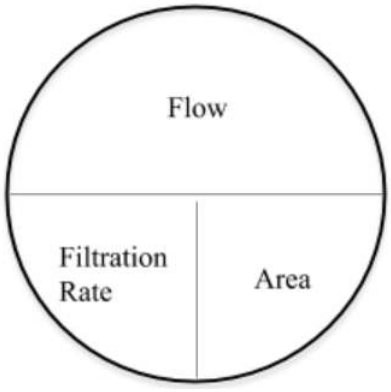


Figure **1.12.3.2**: Pie wheel for Filtration Rates

Remember that the units for the flow and area will determine the unit for filtration rate.

Example 1.12.3.1

A water treatment plant with a 100 ft2 filter has a flow of 1,650 gpm. What is the filtration rate expressed in gpm/ft^2.

Solution

$$\frac{1,650\text{gpm}}{100\text{ft}^2} = 16.5\text{gpm/ft}^2$$

This is a straight forward example with the units given in the same units requested to be expressed in the answer. Let's try another.

Example 1.12.3.2

A water treatment plant has an average daily flow of 10.5 MGD. The filter at the end of the treatment process is 22 ft by 15 ft. What is the filtration rate expressed as gpm/ft^2?

Solution

In this question you need to calculate the area of the filter and determine if you want to convert the daily flow to gpm before or after you divide it by the area. Both ways of solving are explained below.

$$\frac{10.5\text{MGD}}{22\text{ft} \times 15\text{ft}} = \frac{10.5\text{MGD}}{330\text{ft}^2} = 0.032\text{MGD/ft}^2$$

Note that the units are million gallons per day per square feet and need to be converted to gpm/ft^2.

$$\frac{0.032\text{MG}}{\text{Day}} = \frac{32,000\text{gal}}{\text{Day}} \times \frac{1\text{ day}}{24\text{ hours}} \times \frac{1\text{ hour}}{60\text{min}} = 22.2\text{gpm/ft}^2$$

Another way to solve this is to convert the flow to gpm before you divide it by the area.

$$\frac{10,500,000\text{ gal}}{\text{day}} \times \frac{1\text{ day}}{24\text{ hours}} \times \frac{1\text{ hour}}{60\text{ min}} = \frac{7,291.7\text{ gallons}}{\text{minute}}$$

Then plug this into the filtration rate formula.

$$\frac{7,292\text{ gal}}{22\text{ft} \times 15\text{ft}} = \frac{7,291\text{gal}}{330\text{ft}^2} = 22.1\text{gpm/ft}^2$$

Take note that the answers are slightly different (0.1 off.) This is only due to rounding. If both solutions for this problem are rounded to the same number of digits you would get the exact same answer.

Exercise 9.3

(Express all filtration rates as gpm/ft^2)

1. A water treatment plant has a typical flow through a 175 ft^2 filter of 755 gpm. What is the filtration rate?

2. A circular filter with a diameter of 74 feet receives a flow of 2,200 gpm. What is the filtration rate?
3. A three-hour test revealed that 75,000 gallons passed through a filter with dimensions of 10 ft by 20 ft. Find the filtration rate.
4. A water treatment plant has a total of 4 filters. The plant is designed to treat a daily flow of 7.25 million gallons. The target filtration rate is 2.25 gpm/ft^2. Assuming that all 4 filters are identical in size, what is the area of each filter?
5. What is the rated capacity in MGD of a rapid sand filter that is 25 ft long and 16 feet wide when operated at a filtration rate of 1.75 gpm/ft^2?
6. It was determined that the optimum filtration rate of a filter with the dimensions of 12 ft wide and 18 feet long is 2.45 gpm/ft^2. What is the maximum flow rate in cfs?
7. A water treatment plant treated 70 million gallons through 3 identical filters in one week. If the average filtration rate was 3.15 gpm/ft^2, what is the area of each filter?

Periodically, filters will need to be cleaned. Cleaning is done through a routine process called backwash. As filters remove particles, the efficiency decreases and the flow rates slow. At predetermined intervals, treatment operators will backwash the filters. Backwashing is nothing more than reversing the flows. However, backwashing rates are typically 10 or more times greater than filtration rates.

8. After 6 hours in operation a 20ft by 30 ft filter required backwashing. Assuming a flow rate of 10,000 gpm, what was the backwash rate?
9. A 15 ft by 17 ft filter was backwashed at a rate of 22.5 gpm/ft^2 for 20 minutes. How many gallons were used for the backwashing process?
10. It was determined that a filter with a surface area of 725 ft^2 needs to be backwashed for 12 minutes using 94,500 gallons. What would the corresponding backwash rate be in gpm/ft^2?

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SECTION OVERVIEW

1.13: Engineering and Construction

There are a number of different treatment and distribution water utility careers ranging from laborer to skilled technicians. Each has a very important function in making sure the water system is properly maintained and operates efficiently. Something that is often overlooked in many operator certification courses is a discussion on how a system is planned, designed, constructed, and repaired. While this section of the text will focus on several key aspects of introductory concepts of engineering and construction waterworks mathematics, the following paragraphs will highlight a general overview of the planning, design, construction, and repair processes.

1.13.1: Planning

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1.13.1: Planning

Planning is important in many aspects of ones life. From planning out your day to planning out a career path, planning is an important step before tackling many different projects. Just as there are various simplicities and complexities to planning in your personal life, the same can be said in the business world. An example of this is building a water treatment plant. This is one of the more complex examples requiring many different phases of planning. A simpler project, which still requires planning, is the construction of a pipeline installation. Let's take a closer look at several planning steps to a small pipeline installation project.

Pipeline Installation Project Planning

Budget

Any project requires a budget process. There are many different expenses for water utility jobs such as labor, equipment, material, traffic control, disposal, and a variety of other types of costs. Before proceeding with any project, a budget needs to be prepared and staff needs to determine if there is enough money for the project.

Environmental

Any time a construction project is planned there are various environmental review procedures that must be followed. Will there be any environmental impacts such as air, water, noise, or biological species. Some projects are considered small enough to be exempt, while other larger projects may require extensive environmental impact reports.

Timing

When will the project be started and completed? Are there enough staff resources available? Water utility operators are very busy and each project needs to have a protect timeline identifying the required resources and expected start and end dates to avoid conflicts.

Design

In order to properly construct a project there needs to be a minimum amount of engineering work. Some projects, such as water system repairs can require little to no engineering work. While other projects might require extensive engineering design and oversight. Most pipeline construction projects require at least some type of engineering work.

The above examples are by no means an exhausted list. However, it does give a good example of the complexities of water utility construction projects.

Stationing

Stationing is a process to measure distances on construction plans. A "station" is the horizontal measurement distance along a surveyed centerline of a project. Station numbers typically increase from the beginning of a project to the end point of a project. They usually reference points from south to north or from west to east. Station intervals are expressed in 100-foot sections. A half station is 50 feet and is expressed as +50.

In order to understand sectioning, take a look at a few examples below:

Example 1.13.1.1

If a station begins at "0" it is expressed as 0+00. One hundred feet from this station would be expressed as 1+00.

One foot sections increase as 0+01. Therefore, after ten feet, it would look like this 0+10.

The difference between station 101+00 and 100+00 is 100 feet.

If the beginning of a set of construction water plans start at station 100+00 and a valve is located at station 100+99 means the valve is located 99 feet from the start of the plans.

The following is an example of someone calculating the distance between two fire hydrants on a set of construction water plans.

Example 1.13.1.2

Fire hydrant A is located at station 530+50

Fire hydrant B is located at station 527+00

What is the distance between fire hydrant A and B?

Solution

53,050 – 52,700 = 350 feet

As previously stated, stations typically reference points from south to north and from west to east. However, streets sometimes curve and change directions. An “above” segment on a road simply means a direction toward a higher station. A segment below or behind means a direction toward a lower station number.

Exercise 10.1

1. A set of construction water plans shows stationing to mark locations. The start of the plans has a station number of 01+50. The first fire hydrant on the plans is located at station 01+25. How many feet is the fire hydrant located from the start of the plans?
2. A water utility requires fire hydrants to be located 350 feet apart in residential areas. If a street is 1,500 feet long, begins at station 101+55 and the first fire hydrant is located at the start, how many fire hydrants will be installed?
3. A water valve is located at station 345+03 and another at 350+08. What is the distance between the two valves?
4. A domestic water service is located at station 102+45. Two more services need to be installed, one 75 below and one 75 above this station. What is the station of these two new services?
5. A water utility operator is looking at a set of water plans with the following information.

   Fire hydrant located at 534+00

   Valve located at 534+45

   Water service located at 532+99

   What is the total distance between these items?
6. An engineer is designing a water system for a cul-de-sac with 10 homes (5 on each side). The street begins at station 105+30. Each service must be one hundred feet apart and there must be a fire hydrant 25 feet past the second house on either side of the street. Answer the following two questions.

   a. What is the station for the last house on one side of the street?

   b. What is the station of the fire hydrant?
7. On a street 1,250 feet long, a fire hydrant is located at the end of the street at station 12+95. Three services are located at 10+33, 09+04, and 08+94, and a valve located 7 feet from the start of the street. What is the starting station number?
8. In the question above, what is the distance from the start point to each service?

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2.1: Water Resources and The Origin of Contaminants

Learning Objectives

After reading this section, you should be able to:

- Understand and describe water sources
- Describe the water cycle
- Compare the term water contaminants with water pollutants

This chapter presents a brief introduction to the water sources that are available for potable supply; detailed information is presented in Water 132 (Water Supply). Understanding drinking water sources is important to assess the variety of contaminants that can be present in water.

Water Sources

According to the United States Geological Survey (USGS), 71% of the Earth's surface is covered in water, and of that 97% are the oceans. The Earth's water can be broken into two different categories: freshwater and salt water. Fresh water is simply water that is not salty and can be found in the planet's surface water such as streams, lakes, and frozen as ice, but also underground in aquifers. Fresh water is stored on the surface as **surface water** or stored underground in aquifers as **groundwater**. Salt water can be found in the world's oceans.

Figure 1.1 shows that our planet's water sources are limited. Freshwater is much easier to use for potable (drinkable) applications because it requires simpler treatment. However, it represents only a small fraction of the Earth's water portfolio. A large proportion of the freshwater is locked in glaciers and is not accessible. As a result, less than 1% of the water present on the planet is groundwater and surface water that can be more easily used as potable water source. Although desalination plants have become more prevalent, they are very costly, and their overall environmental impacts are unknown.

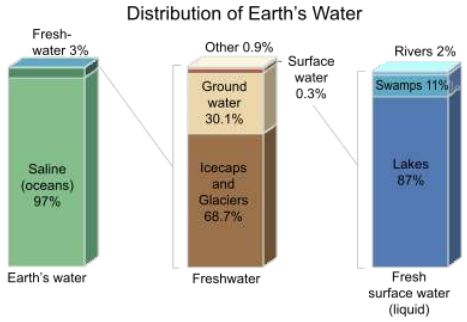


Figure **2.1.1**: Distribution of Earth's Water. (Timothy Bralower is licensed under CC BY-NC-SA 3.0)

The origin of a water source determines its characteristics and the presence of specific contaminants. The concentration and composition of contaminants in water is also influenced by the movements of water, which is illustrated by the water hydrologic cycle (Figure 1.2). The Water Cycle is both driven by gravity (i.e., water flows downhill) and sunlight (i.e., water evaporates and condenses).

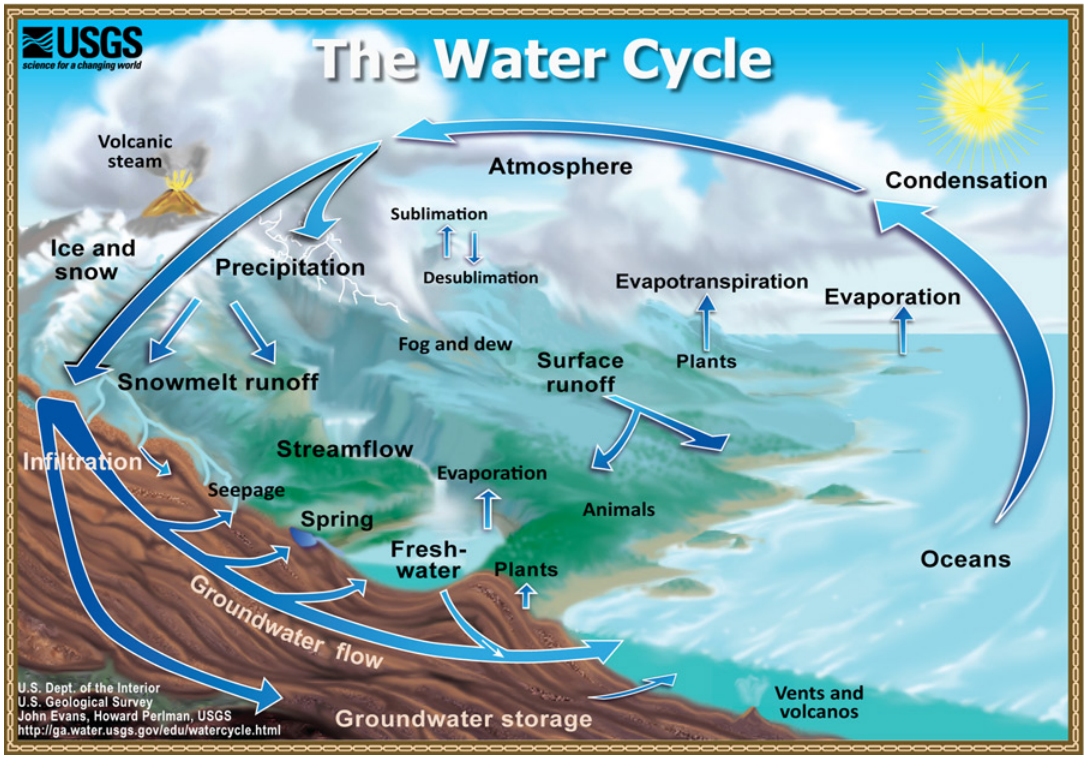


Figure **2.1.2**: Water Hydrologic Cycle. (USGS is in the public domain)

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2.1.1: Classifications of Contaminants

According to the Safe Drinking Water Act, a contaminant is any physical, chemical, biological, or radiological substance in water. While some contaminants are harmless, others are deadly. Contaminants can even mix with water molecules in the atmosphere. Technically, any compound that is not a water molecule is a contaminant when it comes to water.



Pin It! Misconception Alert
Many people think that all contaminants are manmade. They are not! Some have natural sources in the soil, such as arsenic and uranium. These can be expensive to rer rocks around the water source.

Water can be contaminated by various human-caused (anthropogenic) activities or by existing natural features (natural contaminants) like mineral-rich geologic formations. It is not uncommon to find naturally occurring fluoride or arsenic in water.

Agricultural activities, industrial operations, landfills, animal operations, and small and large scale sewage treatment processes, among many other things, all can potentially contribute to contamination. As water runs over the land or infiltrates into the soil and groundwater, it dissolves material left behind by these potential contaminant sources.

There are three major groups of contamination: inorganic chemicals, organic chemicals, and biological agents. The risks and type of remediation for a contaminant depend on the type of chemicals present.



Pin It! Misconception Alert
People use the words contaminants and pollutants interchangeably. What is the difference between a contaminant and a pollutant?

- A contaminant is a substance that is not normally expected.
- A pollutant is a substance found at a concentration that has reached a level that adversely affects the suitability of the water for its intended purpose.

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2.1.2: Key Terms

Key Terms

- **anthropogenic contaminants** – human-caused (manmade) contaminants
- **contaminant** – a substance that is not normally expected
- **groundwater** – water stored in the ground
- **natural contaminants –** contaminants in soil geology, erosion of soils, etc. Examples of contaminants include fluoride and arsenic
- **pollutant** – a substance found at a concentration that has reached a level that adversely affects the suitability of the water for its intended purpose
- **surface water** – water on the surface of the earth

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2.1.3: Review Questions

Review Questions

1. **Outline the water cycle highlighting water sources.**
2. **List the major contaminants of water in the environment.**

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2.1.4: Chapter Quiz

Chapter Quiz

1. How much water on planet earth is easily treated for drinking water?

1. 96%
2. 20.9%
3. 32%
4. < 1.0%

2. Most of the water on earth is found in the _____.

1. atmosphere
2. ocean
3. ground
4. rivers

3. Which of the following is a natural contaminant?

1. Pesticides
2. Nitrates
3. Phosphates
4. Fluoride

4. Anthropogenic contaminants refers to _____.

1. turbidity
2. geological contaminants
3. inorganic contaminants
4. manmade contamination

5. The _____ is(are) essential for the maintenance of most life and ecosystems on the planet.

1. climate
2. water cycle
3. aesthetic characteristic of water
4. atmospheric circulation

6. The _____ drive(s) the water cycle.

1. types of precipitation
2. oxygen concentration
3. nutrient levels
4. sun

7. What portion of surface water is found in the permafrost and ice?

1. 69%
2. 68.7%
3. 96.5%
4. 30.1%

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2.2: Introduction to Chemistry and Matter

Learning Objectives

After reading this section, you should be able to:

- Discuss matter, elements, molecules, and atoms
- Explain electronegativity
- Explain chemical bonding and compounds
- Explain chemical equations and reactions
- Discuss physical states of matter

This chapter presents the fundamentals of chemistry, starting with an introduction on matter and its elemental constituents. Molecular arrangements and chemical bonding are then introduced, followed by examples of chemical nomenclature.

Composition of Matter

Matter can be viewed as anything that has a mass and occupies a space, i.e., that has a specific volume. **Mass** is defined as a measurement of the quantity of matter present.



Pin It! Misconception Alert
Mass is different than weight though people commonly use them interchangeably. Mass is how much matter is present. Weight is a measure of the gravitational pull on the object. So, your weight will change if you travel to the moon, but your mass will not!

Elements and Atoms

At the center of all matter are elements. **Elements** are basic substances that cannot be broken down without altering their basic identities; they cannot be further simplified (e.g., hydrogen, H; oxygen, O). An **atom** is the smallest amount of an element. The center of each atom contains a nucleus made of **protons** (very small particles with a positive electric charge) and **neutrons** (very small particles, without electrical charge), with **electrons** (very small, negatively charged particles) that gravitate around the nucleus. Electrons have an insignificant mass compared to protons and neutrons.

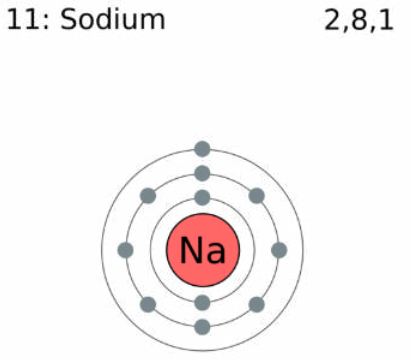


Figure **2.2.1**: Electron Shells Gravitating Around Sodium Atom. (Image by Greg Robson is licensed under CC BY-SA 2.0)

Electrons gravitate around the nucleus of protons and neutrons in layers or shells (Figure **2.2.1**. There is only a limited number of electrons per shell, as shown in Figure \(\PageIndex{2}\.

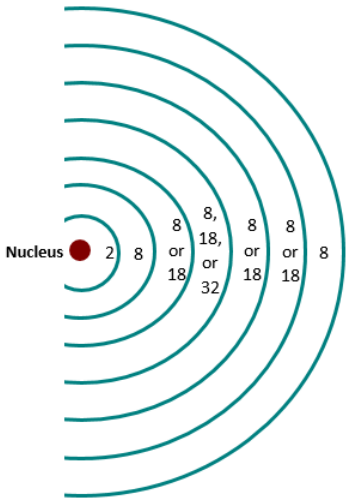


Figure **2.2.2**: Maximum Number of Electrons per Shell. (Image by COC OER is licensed under CC BY 4.0)

Atoms have the same number of protons and electrons; thus, atoms have a neutral electrical charge. However, most atoms tend to gain or lose electrons to complete their last electron shell and obtain a stable electron configuration. Only the Noble Gasses (such as helium, neon, and argon) do not tend to gain or lose electrons because their electron configuration is naturally stable. An atom with an unequal number of protons and electrons is called an **ion**. Atoms that lose electron(s) become positively charged and are called **cation** (e.g., sodium, Na^+). Atoms that gain electron(s) become negatively charged and are called **anion** (e.g., chloride, Cl^-). Note that only electrons are gained, lost, or shared because they are readily available; only radioactive compounds can release protons and neutrons.



Pin It! Misconception Alert
Be careful distinguishing between cations and anions. An atom with an unequal number of protons and electrons is an ion. Cations are positively charged ions and anions are negatively charged ions.

The **Periodic Table** illustrates all elements that have been found or were synthesized to date (Figure **2.2.3**. In this table, elements are ordered in increasing number of protons (from left to right in each row; rows are called periods) and are grouped in columns (called groups) by electron configuration. For example, chlorine appears as number 17 in the Periodic Table (i.e., its atomic number is 17), which means that it has 17 protons. Chlorine is part of the Halogen Family, which all tend to gain an electron to stabilize their last electron shell. While gaining this electron, they become negative charged (e.g., chlorine becomes chloride, Cl^-). Each column represents a family, e.g., Alkali Metals (Column 1), Alkali Earth Metals (Column 2), Halogens (Column 17), and Noble Gases (Column 18). Some families are named after their first element, e.g., Boron Family (Column 13), Nitrogen Family (Column 15), and Oxygen Family (Column 16). Additional characteristics are presented later.

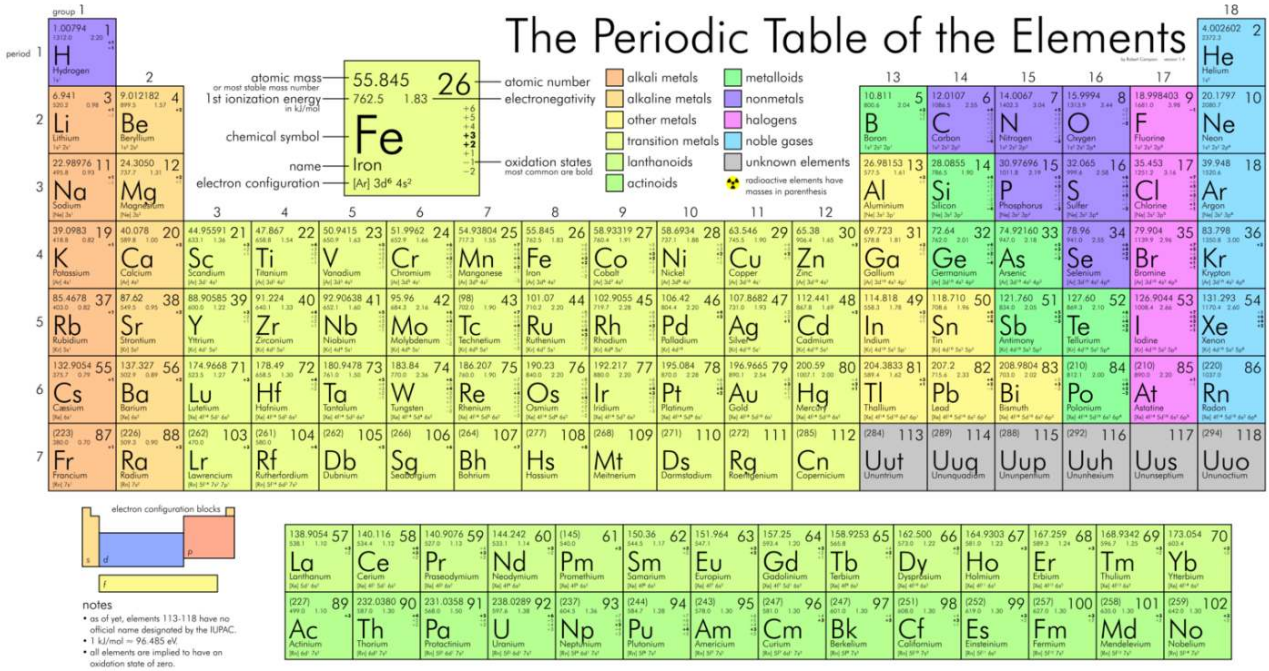


Figure **2.2.3**: Period Table of the Elements. (Image is in the public domain)

The **valence** (also called the ionic state or oxidation state) is the number of electrons gained, lost, or shared between atoms. Because all elements of a family share similar electron configuration, they all tend to have the same valence, as follows:

- Noble Gases are stable, thus their valence is 0.
- Alkali Metals tend to lose one electron, thus their valence is +1.
- Alkali Earth Metals tend to lose two electrons, thus their valence is +2.
- Elements of the Boron Family tend to lose three electrons, thus their valence is +3.
- Halogens tend to gain one electron, thus their valence is -1.
- Elements of the Oxygen Family tend to gain two electrons, thus their valence is -2.
- Elements of the Nitrogen Family tend to gain three electrons, thus their valence is -3.

Certain elements have multiple valences with different characteristics based on their valence. For example, ferrous iron, Fe^{2+}, has lost two electrons (it has a valence of +2) and is highly soluble in water. On the other hand, ferric iron, Fe^{3+} (valence of +3), has lost three electrons and is insoluble in water, i.e., it forms a solid and precipitates. Trivalent chromium (i.e., chromite, also called chromium 3, Cr (III), or Cr^{3+}) has lost three electrons and has a valence of +3. It is an essential element that helps regulate the body's use of sugar, proteins, and fats. However hexavalent chromium (i.e., chromate, also called chromium 6, Cr (VI), or Cr^{6+}) has lost six electrons (valence of +6) and is toxic to humans.

Electronegativity is the degree of attraction of an element for electrons; it defines an element's affinity for electrons. Electronegativity determines whether an atom will gain, lose, or share electrons.

Molecules and Compounds

Molecules or compounds result from the combination of two or more atoms that are chemically joined (or bonded); e.g., oxygen in the air, O_2; water, H_2O. Atoms will tend to combine in such ways to increase their stability and complete their electron configuration. For some molecules, this means that they will obtain a zero net electrical charge.

Chemical bonds can be grouped in two broad categories, as illustrated in Figures \(\PageIndex{4}\ and \(\PageIndex{5}\.

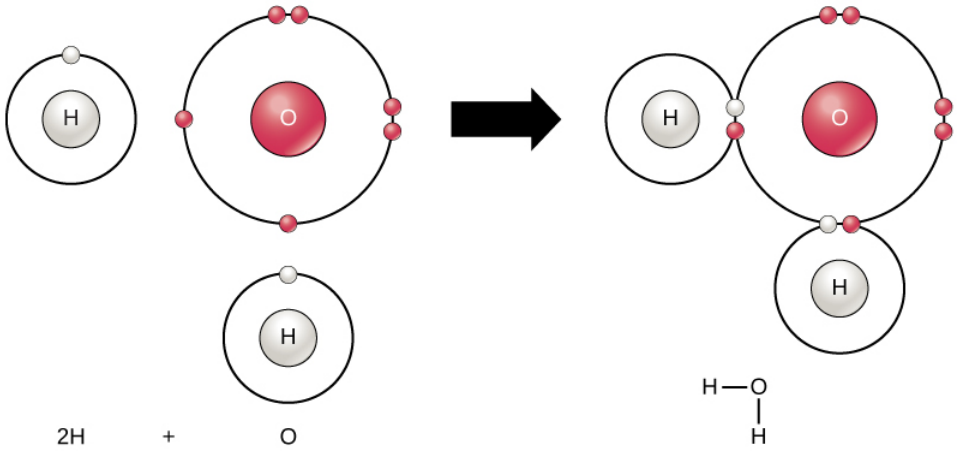


Figure **2.2.4**: Example of a covalent bond. (Image by OpenStax is licensed under CC BY4.0)

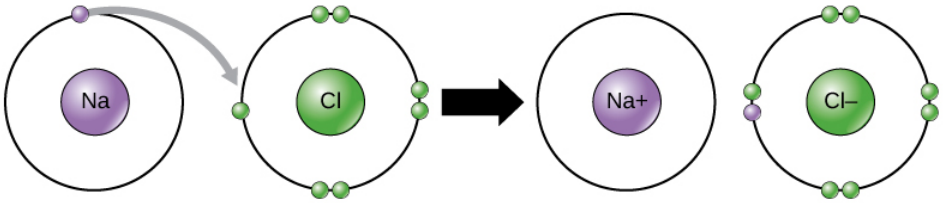


Figure **2.2.5**: Example of an ionic bond. (Image by OpenStax is licensed under CC BY 4.0)

1. In an **ionic bond**, electrons are transferred from one atom to another. The atom that loses electron(s) becomes positively charged and is called a cation. Conversely, the atom that gains electron(s) becomes negatively charged and is called an anion. Examples of ionic bonds are shown in Table \(\PageIndex{1}\.
2. In a **covalent bond**, electrons are shared between atoms. The electronegativity of each atom will determine the polarity of the resulting molecule.

Table \(\PageIndex{1}\: Examples of Ionic Bonds

Example	Explanation
Sodium chloride, NaCl	1. Sodium tends to lose 1 electron to become Na^{+} 2. Chloride tends to gain 1 electron to become Cl^{-} 3. Net zero charge: $Na^{+1} + Cl^{-1} = NaCl^{0}$
Sodium oxide, Na_2O	1. Sodium tends to lose 1 electron to become Na^{+} 2. Oxygen tends to gain 2 electrons to become O^{2-} 3. Net zero charge: $(2 \times Na^{+1}) + (1 \times O^{2-}) = Na_2O$

Table \(\PageIndex{2}\: Examples of Covalent Bonds

Example	Explanation
Homonuclear molecules: Equal attraction for the shared electron(s)	Hydrogen, H_2: Single covalent bond: H– H Chlorine, Cl2: Single covalent bond: Cl– Cl Oxygen, O_2: Double covalent bond: O = O Nitrogen, N_2: Triple covalent bond: N ≡ N
Heteronuclear molecule: Unequal attraction for the shared electron(s) Example: Water, H2O	1. Hydrogen, H^+ Valence of +1: Need 1 bond 2. Oxygen, O^{2-} Valence of -2: Need 2 bonds 3. Net zero charge: $(2 \times H^{+1}) + (1 \times O^{2-}) = H_2O$

The key differences between ionic and covalent bonds are summarized in Table \(\PageIndex{3}\) on the following page.

Table \(\PageIndex{3}\): Comparison of Ionic Bonds and Covalent Bonds

Ionic Bonds	Covalent Bonds
• Transfer of electron(s) from one atom to another • Tend to be inorganic • High melting point • Often solid at room temperature • Good conductor • Resulting substance is called a compound	• Electrons are shared between atoms Organic compounds • Low melting point • Solid, liquid or gas at room temperature • Poor conductor • Resulting substance is called a molecule or molecular compound

Dissociation

Molecules that result from polar covalent bond (i.e., atoms of different types that share electrons) may breakdown or dissociate. This is the case for water, H_2O, which dissociates into hydrogen ion, H^+, and hydroxide, OH^-. The dissociation of water is measured as pH.

Chemical Names[1]

The Period Table (Figure **2.2.3** presents all the elements that are known to mankind to this day.

Cations keep is the same name as the element name listed in the Periodic Table. For example, the sodium ion Na^+. Anions have "-ide" at the end when they are formed from elements. For example, chloride, Cl^- is the anion of the element chlorine.

Binary compounds (contain only two elements) are a little more complicated to name based on whether they have ionic or covalent bonds. If they are composed of a metal and a polyatomic ion (non-metal), then you use the name of the metal in the periodic table and then the name of the polyatomic ion. If the polyatomic ion is a single element, then change the ending to “ide”, even if one element has multiple atoms: for example, magnesium chloride, $MgCl_2$.

Metals with variable valences, such as the Transition Metals (Columns 3 through 12 of the Periodic Table, Figure **2.2.3**, are more complex because they are followed by a symbol that reflects the valence. This was introduced earlier in Section 2.1.1. For example, trivalent chromium (i.e., chromite) has a valence of +3, and is referred to as Cr(III), or Cr^{3+}; hexavalent chromium (i.e., chromate) has a valence of +6 and is referred to as Cr(VI), or Cr^{6+}.

Naming acids and their derivatives is more complex and may depend on the acid’s oxidation state. Generally, the acids with the highest oxidation state end in –ic; e.g., sulfuric acid (H_2SO_4), nitric acid (HNO_3), or phosphoric acid (H_3PO_4). Their salts end in –

ate; e.g., sulfate (SO_4^{2-}), nitrate (NO_3^-), or phosphate (PO_4^{2-}). Acids with the next lowest oxidation state end in –ous; e.g., sulfurous acid, H_2SO_3. Their salts end in –ite; e.g., sulfite, SO_3^{2-}. Acids with the lowest oxidation state begin in hypo– and end in –ous; e.g., hypochlorous acid, HOCl. Their salts begin in hypo– and end in –ite; e.g., hypochlorite ion, OCl^-.

Physical States of Matter

States of matter are distinct forms that matter can take. They are based on how elements are arranged in matter. Matter can take four different states (Figure **2.2.6**:

1. Solid: Volume and shape are fixed;
2. Liquid: Fixed volume, but variable shape that adapts to its container;
3. Gas: Volume and shape are variable;
4. Plasma: Variable volume and shape, with electrical charges.

The physical states of matter reflect different energy levels: solids have the lowest energy level, followed by liquids. Gases have higher energy levels, and plasma have the highest energy level. In water, the first three states (i.e., solid, liquid and gas) are important.

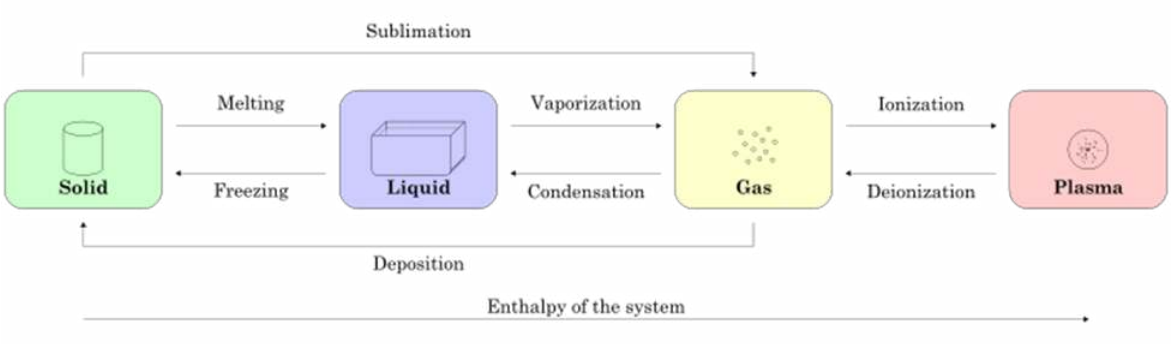


Figure **2.2.4**: Physical States of Matter. (Image by ElfQrin is licensed under CC BY-SA 4.0)

Key Terms

- **anion** – an atom that gains electrons and becomes negatively charged
- **cation** – an atom that loses one or more electrons and becomes positively charged
- **covalent bond** – A type of bond in which electrons are shared between atoms; organic compounds; low melting point; solid, liquid or gas at room temperature; poor conductor; resulting substance is called a molecule or molecular compound
- **electronegativity** – the degree of attraction of an element for electrons; it defines an element's affinity for electrons. Electronegativity determines whether an atom will gain, lose, or share electrons.
- **ionic bond** – Transfer of electron(s) from one atom to another; tend to be inorganic; High melting point; often solid at room temperature; good conductor; resulting substance is called a compound
- **mass –** a measurement of the quantity of matter present
- **matter –** anything that has a mass and occupies a space; can take on four states (solid, liquid, gas, and plasma)
- **periodic table** – an organization of all elements that have been found or synthesized in order from increasing number of protons (from left to right in each row); rows are called periods and columns are called groups
- **valence** - also called the ionic state or oxidation state; the number of electrons gained, lost, or shared between atoms. Because all elements of a family share similar electron configuration, they all tend to have the same valence

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2.2.1: Review Questions

Review Questions

1. **Define matter.**
2. **Define element.**
3. **Define atom.**
4. **Define electronegativity.**
5. **List the types of chemical bonding and define each one.**
6. **What is a chemical reaction?**
7. **List the physical states of matter and describe each one.**

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2.2.2: Chapter Quiz

Chapter Quiz

1. _____ determines whether an atom will gain, lose, or share electrons.

1. Covalent bonding
2. Ionic bonding
3. Physical states of matter
4. Electronegativity

2. The physical states of matter reflect different energy levels; _____ have the lowest energy level.

1. solids
2. liquids
3. gas
4. plasma

3. _____ are basic substances that cannot be broken down without altering their basic identities; they cannot be further simplified.

1. Atoms
2. Molecules
3. Electrons
4. Protons

4. The center of each atom contains a nucleus made of protons (very small particles with a positive electric charge) and neutrons (very small particles, without electrical charge), with electrons (very small, negatively charged particles) that gravitate around the nucleus.

1. protons and neutrons
2. electrons
3. neutrons
4. protons

5. _____ are very small particles with a positive electric charge.

1. protons and neutrons
2. electrons
3. neutrons
4. protons

6. _____ are very small, negatively charged particles.

1. protons and neutrons
2. electrons
3. neutrons
4. protons

7. _____ cannot be created or destroyed over the course of chemical reactions. Thus, the number of _____ must be the same for each element and on each side of the equation.

1. Molecules, molecules
2. Reactants, products
3. Atoms, atoms
4. Products, reactants

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2.3: Chemical Equations

Learning Objectives

After reading this section, you should be able to:

- Describe ionic, covalent, and hydrogen bonding
- Explain synthesis, decomposition, exchange, and combustion reactions
- Describe the energy flow through chemical reactions

Bonding[1]

The model of the atom presented in Chapter 2 is known as the “Bohr” model, and was developed in 1913, by Danish scientist Niels Bohr (1885–1962). His model shows the atom as a central nucleus containing protons and neutrons, with the electrons in circular **orbitals** at specific distances from the nucleus, as Figure 3.1 illustrates. These orbits form electron shells or energy levels, which are a way of visualizing the number of electrons in the outermost shells. These energy levels are designated by a number and the symbol “n.” For example, 1n represents the first energy level located closest to the nucleus.

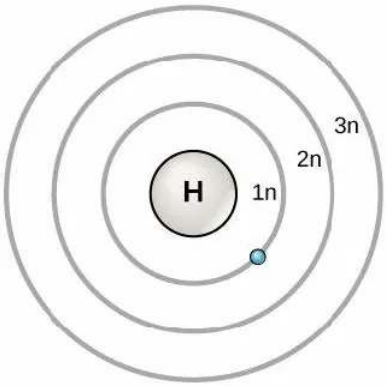


Figure **2.3.1**: In 1913, Niels Bohrs developed the Bohr model in which electrons exist within principal shells. An electron normally exists in the lowest energy shell available, which is the one closest to the nucleus. Energy from a photon of light can bump it up to a higher energy shell, but this situation is unstable, and the electron quickly decays back to the ground state. In the process, it releases a photon of light. (Copyright; by OpenStax is licensed under CC BY 4.0)

Electrons fill orbitals in a consistent order: they first fill the orbitals closest to the nucleus, then they continue to fill orbitals of increasing energy further from the nucleus. If there are multiple orbitals of equal energy, they fill with one electron in each energy level before adding a second electron. The electrons of the outermost energy level determine the atom's energetic stability and its tendency to form chemical bonds with other atoms to form molecules. We refer to the outermost energy level as the **valence shell**.

Under standard conditions, atoms fill the inner shells first, often resulting in a variable number of electrons in the outermost shell. The innermost shell has a maximum of two electrons, but the next two electron shells can each have a maximum of eight electrons. With the exception of the innermost shell, atoms are more stable energetically when they have eight electrons in their valence shell. This is an atom’s natural preferred configuration. As such, an atom may give, take, or share electrons with another atom to achieve a full valence shell, and is how covalent and ionic bonds are formed. Refer back to Tables 2.1 and 2.2 in Chapter 2, for examples of these types of bonds.

Remember,

1. In an **ionic bond**, electrons are transferred from one atom to another. The atom that loses electron(s) becomes positively charged and is called a cation. Conversely, the atom that gains electron(s) becomes negatively charged and is called an anion. Examples of ionic bonds are shown in Table 2.5.
2. In a **covalent bond**, electrons are shared between atoms. The electronegativity of each atom will determine the polarity of the resulting molecule.

There is one more bond to talk about, the hydrogen bond.

Hydrogen Bonds[2]

A hydrogen bond is a special type of bond which occurs when a hydrogen atom bonded to a strongly electronegative atom (like oxygen) in the vicinity of another electronegative atom with a lone pair of electrons. These bonds are much weaker than covalent and ionic bonds.

For a hydrogen bond to occur there must be both a hydrogen donor and an acceptor present. The donor in a hydrogen bond is the atom to which the hydrogen atom participating in the hydrogen bond is covalently bonded, and is usually a strongly electronegative atom such as N, O, or F. The hydrogen acceptor is the neighboring electronegative ion or molecule and must possess a lone electron pair in order to form a hydrogen bond.

The most common example of hydrogen bonding in the natural world occurs between molecules of water. It happens before your eyes whenever two raindrops merge into a larger bead, or a creek spills into a river. Hydrogen bonding occurs because the weakly negative oxygen atom in one water molecule is attracted to the weakly positive hydrogen atoms of two other water molecules (Figure **2.3.2**).

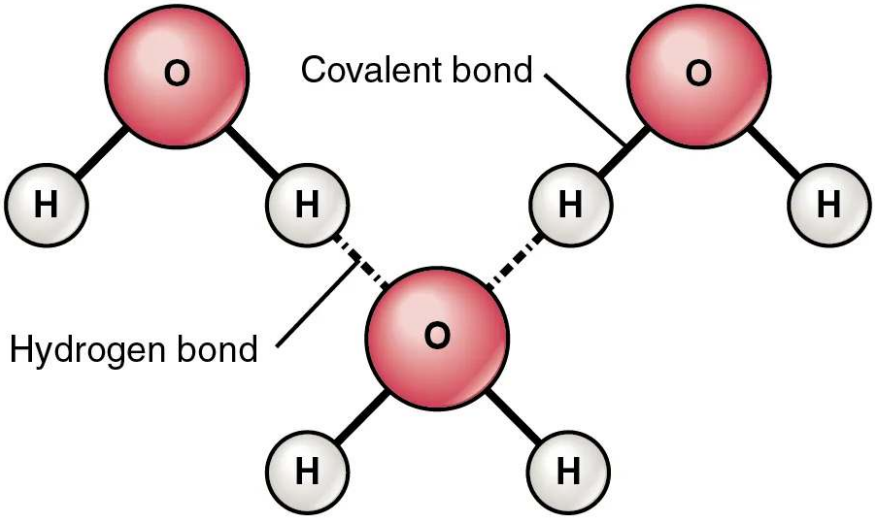


Figure **2.3.2**: Hydrogen Bonds between Water Molecules. Notice that the bonds occur between the weakly positive charge on the hydrogen atoms and the weakly negative charge on the oxygen atoms. Hydrogen bonds are relatively weak, and therefore are indicated with a dotted (rather than a solid) line. (Image by OpenStax is licensed under CC BY 4.0.)

Water molecules also strongly attract other types of charged molecules as well as ions. This explains why "table salt," for example, actually is a molecule called a "salt" in chemistry, which consists of equal numbers of positively-charged sodium (Na^+) and negatively-charged chloride (Cl^-), dissolves so readily in water, in this case forming dipole-ion bonds between the water and the electrically-charged ions (electrolytes). Water molecules also repel molecules with nonpolar covalent bonds, like fats, lipids, and oils. You can demonstrate this with a simple kitchen experiment: pour a teaspoon of vegetable oil, a compound formed by nonpolar covalent bonds, into a glass of water. Instead of instantly dissolving in the water, the oil forms a distinct bead because the polar water molecules repel the nonpolar oil.

Types of Hydrogen Bonds

Hydrogen bonds can occur within one single molecule, between two like molecules, or between two unlike molecules.

- **Intramolecular hydrogen bonds**: Intramolecular hydrogen bonds are those which occur within one single molecule. This occurs when two functional groups of a molecule can form hydrogen bonds with each other. In order for this to happen, both a hydrogen donor an acceptor must be present within one molecule, and they must be within close proximity of each other in the molecule. For example, intramolecular hydrogen bonding occurs in ethylene glycol ($C_2H_4(OH)_2$) between its two hydroxyl groups due to the molecular geometry.
- **Intermolecular hydrogen bonds**: Intermolecular hydrogen bonds occur between separate molecules in a substance. They can occur between any number of like or unlike molecules as long as hydrogen donors and acceptors are present in positions in which they can interact. For example, intermolecular hydrogen bonds can occur between NH_3 molecules alone, between H_2O molecules alone, or between NH_3 and H_2O molecules.

Hydrogen bonding plays a crucial role in many biological processes and can account for many natural phenomena such as the unusual characteristics of water. In addition to being present in water, hydrogen bonding is also important in the water transport system of plants, protein structure, and nucleic acids.

Molecular Mass and Moles[3]

The molecular mass of a substance is the sum of the average masses of the atoms in one molecule of a substance. It is calculated by adding together the atomic masses of the elements in the substance, each multiplied by its subscript (written or implied) in the molecular formula. Because the units of atomic mass are atomic mass units, the units of molecular mass are also atomic mass units.

A mole is defined as the amount of a substance that contains the number of carbon atoms in exactly 12 g of isotopically pure carbon-12. According to the most recent experimental measurements, this mass of carbon-12 contains 6.022142×10^{23} atoms, but for most purposes 6.022×10^{23} provides an adequate number of significant figures. Just as 1 mole of atoms contains 6.022×10^{23} atoms, 1 mole of eggs contains 6.022×10^{23} eggs. The number in a mole is called Avogadro's number, after the 19th-century Italian scientist who first proposed how to measure the number of molecules in a gas.

The mole provides a bridge between the atomic world (amu) and the laboratory (grams). It allows determination of the number of molecules or atoms by weighing them. The numerical value of Avogadro's number, usually written as No, is a consequence of the arbitrary value of one kilogram, called the International Prototype Kilogram, and the choice of reference for the atomic mass unit scale, one atom of carbon-12. Why? Because the number of carbon atoms in exactly 12 g of isotopically pure carbon-12 contains almost exactly 6.022×10^{23} atoms.

So how much does 1 mole of H_2O weigh? The atomic mass of hydrogen is 1. We have two of them in water. The atomic mass of oxygen is 16. So (2 x 1)H + (16)O = 18 g

Chemical Reactions[4]

Chemical energy is the form of potential energy in which energy is stored in chemical bonds. When those bonds are formed, chemical energy is invested, and when they break, chemical energy is released. Notice that chemical energy, like all energy, is neither created nor destroyed; rather, it is converted from one form to another.

All chemical reactions begin with a **reactant**, the general term for the one or more substances that enter into the reaction. Sodium and chloride ions, for example, are the reactants in the production of table salt. The one or more substances produced by a chemical reaction are called the **product**.

In chemical reactions, the components of the reactants—the elements involved and the number of atoms of each—are all present in the product(s). Similarly, there is nothing present in the products that are not present in the reactants. This is because chemical reactions are governed by the law of conservation of mass, which states that matter cannot be created or destroyed in a chemical reaction.

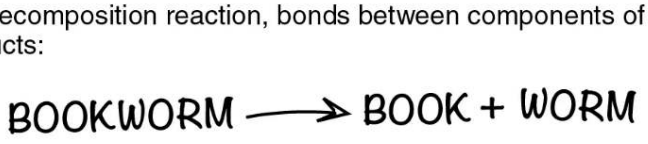
Just as you can express mathematical calculations in equations such as 2 + 7 = 9, you can use chemical equations to show how reactants become products. As in math, chemical equations proceed from left to right, but instead of an equal sign, they employ an arrow or arrows indicating the direction in which the chemical reaction proceeds. For example, the chemical reaction in which one atom of nitrogen and three atoms of hydrogen produce ammonia would be written as $N+3H \rightarrow NH_3$. Correspondingly, the breakdown of ammonia into its components would be written as $NH_3 \rightarrow N + 3H$.

Notice that, in the first example, a nitrogen (N) atom and three hydrogen (H) atoms bond to form a compound. This anabolic reaction requires energy, which is then stored within the compound's bonds. Such reactions are referred to as synthesis reactions. A **synthesis reaction** is a chemical reaction that results in the synthesis (joining) of components that were formerly separate (Figure **2.3.3**. Again, nitrogen and hydrogen are reactants in a synthesis reaction that yields ammonia as the product. The general equation for a synthesis reaction is $A + B \rightarrow AB$.

a) In a synthesis reaction, two components bond to make a larger molecule. Energy is required and is stored in the bond:



b) In a decomposition reaction, bonds between components of a larger molecule are broken, resulting in smaller products:



c) In an exchange reaction, bonds are both formed and broken such that the components of the reactants are rearranged:



Figure **2.3.3**: The Three Fundamental Chemical Reactions. The atoms and molecules involved in the three fundamental chemical reactions can be imagined as words. (Copyright; by OpenStax is licensed and modified under CC BY 4.0.)

In the second example, ammonia is catabolized into its smaller components, and the potential energy that had been stored in its bonds is released. Such reactions are referred to as decomposition reactions. A **decomposition reaction** is a chemical reaction that breaks down or "de-composes" something larger into its constituent parts (see Figure 3.3). The general equation for a decomposition reaction is: AB→A+BAB→A+B.

An **exchange reaction** is a chemical reaction in which both synthesis and decomposition occur, chemical bonds are both formed and broken, and chemical energy is absorbed, stored, and released (see Figure **2.3.3**). The simplest form of an exchange reaction might be: A+BC→AB+C. Notice that, to produce these products, B and C had to break apart in a decomposition reaction, whereas A and B had to bond in a synthesis reaction. A more complex exchange reaction might be: AB+CD→AC+BD. Another example might be: AB+CD→AD+BC.

In theory, any chemical reaction can proceed in either direction under the right conditions. Reactants may synthesize into a product that is later decomposed. Reversibility is also a quality of exchange reactions. For instance, A+BC→AB+C could then reverse to AB+C→A+BC. This reversibility of a chemical reaction is indicated with a double arrow: A+BC⇄AB+C. Many chemical reactions do proceed in a predictable direction, either one way or the other. You can think of this more predictable path as the path of least resistance because, typically, the alternate direction requires more energy.

Combustion Reactions

Combustion reactions are types of chemical reactions where compounds and oxidants react to produce heat and new products. A common combustion reaction is the reaction between oxygen and hydrocarbons to yield water and carbon dioxide:

(Oxygen) + (Hydrocarbon) (Carbon Dioxide) + (Water) + heat

For example:

- $2H_2 + O_2 \rightarrow 2H_2O$ + heat
- $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + heat

It is also common for a combustion reaction to release light and produce a flame. However, it is not necessary. For a combustion reaction to be initiated, the activation energy for the reaction must be overcome. Often combustion reactions are started with a flame, which provides the heat to initiate the reaction. Once combustion begins, the heat that is produced sustains the reaction until the reactants are used.

In order to recognize combustion reactions, oxygen will be on the reactant side of the equation and the release of heat will be on the product side of the equation. Sometimes the fuel molecule contains oxygen. For example, the combustion of ethanol:

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$

Combustion is an exothermic reaction so that it releases heat. However, sometimes the reaction proceeds so slowly that a temperature change is not noticeable. The signs that a combustion reaction occurs is the presence of oxygen as a reactant and carbon dioxide, water, and heat as products. Inorganic combustion reaction may not form the same types of products; however, they are recognizable by the reaction of oxygen. The surest method of recognizing a combustion reaction is that the products contain carbon dioxide and water.

Combustion does not always proceed to completion or 100-percent efficiency. The reactions are prone to limiting reactants. Two types of combustion reactions exist:

1. **Complete Combustion**: known as clean combustion where oxidation of the reactants (hydrocarbons) produces only carbon dioxide and water. The burning of candle wax, where the heat from the wick vaporizes the wax (hydrocarbon), is an example. The reaction results from the oxygen in the air so that carbon dioxide and water are the products. All of the wax burns so that nothing remains once the candle is consumed. The water vapor and carbon dioxide dissipate into the atmosphere.
2. **Incomplete Combustion**: incomplete combustion is the oxidation of a hydrocarbon that is incomplete or dirty. The products are carbon monoxide and carbon (soot) in addition to carbon dioxide. An example would be the combustion of coal, where soot and carbon monoxide are the products. Fossil fuels oxidize incompletely, and they release waste products.

Energy Flow in Chemical Reactions

Chemical bonds represent stored chemical energy, and chemical reactions ultimately result in net absorption or release of energy. Reactions that release energy are called exergonic reactions. These reactions yield products with less energy than the initial reactants, along with energy that can be harvested for use. Catabolic and oxidative reactions are exergonic for the most part.

The products of energy absorbing, endergonic, reactions contain potential energy in their chemical bonds which is more than the energy that the reactants contained. Anabolic reactions are energy absorbing reactions. For example, the energy released when fuel molecules are broken down (oxidized) is captured in ATP molecules and used to synthesize complex biological molecules the body needs to sustain life.

Factors that Influence the Rate of Chemical Reactions[6]

If chemical reactions are to occur quickly, the atoms in the reactants have to have easy access to one another. Thus, the greater the surface area of the reactants, the more readily they will interact. As a general rule, gases tend to react faster than liquids or solids, again because it takes energy to separate particles of a substance, and gases by definition already have space between their particles. Similarly, the larger the molecule, the greater the number of total bonds, so reactions involving smaller molecules, with fewer total bonds, would be expected to proceed faster.

Reactions that involve highly reactive elements like hydrogen proceed more quickly than reactions that involve less reactive elements. Reactions involving stable elements like helium are not likely to happen at all.

Increasing the temperature of a substance increases the kinetic energy of its particles and the force of their collisions. Chemical reactions proceed more quickly at higher temperatures.

Chemical reactions progress more rapidly when the reacting particles are present in high numbers, concentrations, because the chance of collisions are greater. As the concentrations of the reactants declines, the reaction slows. Chemical equilibrium eventually occurs unless additional reactants are added or products are removed from the reaction site.

Smaller particles move faster than large particles and tend to collide more frequently and more forcefully. The smaller the reacting particles, the faster a chemical reaction proceeds at a given temperature and concentration.

Chemical reactions in nonliving systems can be speeded up by heating. However drastic increases in body temperature are life threatening because important biological molecules are destroyed. At normal body temperature, most chemical reactions would proceed at too slow of a pace to maintain life, if catalysts were not present. **Catalysts** are substances that increase the rate of chemical reactions without becoming chemically changed or part of the product. Biological catalysts are called enzymes.

Key Terms

catalysts – substances that increase the rate of chemical reactions without becoming chemically charged or part of the product; biological catalysts are called enzymes

combustion reactions – types of chemical reactions where compounds and oxidants react to produce heat and new products

decomposition reactions – a reaction in which larger molecules are split into smaller molecules, ions, or atoms

mole – one mole of a substance is its molecular weight expressed in grams

synthesis reactions – a reaction in which two or more atoms, ions, or molecules combine to form new and larger molecules

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2.3.1: Review Questions

Review Questions

1. **Describe hydrogen bonding.**
2. **Describe synthesis reactions.**
3. **Describe decomposition reactions.**
4. **Describe exchange reactions.**
5. **Describe combustion reactions**

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2.3.2: Chapter Quiz

Chapter Quiz

1. The _____ or combining capacity of an atom is the number of extra or missing electrons in its outermost electron shell.

1. valence
2. atomic number
3. exchange rate
4. nucleus

2. _____ is the oxidation of a hydrocarbon that is incomplete or dirty. The products are carbon monoxide and carbon (soot) in addition to carbon dioxide.

1. Complete combustion
2. Incomplete combustion
3. Reduction
4. Decomposition

3. _____ is where a hydrogen atom that is covalently bonded to one oxygen or nitrogen atom is attracted to another oxygen or nitrogen atom. These bonds are weak and do not bind atoms into molecules.

1. Ionic bonding
2. Covalent bonding
3. Hydrogen bonding
4. Temporary bonding

4. _____ is an attraction between ions of opposite charge that holds them together to form a stable molecule.

1. Ionic bonding
2. Covalent bonding
3. Hydrogen bonding
4. Temporary bonding

5. _____ are stronger and more common in living organisms than are true ionic bonds. In the hydrogen molecules, H_2, two hydrogen atoms share a pair of electrons.

1. Ionic bonds
2. Covalent bonds
3. Hydrogen bonds
4. Temporary bonds

6. _____ represent stored energy.

1. Chemical bonds
2. Hydrogen bonds
3. Covalent bonds
4. Ionic bonds

7. When two or more atoms, ions, or molecules combine to form new and larger molecules, the reaction is called a _____.

1. decomposition reaction
2. exchange reaction
3. combustion reaction
4. synthesis reaction

8. _____ are substances that increase the rate of chemical reactions without becoming chemically changed or part of the product.

1. Products

2. Reactants
3. Catalysts
4. Chemical bonds

9. For a combustion reaction to be initiated, the _____ energy for the reaction must be overcome.

1. kinetic
2. potential
3. activation
4. decomposition

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2.4: Organic Chemistry

Learning Objectives

After reading this section, you should be able to:

- Explain carbon-based compounds
- Describe molecular structure
- Describe organic matter
- Describe methane, trihalomethanes, acetic acid, haloacetic acid

Organic compounds contain carbon. All organic compounds are covalently bonded molecules, and most organic compounds are large molecules. All other chemicals are considered **inorganic compounds,** which do not contain carbon. Inorganic compounds include water, salts, and many acids and bases. Organic and inorganic compounds are equally essential for life.

Organic materials are derived from plant fibers and animal tissues, which are produced by synthesis reactions that produce materials like rubber, plastics, and other compounds; and fermentation reactions that produce alcohols, acids, antibodies, and other compounds.



Pin It! Misconception Alert
In chemistry, the word “organic” refers to compounds containing carbon. It does not refer to organic food (e.g., grown without chemical fertilizers or pesticides).

Inorganic compounds, in contrast to organic compounds, are combustible, high in molecular weight, and sparingly soluble in water and a source of food for animal consumers and microbial decomposers.

Organic compounds essential life include carbohydrates, lipids, proteins, and nucleotides. Each of these molecules contain carbon and they are referred to as organic compounds. Organic compounds are distinguished by the fact that they contain carbon, and inorganic compounds are defined as compounds that lack carbon. However, carbon dioxide and carbon monoxide are carbon containing compounds but are considered inorganic compounds.

Organic molecules are large molecules. Only small, reactive parts of their structure interact with other compounds. These areas are referred to as active sites and are functional groups, such as acid groups, amines, and others.

Carbon is a special atom. No other small atom is so electroneutral. The consequence of its electroneutrality is that carbon does not lose or gain electrons. It shares them. With four valence shell electrons, carbon forms four covalent bonds with other elements, as well as with other carbon atoms. As a result, carbon helps to form long, chainlike molecules, ring structures, and other structures that are uniquely suited for specific roles in living systems.

Many biologic molecules are polymers like carbohydrates and proteins. Polymers are chainlike molecules made of many similar or repeating units, monomers, which are joined together by dehydration synthesis. During dehydration syntheses, a hydrogen atom is removed from one monomer and a hydroxyl group is removed from another monomer. The resultant products are joined together with a covalent bond, and in the process, a water molecule is released. The removal of a water molecule at the bond site occurs each time a monomer is added to the growing polymer chain.

Hydrocarbons

In organic chemistry, any chemical compound that consists of the elements of carbon and hydrogen is a **hydrocarbon**. Carbon and hydrogen atoms share an electron pair forming covalent bonds in hydrocarbons. One of the special properties of carbon is its ability to form double and triple bonds.

Saturated hydrocarbons contain only the elements of carbon and hydrogen with single bonds between carbon atoms. Methane is the simplest hydrocarbon, and it is a gas produced in the anaerobic decomposition of organic compounds.

When hydrocarbon molecules include one or more double or triple bonds between some of the carbon atoms it is not possible for as many hydrogen atoms to be included in the molecule as when the bonds are single bonds. The term used to describe the presence of one or more double or triple bonds in a molecule of an organic compound is **unsaturated**. If the organic compound contains all single bonds, it is called **saturated**.

Alkanes, Alkenes, and Alkynes

Hydrocarbons are classified as unsaturated or saturated. Alkanes are a group of saturated hydrocarbons meaning that the hydrocarbon contains only single bonded carbon atoms represented as:

C-C-C-C (C_nH_{2n+2})

Alkenes are a group of unsaturated hydrocarbons meaning that the hydrocarbon contains double carbon-carbon bonds represented as:

C=C=C ($C_nH_{2n)}$

Alkynes are hydrocarbons that include triple carbon-carbon bonds (C_nH_{2n-2}).

A bromine solution is used to test for unsaturation of hydrocarbon molecules. Bromine solution is orange in color. When an alkene is added to a bromine solution, the orange color disappears resulting in a colorless solution. Bromine reacts with alkenes forming a new colorless compound. This test is useful in distinguishing alkenes from alkanes because alkanes do not react with bromine solution.

Unsaturated hydrocarbons are distinguished from paraffins by the presence of multiple bonds between some carbon atoms. The multiple bonds between carbon atoms displace hydrogen atoms, creating molecules containing fewer hydrogen atoms.

Vegetable shortenings available as solid fats are produced from oils through the process of hydrogenation which adds hydrogen atoms through the addition of hydrogen gas under controlled conditions. Reducing the number of unsaturated bonds increases the melting point, converting an oil to a solid fat.



Figure **2.4.1**: Vegetable shortening. (Image by doornekamph on Pixabay)

Chemical Structure

The parent compound of aromatic hydrocarbons is benzene. **Benzene** is a 6-carbon ring with double bonds between alternate atoms. Benzene is used in the manufacture of a variety of commercial products including insecticides, plastics, solvents, explosives, and dyes.

Alcohols

Alcohols are formed from hydrocarbons by replacing one or more hydrogen atoms by hydroxyl groups (-OH). **Methanol** is manufactured synthetically by a catalytic process from carbon monoxide and hydrogen. It is used extensively in manufacturing organic compounds, like solvents, fuel additives, and formaldehyde. **Ethyl alcohol** for beverage purposes is produced through the fermentation of a variety of natural organic materials, like corn, wheat, rice, and potatoes. Industrial ethanol is produced from fermentation of waste solutions containing sugars, like blackstrap molasses and residues resulting from the purification of cane sugar.



Figure **2.4.2**: Grains of cane sugar. (Image by Fritzs is licensed under CC BY-SA 3.0)

Propanol has two isomers, the more common is **isopropyl alcohol**, which is widely used by industry and sold as a medicinal rubbing alcohol. The three primary alcohols have boiling points less than 100ºC, and they are miscible with water.

- Methanol or methyl alcohol (CH_3OH)
- Ethanol or ethyl alcohol (CH_3CH_2OH)
- Isopropyl alcohol or 2-Propano (CH_3CH_3CHOH)

Miscible liquids are homogenous when mixed together.

The derivative of benzene containing one hydroxyl group, known as phenol, has a molecular formula of C_6H_5OH. The formula and –ol in the name indicate the characteristics of an alcohol; however, phenol, known as carbolic acid, ionizes in water yielding hydrogen ions, and exhibits features of an acid. It occurs as natural component of wastes from coal, gas, petroleum, and a variety of industrial wastes where phenol is used as a raw material. Phenol is a strong toxin that makes the waste materials particularly difficult to treat in biological systems. Phenols impart undesirable tastes to water at low concentrations.

Aldehydes and Ketones

Aldehydes and ketones are compounds containing a carbonyl group. **Formaldehyde** is used to produce plastics and resins. **Acetone** (dimethyl ketone) is a good solvent of fats and is a common cleaning agent for laboratory glassware.

- Formaldehyde (CH_2OH)
- Acetone (CH_3CHCOH)



Figure **2.4.3**: Nail polish remover (Image by Chris is licensed under CC BY-NC-SA 2.0)

Carboxylic Acids

Organic acids contain the carboxyl group, -COOH. **Carboxylic acid** is the highest state of oxidation that an organic radical can achieve. Further oxidation results in the formation of carbon dioxide and water. Acids through 9-carbons are liquids, and those acids with more carbons are greasy solids, fatty acids. Organic acids are weak and ionize poorly.

Formic, acetic, and propionic acids have sharp penetrating odors, and butyric and valeric acids have extremely disagreeable odors associated with rancid fats and oils. Anaerobic decomposition of long chain fatty acids result in the production of 2 and 3-carbon acids, which are converted to methane and carbon dioxide gas in decomposition reactions.

- Formic acid (HCOOH)
- Acetic acid (CH_3COOH)
- Propionic acid (CH_3CH_2COOH)
- Butyric acid ($CH_3CH_2CH_2COOH$)
- Valeric acid (C_4H_9COOH)
- Caproic acid ($C_5H_{11}COOH$)

Basic compounds react with acids to produce salts. NaOH, sodium hydroxide, reacts with acetic acid to produce sodium acetate. Soaps are salts of long chain fatty acids. Other derivatives of carboxylic acids include esters, such as ethyl acetate and amides.

- Methylamine ($CH_3NH_{2)}$

Organic Matter

Biodegradable organic matter in water is classified into three categories: fats, carbohydrates, and proteins. **Carbohydrates** consist of sugar units containing the elements of carbon, hydrogen, and oxygen. A single sugar is known as a monosaccharide. Disaccharides are composed of two monosaccharide units. Sucrose, table sugar, is glucose plus fructose. The most prevalent sugar in milk is lactose, consisting of glucose plus galactose. Polysaccharides, long chains of sugar units, are divided into two groups: readily degradable starches, like potatoes, rice, corn, and other edible plants; and cellulose which is found in wood, cotton, paper, and similar plant tissues. Cellulose compounds degrade biologically at a slower rate than starches.

Proteins are long strings of amino acids containing carbon, hydrogen, oxygen, nitrogen, and phosphorus. They form an essential part of living tissue and constitute a diet necessary for higher life forms.

Fats refer to a variety of biochemical substances that have the property of being soluble to varying degrees in organic solvents, like ether, ethanol, acetone, and hexane, while being sparingly soluble in water. Because of their limited solubility, degradation by microorganisms is very slow. A simple fat is a triglyceride composed of a glycerol unit with short or long chain fatty acids attached.

The majority of carbohydrates, fats, and proteins in nature are in the form of large molecules that cannot penetrate the cell membrane of microorganisms. Bacteria, in order to metabolize high-molecular weight substances, must be capable of breaking down the large molecules into diffusible fractions for assimilation into the cell. The first step in bacterial decomposition of organic compounds is hydrolysis of carbohydrates into soluble sugars, proteins into amino acids, and fats into short fatty acids. Aerobic biodegradation results in the formation of carbon dioxide and water. Anaerobic digestion, decomposition in the absence of oxygen, results in the formation of organic acids, alcohols, and other liquid intermediates as well as gaseous entities of carbon dioxide, methane, and hydrogen sulfide.

Several organic compounds, like cellulose, long chain saturated hydrocarbons, and complex compounds, although available as a bacterial substrate, are considered non-biodegradable because of the time and environmental limitations of biological treatment systems. Petroleum derivatives, detergents, pesticides, and synthetic organic compounds are also resistant to biodegradation, and some of these compounds are toxic and inhibit the activity of microorganisms in biological processes.

Some waste odors are inorganic compounds, like hydrogen sulfide gas; however, many odors are caused by volatile organic compounds, such as mercaptans and butyric acid. Industries may produce a variety of medicinal odors in the processing of raw materials. Surface water supplies plagued with blooms of blue green algae have fishy or pigpen odors. The cause of odors can be anaerobic decomposition, industrial chemicals, or growths of obnoxious microorganisms.



Figure **2.4.4**: Green ocean water. (Image by Tom Archer is in the public domain.
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Methane and Trihalomethane

Chlorine is used to inhibit or destroy harmful organisms. This method of disinfection alters cell chemistry causing microorganisms to die. Chlorine is the most widely used disinfectant chemical. Chlorine is relatively inexpensive and leaves a residual chlorine that can be measured. An increased interest in disinfection other than chlorine has developed because of the carcinogenic compounds that chlorine may form, trihalomethanes, THMs.

The exact mechanism of chlorine disinfection action is not fully understood. It is felt that chlorine exerts a direct action against bacterial cell, destroying them. Another theory is that the toxic character of chlorine inactivates the enzymes, which enable living microorganisms to use their food supply. As a result, the organisms die. However, the exact mechanism of chlorine disinfection is less important than its demonstrated effects as a disinfectant.

When chlorine is added to water, several chemical reactions take place. Some of the reactions involve the molecules of the water, and some reactions involve organic and inorganic substances suspended in the water.

Chlorine combines with organic and inorganic materials to form chlorine compounds. If chlorine is added continuously, eventually all of the materials in the water that will react with chlorine are used and the chlorine reactions stop. At this point, the chlorine demand is satisfied.

The chemical reactions between chlorine and organic and inorganic substances produce chlorine compounds. Some chlorine compounds have disinfecting properties, and some compounds do not. Chlorine also reacts with the water and produces substances with disinfecting properties. The total of all of the compounds with disinfection properties plus any remaining free, uncombined, chlorine is known as the chlorine residual. The presence of this measurable chlorine residual indicates that all possible chemical reactions with chlorine have taken place and that a sufficient available residual of chlorine is available to kill microorganisms present in the water.

When organic materials are present in water being disinfected with chlorine, the chemical reactions that take place can produce suspected carcinogenic compounds, THMs. The formation of these compounds can be prevented by limiting the amount of chlorination and by removing the organic materials before chlorination of the water.

Methane

Methane is a colorless, odorless, flammable gas, and it is the primary constituent of marsh gas and the firedamp of coal mines. It is obtained commercially from natural gas, and it is the first member of the alkane series of hydrocarbons. The formation of methane can occur through organic matter decomposition or through organic synthesis which involve microorganisms, methanogenesis. The synthesis involves anaerobic and aerobic processes. Naturally occurring methane is produced by microbial methanogenesis. This multistep process is used by microorganisms as an energy source. The net reaction is:

$$CO_2 + 8H^+ \rightarrow CH_4 + 2\,H_2O$$

The final step in the process is catalyzed by the enzyme coenzyme-B sulfoethylthiotransfersase. Methanogenesis is a form of anaerobic respiration used by organisms that occupy landfills, ruminants, and the guts of termites.

Trihalomethanes

Trihalomethanes are harmful by-products arising from a process of water disinfection with chlorine. Trihalomethanes are formed when organic materials react with chlorine to form chlorinated by-products. Trihalomethanes are chemical compounds where 3 of

the 4-hydrogen atoms of methane are replaced by halogen atoms. Trihalomethanes (THMs) are used in industry as solvents or refrigerants. THMs are environmental pollutants, and many of them are considered carcinogenic. Trihalomethanes with all the same halogen atoms are called haloform, and they are considered to be volatile organics. Some examples of trihalomethanes are:

- Chloroform
- Bromodichloromethane
- Bromoform
- Carbon tetrachloride
- Tetrachloroethlene

Trihalomethanes are formed as a by-product when chlorine is used to disinfect drinking water. They represent a group of chemicals referred to as disinfection by-products. They result from the reaction of chlorine or bromine with organic matter present in the water being treated. THMs have been associated through epidemiological studies with adverse health effects. Governmental agencies have set limits on the amount permissible in drinking water. The EPA limits the total concentration of the four chief constituents, chloroform, bromoform, bromodichloromethane, and dibromochloromethane, referred to as total TTHMs to 80 parts per billion in drinking water.

In drinking water, THM levels tend to increase with pH, temperature, contact time with chlorine, and the level of the organic precursors. The precursors, organic material, reacts with chlorine to form THMs. One method that is used to decrease THMs is to eliminate or reduce chlorination before the filters and to reduce precursors. Since more precursors are present before filtration, the treatment process is directed toward reducing or eliminating the time chlorine is in contact with the water. If some oxidation before filtration is required, an alternative disinfectant like potassium permanganate or peroxide should be considered. This strategy is not an option if pre-chlorination is necessary to achieve the required CT, contact time, values.

The EPA has advocated that the best available technology for THM control at treatment facilities is to remove precursors through enhanced coagulation. Enhanced coagulation refers to a process of optimizing the filtration process to maximize removal of precursors. Removal is improved by decreasing pH levels to 4 or 5, increasing the feed rate of coagulants, and using ferric coagulants in place of alum.

Acetic Acid and Haloacetic Acid

Haloacetic acids (HAA) are carboxylic acids where a halogen atom takes the place of hydrogen atoms in acetic acid. In monohaloacetic acid, a single halogen replaces a hydrogen atom. Chloroacetic acid has the structural formula of CH_2ClCO_2H. In this manner, two chlorine atoms are present in dichloroacaetic acid where two hydrogen atoms are replaced with chlorine atoms. Dichloroacetic acid has a structural formula of $CHCl_2CO_2H$.

Haloacetic acids (HAA) are a common undesirable by-product of drinking water chlorination. Exposure to such disinfection by-products in drinking water, at high levels has been associated with undesirable health outcomes through epidemiological studies. The five most common HAAs in water are:

- Monochloroacetic acid ($CLCH_2COOH$)
- Dichloroacetic acid ($Cl_2CHCOOH$)
- Trichloroacetic acid (Cl_3CCOOH)
- Monobromoacetic acid ($BrCH_2COOH$)
- Dibromoacetic acid ($Br_2CHCOOH$)

Collectively, these chemicals are called HAA_5.

HAAs can be formed by chlorination, ozonation, or chloramination of water with the formation of HAAs promoted by slightly acidic water, high organic matter content, and elevated temperature. Chlorine from the water disinfection process reacts with organic matter and small amounts of bromide present in the water to produce various HAAs.

Key Terms

- **acetone** – a good solvent of fats and is a common cleaning agent for laboratory glassware
- **carbohydrates** – sugar units containing the elements of carbon, hydrogen, and oxygen
- **carboxylic acid** – the highest state of oxidation that an organic radical can achieve

- **ethyl alcohol** – alcohol for beverage purposes that is produced through the fermentation of a variety of natural organic materials, like corn, wheat, rice, and potatoes
- **fats** – a variety of biochemical substances that have the property of being soluble to varying degrees in organic solvents, like ether, ethanol, acetone, and hexane, while being sparingly soluble in water
- **formaldehyde** – used to produce plastics and resins
- **haloacetic acids (HAA)** – carboxylic acids where a halogen atom takes the place of hydrogen atoms in acetic acid, a common undesirable by-product of drinking water chlorination
- **inorganic compounds** – molecules that do not contain carbon
- **isopropyl alcohol** – a type of alcohol, which is widely used by industry and sold as a medicinal rubbing alcohol.
- **methanol** – a type of alcohol manufactured synthetically by a catalytic process form carbon monoxide and hydrogen; used extensively in manufacturing organic compounds, like solvents, fuel additives, and formaldehyde
- **methane** – a colorless, odorless, flammable gas, and it is the primary constituent of marsh gas and the firedamp of coal mines
- **organic compounds** – molecules that contain carbon
- **proteins** – long strings of amino acids containing carbon, hydrogen, oxygen, nitrogen, and phosphorus.
- **trihalomethanes (THMs)** – harmful by-products arising from a process of water disinfection with chlorine; formed when organic materials react with chlorine to form chlorinated by-product

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2.4.1: Review Questions

Review Questions

1. **What is an organic compound?**
2. **List some types of organic compounds.**
3. **Define an inorganic compound.**

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2.4.2: Chapter Quiz

Chapter Quiz

1. _____ are covalently bonded molecules, and most are large molecules.

1. Inorganic compounds
2. Hydrocarbons
3. Aldehydes
4. Organic compounds

2. _____ are harmful by-products arising from a process of water disinfection with chlorine. They are formed when organic materials react with chlorine to form chlorinated by-products.

1. Ketones
2. Trihalomethanes
3. Organic compounds
4. Alkehydes

3. _____ can be formed by chlorination, ozonation, or chloramination of water. They are promoted in slightly acidic water, high organic matter content, and elevated temperature. These compounds are precursors to Trihalomethanes.

1. Haloacetic acids
2. Organic compounds
3. Inorganic compounds
4. Carboxylic acids

4. _____ is(are) a colorless, odorless, flammable gas, and it is the primary constituent of marsh gas and the firedamp of coal mines.

1. Bromides
2. Chlorates
3. Methane
4. Chloroform

5. _____ is the highest state of oxidation that an organic radical can achieve. Further oxidation results in the formation of carbon dioxide and water.

1. Haloacetic acids
2. Organic compounds
3. Inorganic compounds
4. Carboxylic acids

6. Biodegradable organic matter in water is classified into three categories _____.

1. THMs, HAA5s, carboxylic acids
2. fats, carbohydrates, and proteins
3. alkanes, alkenes, alkynes
4. chloroform, bromodichloromethane, bromoform

7. The parent compound of aromatic hydrocarbons is _____.

1. benzene
2. alcohol
3. chloroform
4. acetic acid

8. Hydrocarbons are classified as unsaturated or saturated. _____ are a group of saturated hydrocarbons meaning that the hydrocarbon contains only single bonded carbon atoms.

1. All

1. Alkanes
2. Alkenes
3. Alkynes
4. Acetic acids

9. _____ are derived from plant fibers and animal tissues, which are produce by synthesis reactions that produce materials like rubber, plastics, and other compounds; and fermentation reactions that produce alcohols, acids, antibodies, and other compounds.

1. Inorganic materials
2. Biologic acids
3. Hydrocarbons
4. Organic materials

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2.5: Acids, Bases, and Salts

Learning Objectives

After reading this section[1], you should be able to:

- Explain the properties of water
- Describe inorganic and organic acids
- Describe inorganic bases
- Explain pH, acids, and bases
- Describe buffers

Water is the most abundant and important inorganic compound on earth. It makes up 60 to 89-percent of the volume of most living cells, and it possesses several properties that make it vital to life**.** The capability for a molecule to absorb heat energy is called heat capacity. Water has the highest heat capacity of any liquid. It would require calorie of heat energy to change the temperature of water by 1. As a result, it takes water a long time to heat and a long time to cool. This property prevents sudden changes in temperature caused by external factors, such as sun or wind exposure, or by internal conditions that release heat rapidly, such as vigorous muscle activity. As part of blood system or the environment, water redistributes heat among adjacent structures ensuing the temperature remains homeostatic.[2]

When water evaporates, or vaporizes, water changes from a liquid to a gas, water vapor. The transformation requires that large amounts of heat be absorbed to break hydrogen bonds that hold water molecules together. This property is beneficial because as water evaporates from an object or organism large amounts of heat are removed providing efficient cooling. This property is referred to as high heat of vaporization.

Water is the best solvent in nature. It is called the universal solvent. Biological molecules do not react chemically unless they are in solution, and virtually all chemical reactions that occur in the living cells depend on water's solvent properties. Water molecules are referred to as being polar. They orient with their slightly negative ends toward the positive ends of the solutes. . This characteristic is called polarity, and it explains the reason that ionic compounds and other small reactive molecules, such as acids and bases, dissociate in water, where their ions separating from each other and become evenly scattered in the water forming a true solution.

Water also forms layers of water molecules, called hydration layers, around large, charged molecules such as protein, shielding them from the effects of other charged substances in the areas and preventing them from settling out of solution. Such protein water mixtures are biological colloids. Water is also the major transport medium because it is an excellent polar solvent. Nutrients, gases, and metabolic wastes are carried dissolved in water based fluids. Wastes are excreted form living organisms in watery fluids. Specialized molecules that lubricate organisms also use water as the dissolving medium.

As a reactant, water is involved in many important chemical reactions. Nutrients are decomposed by adding a water molecule to each chemical bond that is broken. Decomposition reactions are more specifically referred to as hydrolysis reactions. When large carbohydrates or protein molecules are synthesized from smaller molecules, a water molecule is removed for every bond formed, a reaction that is called dehydration synthesis.

Water forms resilient cushions, cushioning around certain biological structures providing protection from physical trauma.

Other than binary molecular compounds, most inorganic compounds can be classified as acids, bases, or salts. Acids are characterized by the H^+ion, the presence of which in water, makes the water acidic. An acid either contains this ion or produces it when it dissolves in water. A base either contains hydroxide ion, OH^-, or reacts with water to produce hydroxide. Most bases that contain hydroxide consist of metal cations and hydroxide; examples are sodium hydroxide, NaOH, and calcium hydroxide, $Ca(OH)_2$. Acids and bases react to form a salt, an ionic compound that has a cation other than H+ and an anion other than OH^-. This kind of reaction always produces water.

Acids

Salts, acids, and bases are electrolytes. They ionize and dissociate in water and can conduct an electrical current.

Acids have a sour taste, and they can react with or dissolve metals. The definition of an acid is a substance that releases hydrogen ions (H^+) in measurable amounts. Acids are also characterized as being proton donors because a hydrogen ion is a hydrogen nucleus, or a single proton.

When acids dissolve in water, they release hydrogen ions (protons) and anions, negative charged particles. The concentration of the protons determines the acidity of the solution. The anions have little or no effect on the acidity of the solution. Hydrochloric acid (HCl) dissociates into a proton and a chloride ion:

$$HCl \rightarrow H^+, \text{proton} + Cl^-, \text{anion}$$

Living organisms require a balance of acids and bases to function. We can measure this balance by determining the number by the amount of H^+, and OH^- dissociated in a solution. Simply stated, more H^+ hydrogen ions in a solution means more acidic. More OH^- hydroxide ions means more basic (alkaline).

Biochemical reactions are sensitive to small changes in the acidity or alkalinity of the environment in which they occur. H^+ and OH^- are involved in almost all biochemical processes, and any deviation from a narrow band of the normal H^+ and OH^- concentration dramatically modifies the systems' functioning. Acids and bases that are formed in living systems must be kept in balance.

It is convenient to express the amount of H^+ in a solution by a logarithmic pH scale that ranges from 0 to 14. The term **pH** means potential of hydrogen ion concentration. On a log scale, a change of one whole number has 100 times more hydrogen ions than a solution of pH 2, and a pH of 2 has 100 times more hydrogen ions than a solution of pH 3.

Acidic solutions contain more H^+ than OH^- and have a pH lower than 7. If a solution has more OH^- than H^+, it is a basic or alkaline solution. In pure water, a small percentage of molecules are dissociated into H^+ and OH^- ions so that it has a pH of 7. When the ion concentrations of a solution are equal, the solution has a pH of 7 and is considered to be neutral.

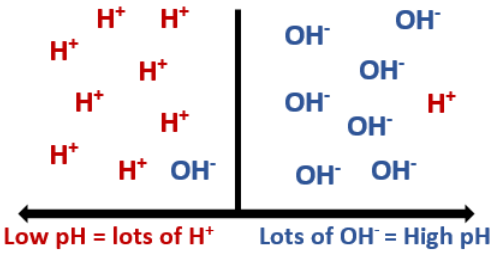


Figure **2.5.1**: Depiction demonstrating the concentrations of H+ and OH- at differing pH levels. (Copyright; [3] Image by COC OER is licensed under CC BY 4.0.)

The pH of a solution can be managed with buffers. Buffers resist a change in pH and will be discussed later in the chapter.

Bases

Bases have a bitter taste, feel slippery, and are proton acceptors. They take up hydrogen ions in measurable amounts. Common inorganic bases include the hydroxides like magnesium hydroxide and sodium hydroxide. Lye acids, hydroxides dissociate when dissolved in water. In this case, hydroxyl ions (OH^-) and cations are released. Ionization of sodium hydroxide produces a hydroxyl ion and a sodium ion. The hydroxyl ion binds to a proton present in the solution. This reaction produces water and simultaneously reduces the acidity of the solution by taking up free H^+ ions:

$$NaOH \rightarrow Na^+ + OH^-$$

$$OH^- + H^+ \rightarrow H_2O$$

The term pH is used to express the intensity of an acid or alkaline solution.

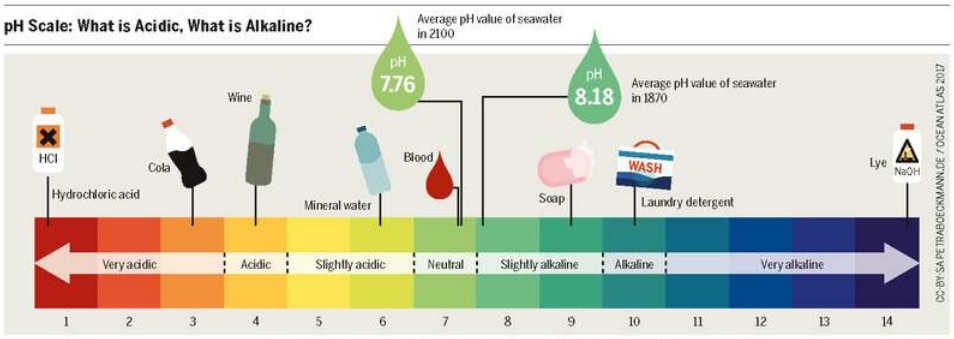


Figure **2.5.2**: pH scale from 0 to 14 demonstrating acid, neutral, and base. (Copyright; Image by Heinrich-Böll-Stiftung is licensed under CC BY-SA 2.0)

Salts and Neutralization

Acids and bases react to form salts, an ionic compound that has a cation other than H+ and an anion other than OH^-. This kind of reaction always produces water and is known as a neutralization reaction. The most well-known salt is sodium chloride, NaCl.

$$HCl + NaOH \rightarrow NaCl + H_2O$$

Acid Base Salt Water

The salt produced is dissolved in the aqueous solution and disassociated into Na^+ and Cl^- ions. Although sodium chloride is commonly what one means in referring to "salt," there are many other salts as well. For example, Sodium sulfate, Na_2SO_4, dissociates into two Na^+ ions and one SO_4^{-2}. The salt dissociates because the ions are formed. The water overcomes the attraction between the oppositely charged ions, and they disassociate.

All ions are electrolytes which are substances that conduct an electrical current in solution. Salts dissociate in aqueous solutions into ions, and the most common salts are sodium salts. In their ionized form, salts play a vital role in nature and aqueous solutions.

Buffers[3]

How can organisms whose bodies require a near-neutral pH ingest acidic and basic substances (a human drinking orange juice, for example) and survive? Buffers are the key. Buffers usually consist of a weak acid and its conjugate base; this enables them to readily absorb excess H^+ or OH^-, keeping the system's pH within a narrow range. Organisms are extremely sensitive to slight changes in the pH of the environment. In high concentrations, acids and bases are damaging to cells. Homeostasis of acid-base balance is regulated by chemical systems called buffers.

Buffers resist abrupt and large changes in the pH of a solution by releasing hydrogen ions when the pH begins to rise and by binding hydrogen ions when the pH drops.

Chemical buffer systems react by binding hydrogen ions or by releasing hydrogen ions. The acidity of a solution reflects the free hydrogen ions and not the hydrogen ions bound to anions. Acids that dissociate completely and irreversibly in water are called strong acids. They can dramatically change the pH of a solution. Acids that do not dissociate completely, like carbonic acid (H_2CO_3) and acetic acid, are weak acids. Undissociated acids do not affect pH, so that acetic acid solutions are much less acidic than hydrochloric acid solution. Weak acids disassociate in predictable ways, and molecules of the intact acid are in dynamic equilibrium with the dissociated ions.

For this reason, when a strong acid is added to a solution of a weak acid the equilibrium will shift to the left and some H^+ will recombine to form acetic acid. On the other hand, if a strong base is added and the pH begins to rise, the equilibrium shifts to the right and more acetic molecules disassociate to release H^+ ions. This characteristic of weak acids allows them to play a role in the chemical buffer systems found in nature.

$$H^+ \text{ acetic acid} \leftrightarrow H^+ + \text{Acetic}^-$$

Bases are proton acceptors. Strong bases are those bases, like hydroxides, which dissociate easily in water and quickly bind H^+ ions. Sodium bicarbonate ionizes incompletely and reversibly. Since it accepts relatively few protons, its released bicarbonate ion is

considered to be a weak base.

One of the buffer system that helps to maintain the pH in aqueous solutions is the carbonic acid-bicarbonate system. Carbonic acid dissociates reversibly in aqueous solutions releasing bicarbonate ions and protons, H^+. The chemical equilibrium between carbonic acid, a weak acid, and bicarbonate ion, a weak base, resists changes in pH by shifting to the right or the left as H^+ ions are added to or removed from the solution:

Rise in pH

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

Drop in pH

As the pH rises and becomes more alkaline, the equilibrium shifts to the right, forcing more carbonic acid to dissociate. Similarly, as the pH begins to drop, the equilibrium shifts to the left as more bicarbonate ions begin to bind with protons. Strong bases are replaced by a weak base, bicarbonate ion. Protons are released by strong acids and are tied up in weak acids, carbonic acid. As a result, the pH changes are much less than they would be in the absence of the buffering system.

Key Terms

- **acid** – a substance that dissociates into one or more hydrogen ions (H+); proton donors; acids release hydrogen ions in measurable amounts; sour taste
- **base** – a substance that dissociates into one or more positive ions (cations) that can accept or combine with protons; proton acceptors; bases take up hydrogen ions in measurable amounts; bitter taste
- **buffer** – buffers prevent the pH of a solution from changing drastically
- **pH** – the potential of hydrogen ion concentration

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2.5.1: Review Questions

Review Questions

1. **What properties of water make it essential for life?**
2. **What are acids and bases?**
3. **Define a buffer.**

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2.5.2: Chapter Quiz

Chapter Quiz

1. _____ is the most abundant and important inorganic compound on earth.

1. Salt
2. Water
3. Bicarbonate
4. Oxygen

2. A(n) _____ can be defined as a substance that dissociates into one or more hydrogen ions (H+) and one or more negative ions (anions) an acid is also called a proton donor (H+).

1. base
2. buffer
3. acid
4. salt

3. _____ are added to solutions or to the natural environment to prevent changes in pH.

1. Base
2. Buffer
3. Acid
4. Salt

4. _____ have a bitter taste, feel slippery, and are proton acceptors. They take up hydrogen ions in measurable amounts.

1. Bases
2. Buffers
3. Acids
4. Salts

5. When acids and bases are mixed, they react with each other in displacement reactions to form water and a(n) _____.

1. base
2. buffer
3. acid
4. salt

6. Nutrients are decomposed by adding _____ to each chemical bond that is broken.

1. a salt
2. water
3. bicarbonate
4. oxygen

7. _____ system that helps to maintain the pH in aqueous solutions is the carbonic acid-bicarbonate system.

1. A base
2. A buffer
3. An acid
4. A salt

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2.6: Basic Microbiology Principles

Learning Objectives

After reading this section, you should be able to:

- Describe the nomenclature and classification that is used for microorganisms
- Evaluate the factors that affect growth of microorganisms
- Describe the structure of microorganisms

In a simpler time when scientists began to classify all living things visible to the naked eye, there were only two categories or so called “Kingdoms” to consider for living things. You were either a plant or an animal. Botanist and physician Carolus Linnaeus was responsible for initial significant developments in the science of classifying living things with his publication *Systema Naturae*, in 1735. During that era, new discoveries were being made through observations in microscopes and what appeared to be very small living things. These small living things are referred to as **microorganisms**, or microbes for short. You can imagine how complex the classification of life forms was about to become. Of course, today we now know just how ubiquitous microbes are. They are found in all of nature; on land, soil and water including oceans and lakes. They include bacteria, algae, yeasts, molds, mushrooms, and other fungi. The human body alone contains millions of microorganisms.

Currently, almost 2 million organisms have been identified so far, and the estimate is that 10-100 million total organisms occupy the earth. All cellular organisms evolved from a common ancestor.

Naturally occurring microbes play an important role in many processes necessary to sustain life on our planet. Microbes are used in food preparation, pharmaceuticals, food supplements and even to safely reduce pollutants in the environment.



Figure Figure **2.6.1**. Beer (Image by Engin_Akyurt on Pixabay)



Figure Figure **2.6.2** White Vinegar (Image by Willis Lam is licensed under CC BY-SA 2.0)



Figure Figure **2.6.3** Yogurt (Image by Jin Zan is licensed under CC BY-SA)

A minority of microorganisms are **pathogenic** or disease-producing.



Pin It! Misconception Alert
People frequently think all microorganisms are pathogenic. But only a few are actually pathogenic or disease-producing!

Classifying Microbes

The process of classifying all living things is called Taxonomy. The Meriam Webster dictionary defines taxonomy as:

The study of the general principles of orderly scientific classification of plants and animals according to their presumed natural relationships.

Carolus Linnaeus introduced a binomial nomenclature system, where each species is given a unique two-part Latin name; a genus and species. For example, a domestic dog would have the scientific name Canis lupus familiaris. Genus: Canis, Species: lupus. A wolf is also from the Genus: Canis. Linnaeus' work laid the foundation for the modern system of naming and categorizing living organisms. All living things can be identified and classified based on their evolutionary relationships. The hierarchy, from broader to more specific levels, is shown in the figure below.

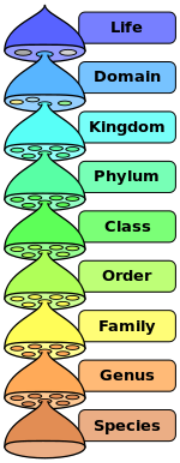


Figure **2.6.4**: Hierarchal system of scientific nomenclature for classification of living organisms. (Copyright; Image by Pengo is in the public domain)

Kingdoms

In 1969, a five-kingdom scheme proposed by biologist Robert Whittaker gained attention and it serves as the basis for current classification systems. Whittaker organized living organisms into five kingdoms based on their cellular organization, nutritional patterns, and other characteristics:

1. Kingdom Prokaryote, which includes all bacteria.
2. Kingdom Protista (unicellular eukaryotes) are algae and protozoa, and they are nutritionally diverse: autotrophs, heterotrophs, and intracellular parasite.
3. Kingdom Fungi are yeasts, molds, and mushrooms that absorb organic material through their plasma membrane.
4. Kingdom Animalia are multicellular animals that ingest organic food through a mouth and have cells organized into tissues.
5. Kingdom Plantae are multicellular plants that undergo photosynthesis to convert carbon dioxide and water into organic molecules. This Kingdom has cells that are organized into tissues.

Domains

The most popular scheme found in textbooks today is one which basically classifies life forms based on whether it is a bacteria or not a bacteria. That's pretty much it. So, what is so special about bacteria? Well, when you study tiny microbes with taxonomy in mind, you are looking at similarities in appearance of cells and how they will react with dyes and stains, and also cell chemistry.

Definition: Term

The Oxford dictionary defines a microscopic cell as:

- The smallest structural and functional unit of a living organism.
- That cell contains all the structure like the cell nucleus and information necessary for energy capture, growth, and reproduction.
- But bacteria do not have a distinct cell nucleus. All other life forms do have a distinct nucleus.

Biologists refer to cells without a distinct nucleus as **prokaryotes** and cells with a distinct nucleus as **eukaryotes**. Another way to classify if a life form is a bacteria or not can be described as either being a prokaryote (bacteria) or eukaryote (everything else). It should be noted that bacteria represent the oldest life forms on our planet. They have a simple cell structure with an average size of 1 to 2 micrometers. Biologists have identified ancient types of bacteria which have some differences from other bacteria. So much so, that the classification system of bacteria or not bacteria is officially comprised of three domains which you will find in most microbiology textbooks. We call this the Three Domain System.

- Domain Eubacteria
- Domain Archaea
- Domain Eukarya.

The Domain, Archaea is where you will find the ancient bacteria. Fungi, Plantae, and Animalia Kingdoms are all included in the Domain Eukarya. Most scientists will refer to Eubacteria and Archaea as bacteria, and not make a distinction. So, think of Eubacteria and Archaea simply as bacteria (prokaryotes).

Eukaryotes have a complex cell structure and are much larger than prokaryotes on average by several thousand in terms of volume.

Bacteria may be further differentiated by their morphology. They are classified into five groups based on their basic cell shapes. These shapes include spherical (cocci), spiral (spirilla), rod (bacilli), comma (vibrios), or corkscrew (spirochaetes). These cells can exist as single cells, in pairs, chains, or in clusters.

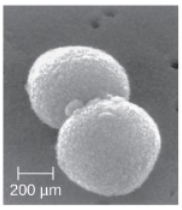
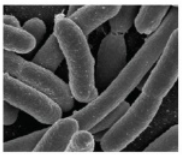
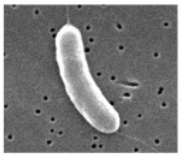
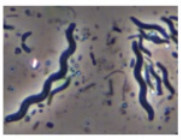
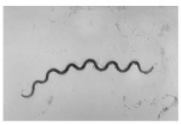
Common Prokaryotic Cell Shapes			
Name	**Description**	**Illustration**	**Image**
Coccus (pl. cocci)	Round		
Bacillus (pl. bacilli)	Rod		
Vibrio (pl. vibrios)	Curved rod		
Coccobacillus (pl. coccobacilli)	Short rod		
Spirillum (pl. spirilla)	Spiral		
Spirochete (pl. spirochetes)	Long, loose, helical spiral		

Figure **2.6.5**: Basic Shapes of Bacteria. (Copyright; Image by OpenStax is licensed under CC BY 4.0.)

Another method used to classify bacteria based on their cell wall structure and composition is the Gram stain method. It was developed in 1884 by Hans Christian Gram and remains a hallmark technique used by microbiologists. Bacteria are classified into two groups, either **Gram positive** (purple) or **Gram negative** (red or pink).

Structure

Prokaryotes–Structure/Function

Prokaryotes are distinguished from eukaryotes by their smaller size (0.2- 10µm), their lack of internal organelles (mitochondria), the presence of a cell wall, and their cell division by binary fission rather than mitosis. They lack introns, are not capable of endo/exocytosis, and have single-stranded circular DNA rather than multiple discrete chromosomes.

Gram positive bacteria have a large peptidoglycan structure. This structure accounts for the differential staining with Gram stain. Some Gram positive bacteria are also capable of forming spores under stressful environmental conditions such as when there is limited availability of carbon and nitrogen. Spores therefore allow bacteria to survive exposure to extreme conditions.

Gram negative bacteria have a small peptidoglycan layer but have an additional membrane, the outer cytoplasmic membrane. This membrane creates an additional permeability barrier and results in the need for transport mechanisms across it. A major component of the cytoplasmic membrane that is unique to Gram negatives is endotoxin.

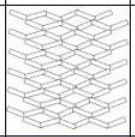
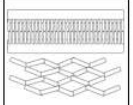
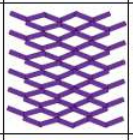
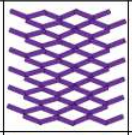
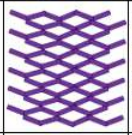
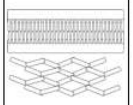
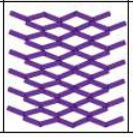
Gram Staining Procedure		Gram Positive Cell Wall		Gram Negative Cell Wall	
Process of test	Appearance of Cells	Effect of Step	Effect on Cell Wall	Effect of Step	Effect on Cell Wall
Step 1: Begin with heat fixed cells		**Step 1:** Cell wall remains clear.		**Step 1:** Cell wall remains clear.	
Step 2: Flood slide with crystal violet dye for 1 min.		**Step 2:** Peptidoglycan cell wall is flooded with crystal violet and appears purple.		**Step 2:** Cell wall is stained purple from the crystal violet dye.	
Step 3: Add iodine solution for 1 min.		**Step 3:** A crystal violet – iodine complex is formed within the peptidoglycan cell wall trapping the purple stain.		**Step 3:** A crystal violet-iodine complex is formed but does not adhere to the cell wall due to the thin layer of peptidoglycan.	
Step 4: Wash slide with alcohol for 20sec.		**Step 4:** The crystal violet – iodine complex is trapped with the peptidoglycan cell wall and doesn't wash out.		**Step 4:** The crystal violet – iodine structure is washed out of the thin peptidoglycan layer.	
Step 5: Counter stain with safranin.		**Step 5:** As the peptidoglycan cell wall remains stained purple the red safranin has no effect.		**Step 5:** The red safranin stains the washed gram negative cells.	

Figure **2.6.6**: Gram staining of bacterial cell for identification. (Image by Michigan State University. Microbiology 301-702 Summer 2016 is licensed under CC BY-SA 4.0)

Microorganism Identification

The classification is based on morphological characteristics that refer to size, shape, cellular characteristics (capsule, flagella, endospores), differential staining (Gram stain, Acid fast stain), and biochemical tests that probe for specific enzyme activities that lead to carbohydrate fermentation, nitrogen fixation, sulfur oxidation, gas production, acid production, and nitrate reduction.

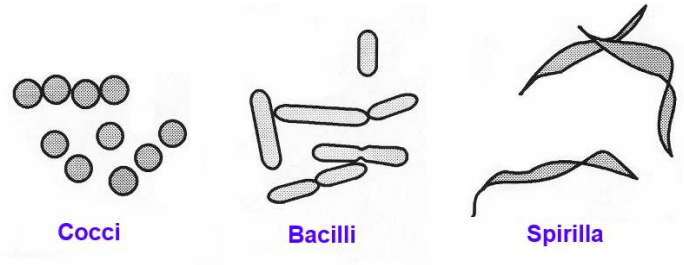


Figure **2.6.7**: lassification of bacteria by shape and environmental appearance. (Image by CKRobinson is licensed under CC BY-SA 4.0)

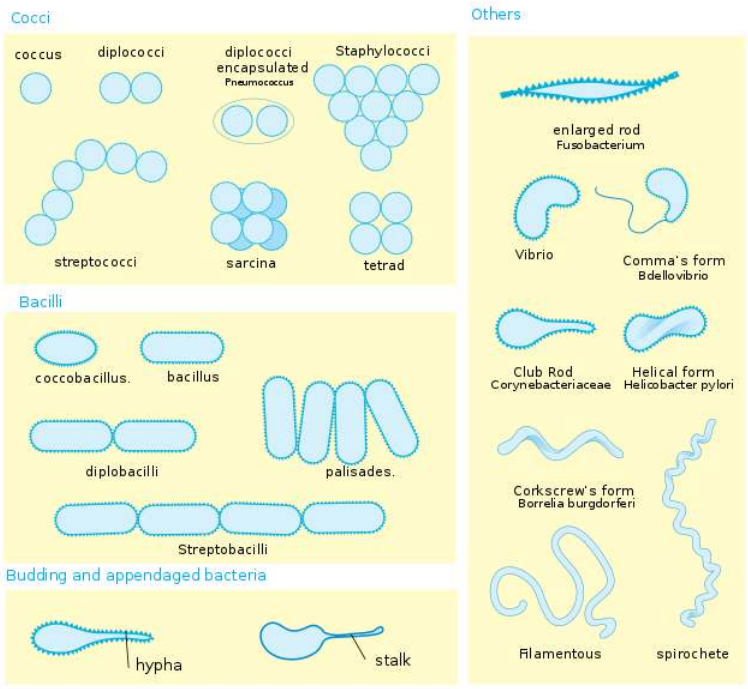


Figure **2.6.8**: Morphology of bacterial cells (Image by LadyofHats is in the public domain)

Growth of Microorganisms

All microorganisms require energy to grow. They obtain their energy primarily from chemical reactions or the sun utilizing photosynthesis. They use the energy to help produce nutrients to help them grow. Almost half of a bacteria's dry weight is carbon. They need it to grow and can access it from the environment, or from carbon dioxide.

Microbe requirements can include nitrogen, phosphorous and sulfur. Water is a requirement for almost all microbes. Most microorganisms require oxygen, but there are some which thrive in a zero oxygen environment. Other microbes also utilize the so-called trace elements of zinc, copper, and iron to grow. Iron bacteria, which is a common nuisance in groundwater wells, is a good example.

Microorganisms can grow in cold temperatures as low as 0 , or at temperatures higher than 40 ,. But most prefer temperatures between 20 , to 40 ,. Different species have typically their own optimal temperature that will produce a maximum growth rate.

The pH is also very important. For bacteria, the range is between 6.5 to 7.5. Some bacteria used in food processing prefer a pH less than 6 (an acidic environment).

Another growth factor involves the osmotic pressure in a microorganism and is largely influenced by the salt concentration in its surroundings. If the salt concentration is less than 1%, microbes will grow well. If the salt concentration rises, the microbe is likely to die as water will flow out of the cell. As you can probably surmise, one way to control the growth of microorganisms is to create an environment which keeps them out of their optimal chemical and physical ranges to grow and thrive.

Phylogenetic Tree of Life for Microbes

A universal Phylogenetic Tree has been developed for living organisms that establishes a tripartite division of all living organisms– bacteria, archaea, and eukarya. The classification is based on a comparison of 16s ribosomal RNA sequences. These sequences are highly conserved and undergo change at a slow, gradual, and consistent rate. They are therefore useful for making comparisons among different living organisms.

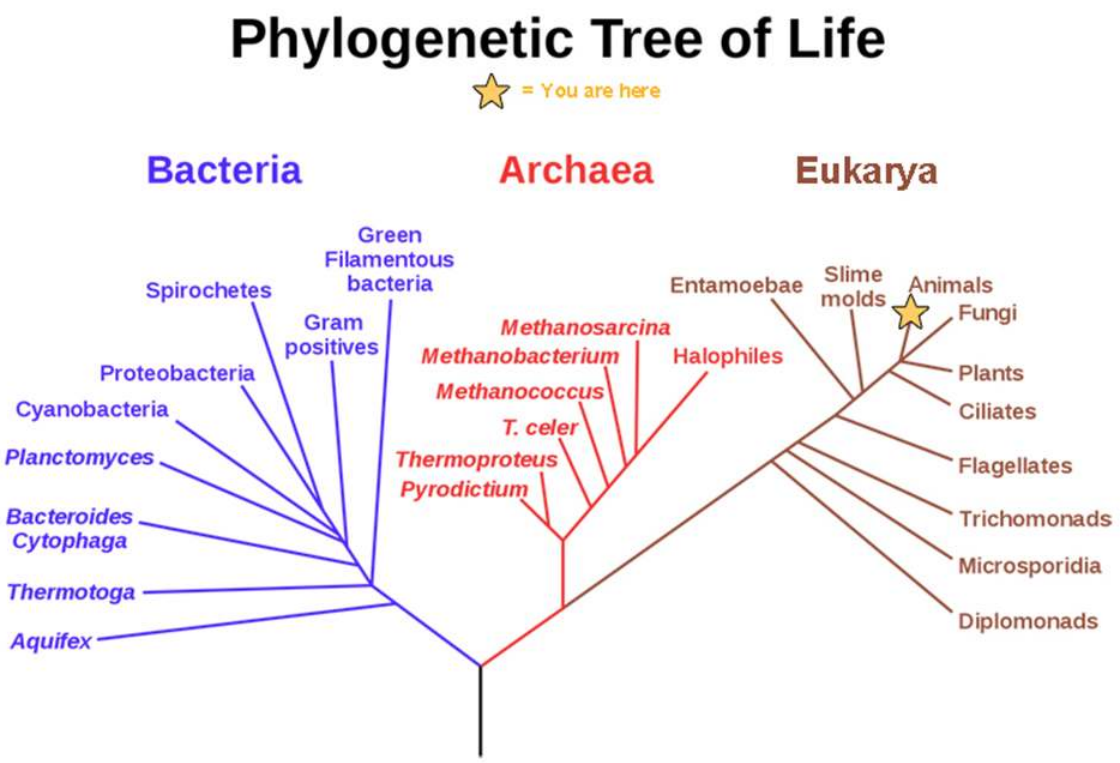


Figure **2.6.1**: Phylogenetic Tree for microorganisms (Copyright; Image by OpenStax is licensed under CC BY 4.0)

Taxonomic/Phylogenetic Hierarchy groups are based on similarities. The groups begin very general and become more restricted. DNA hybridization and rRNA sequencing are used to determine evolutionary relationships and classification. Organisms that are grouped together are based on relatedness; very general relatedness at the top, followed by more and more specific and restricted subgroups where genus is all related species, and species is a single unique organism group.

Prokaryotic Classification-prokaryotes have two domains:

1. Eubacteria are all pathogenic prokaryotes, many non-pathogenic prokaryotes, and all photoautotrophic prokaryotes. They include the oldest and smallest living organisms ever discovered which date back 3.5 million years.
2. Archaea are all prokaryotes with walls that are not peptidoglycan, that carryout unusual metabolism and live in extreme environments, and are groupings based entirely on gene sequencing since most look similar. Archaea are associated with extreme environments.

Viral Classification

Viruses do not fit into a domain system because they are acellular. They are usually only classified by Family and Genus. Viral species are defined as a population of viruses with similar characteristics (including morphology, genes, and enzymes) that occupy a particular ecological niche.

In early 2020, one virus that became very well-known was coronavirus-19, which swept the world as a pandemic. This virus was a type of coronavirus that was extremely contagious and had a wide range of symptoms. It is currently not well understood

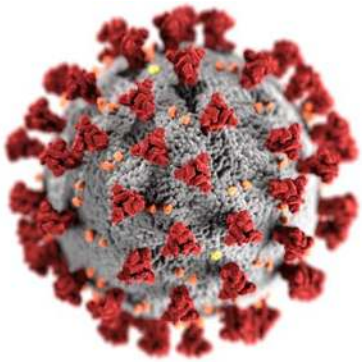


Figure **2.6.1**: Corona Virus(Copyright; Image by OpenStax is licensed under CC BY 4.0)

Key Terms

- **algae** – diverse group of photosynthetic eukaryotic protists[1]
- **Archaea** – prokaryotes that are found in extreme environments; non-disease causing
- **Bacteria (prokaryotes)** – the domain that includes the pathogenic prokaryotes as well as many of the nonpathogenic prokaryotes found in soil and water; simple single-celled organisms
- **Eukarya (eukaryotes)** – the domain that includes animals, plants, and fungi
- **fungi** – eukaryotes with cells which contain a distinct membrane bound nucleus, mitochondria, and a complex system of internal membranes[2]
- **gram negative** – bacteria with a small peptidoglycan structure and additional membranes that creates additional permeability barriers and results in the need for transport mechanisms across it
- **gram positive** – bacteria with a large peptidoglycan structure and causes differential staining with Gram staining
- **pathogenic** – disease-causing
- **peptidoglycan** - a building block of cell walls of bacteria
- **Prokarya (prokaryotes)** – distinguished from eukaryotes by their smaller size (0.2- 10µm), their lack of internal organelles (mitochondria), the presence of a cell wall, and their cell division by binary fission rather than mitosis
- **protozoa** – unicellular eukaryotic protists which have the ability to move with some sort of cilia or flagella and must obtain their energy from other sources[3]
- **scientific nomenclature** – a binomial nomenclature so that every organism has a unique binomial identification that indicates the individual and its taxonomic placement among other organisms
- **taxonomy** – the science of classification.
- **viruses** – microorganisms so small that most can be seen only with an electron microscope; acellular; reproduction occurs using cellular machinery of other organisms

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2.6.1: Review Questions

Review Questions

1. **Name the two major types of cells found in nature.**
2. **List and describe the five types of microorganisms.**
3. **List the classifications in descending order for the hierarchal system of scientific nomenclature for the classification of living organisms.**
4. **Distinguish the features between gram positive and gram negative bacteria.**

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2.6.2: Chapter Quiz

Chapter Quiz

1. Microorganisms that are disease-producing are _____.

1. pathogenic
2. Streptococcus
3. Staphylococcus
4. gram negative

2. Bacteria and archaea are referred to as _____ cells.

1. eukaryotic
2. prokaryotic
3. gram negative
4. gram positive

3. Cells with cell walls that lack peptidoglycan are _____.

1. bacteria
2. algae
3. protozoans
4. archaea

4. _____ are eukaryotes. They are organisms whose cells have a distinct nucleus containing the cell's genetic material, surrounded by a special envelope called a nuclear membrane.

1. Archaea
2. Bacteria
3. Viruses
4. Fungi

5. _____ bacteria have a large peptidoglycan structure.

1. Streptococcus
2. Staphylococcus
3. Gram negative
4. Gram positive

6. Most bacteria grow best in a narrow pH range near neutrality, between _____.

1. 2.0 to 6.5
2. 6.5 to 7.5
3. 8.0 to 10.0
4. 11.0 to 14.0

7. _____ is a binomial nomenclature so that every organism has a unique binomial identification that indicates the individual and its taxonomic placement among other organisms.

1. Taxonomy
2. Scientific nomenclature
3. DNA hybridization
4. Genus species

8. _____ is the science of classification.

1. Taxonomy
2. Scientific nomenclature
3. DNA hybridization

4. Genus species

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2.7: Microbiology Regulations

Learning Objectives

After reading this section, you should be able to:

- Explain the Total Coliform Rule
- Compare the Groundwater Treatment Rule and Surface Water Treatment Rule
- Describe the concern with Cryptosporidium

Total Coliform Rule

The Total Coliform Rule (TCR), a National Primary Drinking Water Regulation (NPDWR), was published in 1989 and became effective in 1990. The rule sets a health goal (Maximum Contaminant Level Goal (MCLG)) and legal limits (Maximum Contaminant Levels, MCLs)) for the presence of total coliforms in drinking water.

The Environmental Protection Agency (EPA) published the Revised Total Coliform Rule (RTCR) in the Federal Register (FR) in February 2013 (78 FR 10269) and minor corrections in February 2014 (79 FR 10665). The RTCR is the revision to the 1989 Total Coliform Rule (TCR) and is intended to improve public health protection. All public water systems (PWSs), except aircraft PWSs subject to the Aircraft Drinking Water Rule (ADWR) (40 CFR 141 Subpart X), must comply with the RTCR starting April 2016, or an earlier state effective date.

Total coliforms are a group of related bacteria that are, with few exceptions, not harmful to humans. This is very important to note. The EPA considers total coliforms a useful indicator of other pathogens for drinking water. Total coliforms are used to determine the adequacy of water treatment and the integrity of the distribution system.

Key provisions of the RTCR include:

1. Setting a maximum contaminant level goal (MCLG) and maximum contaminant level (MCL) for E. coli for protection against potential fecal contamination.
2. Setting a total coliform treatment technique (TT) requirement.
3. Requirements for monitoring total coliforms and E. coli according to a sample siting plan and schedule specific to the PWS.
4. Provisions allowing PWSs to transition to the RTCR using their existing Total Coliform Rule(TCR) monitoring frequency, including PWSs on reduced monitoring under the existing TCR.
5. Requirements for seasonal systems (such as, Non-Community Water Systems not operated on a year-round basis) to monitor and certify the completion of a state-approved start-up procedure.
6. Requirements for assessments and corrective action when monitoring results show that PWSs may be vulnerable to contamination.
7. Public notification (PN) requirements for violations.
8. Specific language for CWSs to include in their Consumer Confidence Reports (CCRs) when they must conduct an assessment or if they incur an E. coli MCL violation.

Revised Total Coliform Rule

Overview of the Rule

Revised Total Coliform Rule (RTCR) 78 FR 10269, February 2013, Vol. 78, No. 30

Purpose: Increase public health protection through the reduction of potential pathways of entry for fecal contamination into distribution systems.

General Description

The rule establishes a maximum contaminant level (MCL) for E. coli and uses E. coli and total coliforms to initiate a find and fix approach to address fecal contamination that could enter into the distribution system. It requires public water systems (PWSs) to perform assessments to identify sanitary defects and subsequently take action to correct them.

The Total Coliform Rule applies to all Public Water Systems.

Implementation of the Total Coliform Rule will result in:

1. A decrease in the pathways by which fecal contamination can enter the drinking water distribution system.
2. Reduction in fecal contamination should reduce the potential risk from all waterborne pathogens including bacteria, viruses, parasitic protozoa, and their associated illnesses.

Requirements:

1. Public Water Systems must develop a written sample siting plan that identifies the system's sample collection schedule and all sample sites, including sites for routine and repeat monitoring.
2. PWSs monitoring quarterly or annually must also identify additional routine monitoring sites in their sample siting plans.
3. Sample siting plans are subject to state review and revision.

Routine Sampling Requirements

1. Total coliform samples must be collected by Public Water Systems at sites which are representative of water quality throughout the distribution system according to a written sample siting plan subject to state review and revision.
2. For Public Water Systems collecting more than one sample per month, collect total coliform samples at regular intervals throughout the month, except that ground water systems serving 4,900 or fewer people may collect all required samples on a single day if the samples are taken from different sites.

Repeat Sampling Requirements

Within 24 hours of learning of a Total Coliform positive routine sample result, at least 3 repeat samples must be collected and analyzed for total coliform:

1. One repeat sample must be collected from the same tap as the original sample.
2. One repeat sample must be collected from within five service connections upstream.
3. One repeat sample must be collected from within five service connections downstream.
4. The PWS may propose alternative repeat monitoring locations that are expected to better represent pathways of contamination into the distribution system.

If one or more repeat sample is Total Coliform Positive:

1. The TC+ sample must be analyzed for the presence of E. coli.
2. If any repeat TC+ sample is also EC+, then the EC+ sample result must be reported to the state by the end of the day that the PWS is notified.
3. The PWS must collect another set of repeat samples, unless an assessment has been triggered and the PWS has notified the state.

Routine Sampling Requirements

1. Each total coliform-positive (TC+) routine sample must be tested for the presence of E. coli.
2. If any coliform-positive (TC+) sample is also E. coli-positive (EC+), then the EC+ sample result must be reported to the state by the end of the day that the PWS is notified.
3. If any routine sample is TC+, repeat samples are required.
4. Public Water Systems on quarterly or annual monitoring must take a minimum of three additional routine samples (known as additional routine monitoring) the month following a TC+ routine or repeat sample.
5. Reduced monitoring may be available for Public Water Systems using only ground water and serving 1,000 or fewer persons that meet certain additional Public Water System criteria.

Assessments and Corrective Action

The RTCR requires PWSs that have an indication of coliform contamination (e.g., as a result of TC+ samples, E. coli MCL violations, performance failure) to assess the problem and take corrective action. Two levels of assessments exist (i.e., Level 1 and Level 2) based on the severity or frequency of the problem.

Purpose of Level 1 and Level 2 Assessments

To find sanitary defects at the Public Water System including:

1. Sanitary defects that could provide a pathway of entry for microbial contamination
2. Sanitary defects that indicate failure (existing or potential) of protective barriers against microbial contamination.

Deadline for Completing Corrective Actions

When sanitary defects are identified during a Level 1 or Level 2 Assessment, they should be corrected as soon as possible to protect public health. The Public Water System must complete corrective actions by one of the following timeframes:

1. No later than the time the assessment form is submitted to the state, which must be within 30 days of triggering the assessment, or
2. Within state-approved timeframe which was proposed in the assessment form.

Level 1 Assessments

Conducting Level 1 Assessments

1. Performed by the PWS owner or operator each time a Level 1 Assessment is triggered.
2. Upon trigger of a Level 1 Assessment, the Level 1 Assessment form must be submitted within 30 days to the state.

Level 1 Assessment Triggers

Level 1 Assessment is triggered if any one of the following occurs:

1. A Public Water System collecting fewer than 40 samples per month has 2 or more TC+ routine/ repeat samples in the same month.
2. A PWS collecting at least 40 samples per month has greater than 5.0 percent of the routine/repeat samples in the same month that are TC+.
3. A PWS fails to take every required repeat sample after any single TC+ sample.

Level 2 Assessments

Conducting Level 2 Assessments

Performed by the state or state-approved entity each time a Level 2 Assessment is triggered.

1. The Public Water System is responsible for ensuring that the Level 2 Assessment is conducted regardless of the entity conducting the Level 2 Assessment.
2. (3)Upon trigger of a Level 2 Assessment, the Level 2 Assessment form must be submitted within 30 days to the state.

Level 2 Assessment Triggers

Level 2 Assessment is triggered if any one of the following occurs:

1. A Public Water System incurs an E. coli MCL violation.
2. A Public Water System has a second Level 1 Assessment within a rolling 12-month period.
3. A Public Water System on state-approved annual monitoring has a Level 1 Assessment trigger in 2 consecutive years.

Seasonal System Provisions

The Total Coliform Rule defines seasonal systems and specifies additional requirements for these types of PWSs:

1. A seasonal system is defined as a non-community water system that is not operated as a PWS on a year round basis and starts up and shuts down at the beginning and end of each operating season.

Start-up Procedures for Seasonal Systems

At the beginning of each operating period, before serving water to the public, seasonal water systems must:

1. Conduct state-approved start-up procedures.
2. Certify completion of state-approved start-up procedures.

3. An exemption from conducting state-approved start-up procedures may be available for seasonal systems that maintain pressure throughout the distribution system during non-operating periods.

Examples of state-approved start-up procedures, which need to be completed prior to serving water to the public, may include one or more of the following:

1. Disinfection.
2. Distribution system flushing.
3. Sampling for total coliform and E. coli.
4. Site visit by state.
5. Verification that any current or historical sanitary defects have been corrected.

Routine Monitoring for Seasonal Systems

1. The baseline monitoring frequency for seasonal systems is monthly.
2. A reduced monitoring frequency may be available for seasonal systems that use ground water only and serve fewer than 1,000 persons.

Other Provisions for the State Drinking Water Agency Special Monitoring Evaluation

The state must perform a special monitoring evaluation at all ground water systems serving 1,000 or fewer persons during each sanitary survey to review the status of the Public Water System and to determine whether the sample sites and monitoring schedule need to be modified.

Major Violations

E. coli MCL Violation

A Public Water System will receive an E. coli MCL violation when there is any combination of an E.coli positive sample result with a routine/repeat Total Coliform positive or E. coli positive sample result:

E. coli MCL Violation Occurs with the Following Sample Result Combination

Routine Repeat

- EC+ TC+
- EC+ Any missing sample
- EC+ EC+
- TC+ EC+
- TC+ TC+ (but no E. coli analysis)

Treatment Technique Violation

A PWS will receive a Treatment Technique violation when any of the following occur:

1. Failure to conduct a Level 1 or Level 2 Assessment within 30 days of a trigger.
2. Failure to correct all sanitary defects from a Level 1 or Level 2 Assessment within 30 days of a trigger or in accordance with the state-approved timeframe.
3. Failure of a seasonal system to complete state-approved start-up procedures prior to serving water to the public.

Key Points for Public Water Systems to Remember

Find and correct sanitary defects as soon as you become aware of them. This can help reduce E. coli MCL violations, which trigger a Level 2 Assessment. This can help reduce TC+ sample results, which may trigger a Level 1 Assessment.

Make sure to collect all routine and repeat samples as required. Timely and correct monitoring can help reduce triggering a Level 1 or Level 2 Assessment because:

1. Failure to conduct repeat monitoring triggers a Level 1 Assessment.
2. A Level 1 Assessment triggered twice within a certain timeframe triggers a Level 2 Assessment.

Ground Water Treatment Rule

EPA issued the **Ground Water Rule (GWR)** to improve drinking water quality and provide protection from disease-causing microorganisms. Water systems that have groundwater sources may be susceptible to fecal contamination. In many cases, fecal contamination can contain disease-causing pathogens.

The purpose of the Ground Water Rule (GWR) is to reduce disease incidence associated with harmful microorganisms in drinking water.

The Ground Water Rule applies to public water systems that use ground water as a source of drinking water. The rule also applies to any system that delivers surface and ground water to consumers where the ground water is added to the distribution system without treatment. The Ground Water Rule was published in the Federal Register in November 2006.

Overview of the Rule

Ground Water Rule (GWR)

71 FR 65574, November 2006, Vol. 71, No. 216

Correction 71 FR 67427, November 2006, Vol. 71, No. 224

Purpose

The rule should reduce the risk of illness caused by microbial contamination in public ground water systems (GWSs).

General Description

The Groundwater Rule establishes a risk-targeted approach to identify groundwater systems susceptible to fecal contamination, and the rule requires corrective action to correct significant deficiencies and source water fecal contamination in all public groundwater systems.

Utilities Covered

The Ground Water Rule applies to all public water systems that use groundwater, including consecutive systems, except that it does not apply to public water systems that combine their groundwater with surface water or with groundwater under the direct influence of surface water prior to treatment.

Public Health Benefits

Targeted protection for over 70 million people served by groundwater sources that are not disinfected or receive less than 4-log treatment or reduction in 99.99% harmful microorganisms. Implementation created an avoidance of 42,000 viral illnesses and 1 related death annually.

Requirements for Drinking Water Systems

New groundwater sources must meet triggered source water monitoring requirements or conduct compliance monitoring. Groundwater systems must conduct triggered source water monitoring if the system does not provide at least 4-log virus inactivation, removal, or a state-approved combination of these technologies before or at the first customer and the system is notified that a sample collected for the Total Coliform Rule (TCR) is total coliform-positive.

Groundwater systems identified as a significant deficiency and systems that have had at least one of the five additional groundwater source samples that has tested positive for fecal contamination must comply with the treatment technique requirements.

Analytical Methods for Source Water Monitoring

Fecal Indicator Methodology Method

EPA Method 1604

1. E. coli Colilert
2. Colisure
3. Membrane Filter Method with MI Agar

4. m-ColiBlue24 Test
5. E*Colite Test
6. EC-MUG
7. NA-MUG
8. 9223 B
9. 9223 B
10. 9221 F
11. 9222 G
12. Enterococci Multiple-Tube Technique
13. Membrane Filter Technique
14. Enterolert
15. 9230 B
16. 9230 C
17. EPA Method 1600.
18. Coliphage Two-Step, Enrichment, Presence-Absence Procedure
19. Single Agar Layer Procedure
20. EPA Method 1601
21. EPA Method 1602

Major Provisions of Rule

1. Compliance Monitoring
2. Treatment
3. Technique
4. Compliance
5. Monitoring

In order not to be subject to triggered source water monitoring, a groundwater system can notify the state that it provides at least 4-log treatment of viruses using virus inactivation, removal, or a state-approved combination of 4-log virus inactivation and removal before or at the first customer. The groundwater system must then begin compliance monitoring designed to show the effectiveness of their treatment processes.

Groundwater systems that use chemical disinfection and serve more than 3,300 people must continuously monitor their disinfectant concentration. These systems must maintain the minimum disinfectant residual concentration determined by the state.

Groundwater systems that use chemical disinfection and serve 3,300 people or fewer must take daily grab samples or meet the continuous monitoring requirements described for public groundwater systems serving more than 3,300 people.

Groundwater systems using membrane filtration for 4-log treatment of viruses must monitor the membrane filtration process according to state-specified monitoring requirements.

Groundwater systems may use alternative treatment technologies (e.g., ultraviolet radiation [UV]) approved by the state. Groundwater systems must monitor the alternative treatment according to state specified monitoring requirements and must operate the alternative treatment according to compliance requirements established by the state.

Source Water Monitoring

Triggered Source Water Monitoring

Groundwater systems that do not conduct compliance monitoring and are notified of a total coliform-positive routine sample collected in compliance with the Total Coliform Rule (40 CFR 141.21) must conduct triggered source water monitoring.

Groundwater systems must collect at least one ground water source sample from each source in use at the time the total coliform-positive sample was collected. The triggered source water sample must be analyzed for the presence of a fecal indicator as specified in the rule.

If the triggered source water sample is fecal indicator-positive, the Groundwater system must either take corrective action, as directed by the state, or if corrective action is not required by the state and the sample is not invalided by the state, the Groundwater system must conduct additional source water sampling.

States may waive the triggered source water monitoring requirement if the state determines and documents, in writing, that the total coliform-positive routine sample is the result of a documented distribution system deficiency.

States may develop criteria for distribution system conditions that cause total coliform positive samples. A Groundwater system can document to the state that it met the state criteria within 30 days of the total coliform-positive sample and be exempt from collecting triggered source water sample(s).

States may invalidate a fecal indicator-positive groundwater source sample under specific conditions. If a fecal indicator-positive source sample is invalidated, the Groundwater system must collect another source water sample within 24 hours of being notified by the state of its invalidation decision.

Additional Source Water Sampling

If the state does not require corrective action in response to a fecal indicator-positive triggered source water sample, the Groundwater system must collect five additional source water samples (from the same source), using the same indicator as used in triggered source water monitoring, within 24 hours of being notified of the fecal indicator-positive sample.

Assessment Source Water Monitoring

States have the opportunity to target higher risk GWSs for additional testing. States independently can determine on a case by case basis whether monitoring is necessary and when corrective action needs to be taken.

Treatment Technique Requirements

Groundwater Systems with Significant Deficiencies or Source Water Fecal Contamination

Groundwater systems must take corrective action if a significant deficiency is identified, or if the initial source samples (if required by the state) or one of the five additional groundwater source samples tests positive for fecal contamination. The Groundwater systems must implement at least one of the following corrective actions:

1. Correct all significant deficiencies
2. Provide an alternate source of water
3. Eliminate the source of contamination
4. Provide treatment that reliably achieves at least 4-log treatment of viruses (using inactivation, removal, or a state-approved combination of 4-log virus inactivation and removal) before or at the first customer for the groundwater source.

New Sources

New Ground Water Sources

New sources which come online after November 2009 are required either to conduct triggered source water monitoring as required by the Groundwater Rule, or provide at least 4-log inactivation, removal, or a state-approved combination of these technologies and conduct compliance monitoring within 30 days of the source being put in service.

Sanitary Surveys

All Ground Water Systems

States are required to conduct sanitary surveys of all Groundwater systems in order to identify significant deficiencies, including deficiencies which may make a system susceptible to microbial contamination.

Following the initial sanitary survey, states must conduct sanitary surveys every 3 years for most Community Water Systems and every 5 years for Non-community Water Systems that provide at least 4-log treatment of viruses or have outstanding performance records, as determined by the state.

Surface Water Treatment Rule

The purpose of the **Surface Water Treatment Rules (SWTRs)** is to reduce illnesses caused by pathogens in drinking water. The disease-causing pathogens include *Legionella*, *Giardia lamblia*, and *Cryptosporidium*.

The SWTRs requires water systems to filter and disinfect surface water sources. Some water systems are allowed to use disinfection only for surface water sources that meet criteria for water quality and watershed protection. This combination of rules is designed to provide protection from microbial pathogens.

Simultaneously, the rules minimize health risks to the population from disinfection byproducts.

For PWSs that use surface water sources and are not required to filter, existing regulations do not require any treatment for Cryptosporidium. New survey data suggest that typical Cryptosporidium levels in the treated water of unfiltered PWSs are higher than in the treated water of filtered PWSs. Thus, Cryptosporidium treatment by unfiltered PWSs is needed to achieve comparable public health protection.

Further, results from recent treatment studies has allowed EPA to develop standards for the inactivation of Cryptosporidium by ozone, ultraviolet (UV) light, and chlorine dioxide. Based on these developments, the EPA has established requirements for all unfiltered PWSs to treat for Cryptosporidium, with the required degree of treatment depending on the source water contamination level. Additionally, the long-term rule addresses risks in uncovered finished water storage facilities, in which treated water can be subject to significant contamination as a result of runoff, bird and animal wastes, human activity, algal growth, insects, fish, and airborne deposition. Existing regulations prohibit the building of new uncovered finished water storage facilities. Under the long-term rule, PWSs must limit potential risks by covering or treating the discharge of such storage facilities. The requirements in the Surface Water Treatment Rule reflect consensus recommendations from the Stage 2 Microbial and Disinfection Byproducts (M–DBP) Federal Advisory Committee. These recommendations are set forth in the Stage 2 M–DBP Agreement in Principle.

Long-Term Surface Water Treatment Rule

Source Water Monitoring. The rule requires PWSs using surface water or groundwater under the direct influence (GWUDI) of surface water to monitor their source water (the influent water entering the treatment plant) to determine an average Cryptosporidium level. Monitoring results determine the extent of Cryptosporidium treatment requirements.

Large PWSs (serving at least 10,000 people) must monitor for Cryptosporidium (plus E. coli and turbidity in filtered PWSs) for a period of two years. To reduce monitoring costs, small filtered PWSs (serving fewer than 10,000 people) initially monitor just for E. coli for one year as a screening analysis and are required to monitor for Cryptosporidium only if their E. coli levels exceed specified trigger values. Small filtered PWSs that exceed the E. coli trigger, as well as all small unfiltered PWSs, must monitor for Cryptosporidium for one or two years, depending on the sampling frequency.

Under the long-term rule, specific criteria are set for sampling frequency and schedule, sampling location, using previously collected data, providing treatment instead of monitoring, sampling by PWSs that use surface water for only part of the year, and monitoring of new plants and sources. The long-term rule also establishes requirements for reporting of monitoring results, using analytical methods, and using approved laboratories. The rule also requires a second round of monitoring to begin approximately 6.5 years after the first round concludes in order to determine if source water quality has changed to a degree that should affect treatment requirements.

The long-term rule establishes risk-targeted treatment technique requirements to control *Cryptosporidium* in PWSs using surface water or GWUDI. These treatment requirements supplement those established by existing regulations. Filtered PWSs are classified in one of four treatment categories (or bins) based on the results of the source water *Cryptosporidium* monitoring. This bin classification determines the degree of additional *Cryptosporidium* treatment, if any, that filtered PWS must provide. PWSs classified in Bins 2, 3, or 4 must achieve 1.0 to 2.5-log of treatment (90 to 99.7 percent reduction) for *Cryptosporidium* over and above that provided with conventional treatment. Different additional treatment requirements may apply to PWSs using other than conventional treatment, such as direct filtration, membranes, or cartridge filters.

Filtered PWSs must meet the additional *Cryptosporidium* treatment required in Bins 2, 3, or 4 by using one or more treatment or control processes from a microbial toolbox of options. The long-term rule requires all unfiltered PWSs to provide at least 2-log (99 percent) inactivation of *Cryptosporidium*. If the average source water *Cryptosporidium* level exceeds 0.01 oocysts/L, the unfiltered PWS must provide at least 3-log (99.9 percent) inactivation of *Cryptosporidium*. Further, under the long-term rule, unfiltered PWSs

must achieve their overall inactivation requirements (including *Giardia lamblia* and virus inactivation) using a minimum of two disinfectants.

PWSs with uncovered finished water storage facilities must take steps to address contamination risks. Existing regulations require PWSs to cover all new storage facilities for finished water but do not address existing uncovered finished water storage facilities. Under the long-term rule, PWSs using uncovered finished water storage facilities must cover the storage facility or treat the storage facility discharge to achieve inactivation and/or removal of 4-log virus, 3-log *Giardia lamblia*, and 2-log *Cryptosporidium* on a state-approved schedule.

The rule applies to all PWSs using surface water or GWUDI, including large and small PWSs, community and non-community PWSs, and non-transient and transient PWSs. Wholesale PWSs must comply with the requirements of the rule based on the population of the largest PWS in the combined distribution system.

Consecutive PWSs that purchase treated water from wholesale PWSs that fully comply with the monitoring and treatment requirements of the rule are not required to take additional steps for that water.

Existing Regulations for Microbial Pathogens in Drinking Water

1. The Surface Water Treatment Rule (SWTR) (54 FR 27486, June 1989) applies to all PWSs using surface water or ground water under the direct influence (GWUDI) of surface water as sources (Subpart H PWSs). It established MCLGs of zero for *Giardia lamblia*, viruses, and *Legionella*, and includes the following treatment technique requirements to reduce exposure to pathogenic microorganisms:
    a. Filtration, unless specific avoidance criteria are met
    b. Maintenance of a disinfectant residual in the distribution system
    c. Removal and/or inactivation of 3-log (99.9%) of *Giardia lamblia* and 4-log (99.99%) of viruses
    d. Maximum allowable turbidity in the combined filter effluent (CFE) of 5 nephelometric turbidity units
    e. (NTU) and 95th percentile CFE turbidity of 0.5 NTU or less for plants using conventional treatment or direct filtration
    f. Watershed protection and source water quality requirements for unfiltered PWSs
2. The Total Coliform Rule (TCR) (54 FR 27544, June 1989) applies to all PWSs. It established an MCLG of zero for total and fecal coliform bacteria and an MCL based on the percentage of positive samples collected. Coliforms are used as an indicator of fecal contamination and to determine the integrity of the water treatment process and distribution system. Under the Total Coliform Rule, no more than 5 percent of distribution system samples collected in any month may contain coliform bacteria (no more than 1 sample per month may be coliform positive in those PWSs that collect fewer than 40 samples per month). The number of samples to be collected in a month is based on the number of people served by the PWS.
3. Interim Enhanced Surface Water Treatment Rule (63 FR 69478, December 16, 1998) (USEPA 1998a) applies to PWSs serving at least 10,000 people and using surface water or GWUDI sources. Key provisions established by the interim rule include the following:
    a. An MCLG of zero for *Cryptosporidium*
    b. *Cryptosporidium* removal requirements of 2-log (99 percent) for PWSs that filter
    c. More stringent turbidity performance standards of 1.0 NTU as a maximum and 0.3 NTU or less at the 95th percentile monthly for treatment plants using conventional treatment or direct filtration
    d. Requirements for individual filter turbidity monitoring
    e. Disinfection benchmark provisions to assess the level of microbial protection that PWSs provide as they take steps to comply with new disinfection by-products standards
    f. Inclusion of Cryptosporidium in the definition of GWUDI and in the watershed control requirements for unfiltered PWSs
    g. Requirements for covers on new finished water storage facilities
    h. Sanitary surveysfor all surface water systems regardless of size

The interim surface water treatment rule was developed in conjunction with the Stage 1 Disinfectants and Disinfection Byproducts Rule (Stage 1 DBPR) (63 FR 69389, December 1998), which reduced allowable levels of certain DBPs, including trihalomethanes, haloacetic acids, chlorite, and bromate.

4. Long Term 1 Enhanced Surface Water Treatment Rule (67 FR 1812, January 2002) builds on the microbial control provisions established by the interim rule for large PWSs through extending similar requirements to small PWSs. The long-term interim rule applies to PWSs that use surface water or GWUDI as sources and that serve fewer than 10,000 people. Like the interim rule, the long-term rule established the following:
    a. 2- log (99 percent) *Cryptosporidium* removal requirements by PWSs that filter
    b. Individual filter turbidity monitoring and more stringent combined filter effluent turbidity standards for conventional and direct filtration plants
    c. Disinfection profiling and benchmarking; inclusion of *Cryptosporidium* in the definition of GWUDI and in the watershed control requirements for unfiltered PWSs
    d. The requirement that new finished water storage facilities be covered.
5. Filter Backwash Recycle Rule (66 FR 31085, June 2001) requires PWSs to consider the potential risks associated with recycling contaminants removed during the filtration process. The provisions of the filter backwash rule apply to all PWSs that recycle, regardless of population served. In general, the provisions include the following:
    a. PWSs must return certain recycle streams to a point in the treatment process that is prior to primary coagulant addition unless the State specifies an alternative location
    b. Direct filtration PWSs recycling to the treatment process must provide detailed recycle treatment information to the State
    c. Certain conventional PWSs that practice direct recycling must perform a one-month, one-time recycling self-assessment

Introduction to Cryptosporidium

Concern with Cryptosporidium in Drinking Water

EPA is promulgating the Long-Term Surface Water Treatment Rule to reduce the public health risk associated with *Cryptosporidium* in drinking water.

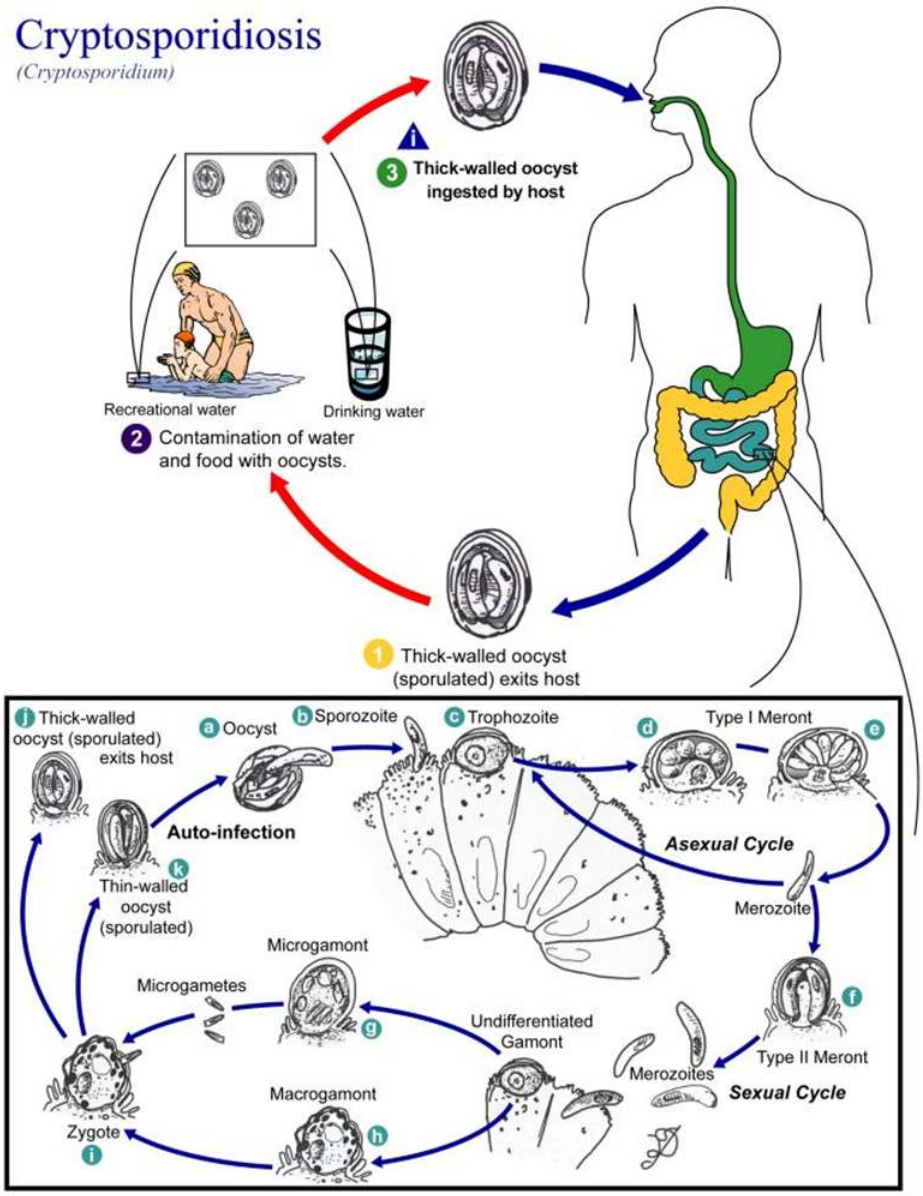


Figure **2.7.1**: Cryptosporidiosis.(Copyright: Image by the CDC is in the public domain)

Cryptosporidium is a protozoan parasite that lives and reproduces entirely in one host. Ingestion of *Cryptosporidium* can cause cryptosporidiosis, a gastrointestinal (GI) illness. Cryptosporidium is excreted in feces. Transmission of cryptosporidiosis occurs through consumption of water or food contaminated with feces or by direct or indirect contact with infected persons or animals. In the environment, Cryptosporidium is present as a thick-walled oocyst containing four organisms (sporozoites).

The oocyst wall insulates the sporozoites from harsh environmental conditions. Oocysts are 4–5 microns in length and width. Upon a host's ingestion of oocysts, enzymes and chemicals produced by the host's digestive system cause the oocyst to excyst, or break open. The excysted sporozoites embed themselves in the surfaces of the epithelial cells of the lower small intestine. The organisms then begin absorbing nutrients from their host cells. When these organisms sexually reproduce, they produce thick and thin-walled oocysts. The host excretes the thick-walled oocysts in its feces. The thin-walled oocysts excyst within the host and contribute to further host infection.

The exact mechanism by which *Cryptosporidium* causes GI illness is not known. Factors may include damage to intestinal structure and cells, changes in the absorption/secretion processes of the intestine, toxins produced by *Cryptosporidium* or the host, and proteins that allow *Cryptosporidium* to adhere to host cell surfaces. Upon excretion, *Cryptosporidium* oocysts may survive for

months in various environmental media, including soil, river water, seawater, and human and cattle feces at ambient temperatures. *Cryptosporidium* can also withstand temperatures as low as 20 °C for periods of a few hours, but they are susceptible to desiccation.

Cryptosporidium is a widespread contaminant in surface water used as drinking water supplies. *Cryptosporidium* contamination can come from animal agriculture, wastewater treatment plant discharges, slaughterhouses, birds, wild animals, and other sources of fecal matter. *Cryptosporidium parvum* (C. *parvum*) has been the primary species of concern to humans.

Cryptosporidium infection is characterized by mild to severe diarrhea, dehydration, stomach cramps, and/or a slight fever. Incubation is thought to range from 2 to 10 days. Symptoms typically last from several days to 2 weeks. In a small percentage of cases, the symptoms may persist for months or longer in healthy individuals. Symptoms may be more severe in immunocompromised persons. Such persons include those with AIDS, cancer patients undergoing chemotherapy, organ transplant recipients treated with drugs that suppress the immune system, and patients with autoimmune disorders.

Cryptosporidium oocysts are highly resistant to standard disinfectants like chlorine and chloramines. Consequently, control of *Cryptosporidium* in most treatment plants is dependent on physical removal processes. However, due to their size (4–5 microns), oocysts can sometimes pass through filters. Monitoring data on finished water show that *Cryptosporidium* is sometimes present in filtered, treated drinking water.

Certain alternative disinfectants can be more effective in treating for *Cryptosporidium*. Ozone and chlorine dioxide have been shown to inactivate *Cryptosporidium* at doses higher than those required to inactivate *Giardia*, which has typically been used to set disinfectant doses. Studies have also demonstrated a synergistic effect of treatment using ozone followed by chlorine or monochloramine. UV light has recently been shown to achieve high levels of *Cryptosporidium* inactivation at feasible doses. Other processes that can help reduce *Cryptosporidium* levels in finished water include watershed management programs, pretreatment processes like bank filtration, and additional clarification and filtration processes during water treatment. Further, optimizing treatment performance and achieving very low levels of turbidity in the finished water has been shown to improve *Cryptosporidium* removal in treatment plants.

Cryptosporidium has caused a number of waterborne disease outbreaks since 1984 when the first was reported in the United States. Data from the Centers for Disease Control and Prevention include ten outbreaks caused by *Cryptosporidium* in drinking water between 1984 and 2000, with approximately 421,000 cases of illness. The most serious outbreak occurred in 1993 in Milwaukee; an estimated 403,000 people became sick, and at least 50 *Cryptosporidium*-associated deaths occurred among the severely immunocompromised.

A PWS that begins using a new surface water source after the date the PWS is required to conduct source water monitoring under the Long-Term 2 Surface Water Treatment Rule must monitor the new source on a schedule approved by the State. This applies to new plants that begin operation and previously operating plants that bring a new source on-line after the required monitoring date for the PWS. The State may determine that monitoring should be conducted before a new plant or source is brought on-line or initiated within some time period afterward.

The new source monitoring must meet all long-term rule requirements. The PWS must also determine its treatment bin classification and comply with any additional *Cryptosporidium* treatment requirements based on the monitoring results on a schedule approved by the State.

Background and Analysis Monitoring requirements in the rule are designed to ascertain *Cryptosporidium* levels with suitable accuracy for making treatment bin classifications and in a time frame that does not delay the installation of *Cryptosporidium* treatment where needed. A mean *Cryptosporidium* concentration of 0.01 oocysts/L determines whether unfiltered PWSs are required to provide 2 or 3-log *Cryptosporidium* inactivation. No *E. coli* concentration was effective in determining whether PWSs were likely to fall above or below this level. Consequently, the rule requires all unfiltered PWSs to monitor for *Cryptosporidium*, unless they choose to provide 3-log *Cryptosporidium* inactivation.

Sampling location

The requirements in the rule for the source water sample collection location are designed to achieve two objectives:

1. Characterize the influent water to the treatment plant at the time each sample is collected.
2. Ensure that samples are not affected by treatment chemicals that could interfere with *Cryptosporidium* analysis.

The first objective is the basis for requiring PWSs that use multiple sources to analyze a blended source sample or calculate a weighted average of sources that reflects the influent at the time of sample collection. It is also the reason that PWSs are required to sample after certain pretreatment processes like bank filtration that do not involve chemical addition.

The second objective is why PWSs are generally required to sample upstream of chemical addition and prior to backwash addition (for PWSs that recycle filter backwash). However, EPA recognizes that in some situations, sampling prior to chemical addition will not be feasible and discontinuing chemical addition for a period of time prior to sampling will not be advisable. This situation could occur when a treatment chemical is added at an intake that is difficult to access. Further, some treatment chemicals may not interfere with *Cryptosporidium* analyses when present at very low levels. Consequently, the rule allows States to approve PWSs sampling after chemical addition when the State determines that collection prior to chemical treatment is not feasible, and the treatment chemical is not expected to interfere with the analysis of the sample. EPA believes that States should review source water monitoring locations for their PWSs.

Sampling Schedule

The requirement will help to ensure that monitoring determines the mean concentration of *Cryptosporidium* in the treatment plant influent. To achieve this objective, the timing of sample collection must not be adjusted in response to fluctuations in water quality, such as the avoidance of sampling when the influent water is expected to be of poor quality. EPA believes that the 5-day window for sample collection and associated allowances for sampling outside this window provide sufficient flexibility. If circumstances arise that prevent the PWS from sampling within the scheduled 5-day window, such as a weather event or plant emergency, the PWS must collect a sample as soon as feasible. In this case, feasibility includes the ability of the PWS to safely collect a sample and the availability of an approved laboratory to conduct the analysis within method specifications. In addition, the rule allows States to authorize a different date for collecting the delayed sample.

Failing to Monitor

For most monitoring and testing procedure violations under the Long-Term Rule 2, PWSs must provide a Tier 3 public notification, which is standard for this type of violation under an NPDWR. However, if a PWS fails to collect three or more *Cryptosporidium* samples, the violation is elevated to a Tier 2 special public notice. The reason for elevating the public notice at this point is the persistence of the violation and the difficulty the PWS will have in collecting the required number of samples for bin classification by the compliance date. The rule requires bin classification within six months following the end of the monitoring period specified for the PWS. This six-month period provides some opportunity for collecting and analyzing missed samples. The number of samples that can be made up in this period is limited, though, due to the need for samples to be evenly distributed throughout the year, as well as for PWSs and States to spend time during this period evaluating monitoring results to determine bin classification.

Failure by a PWS to collect the required number of *Cryptosporidium* samples for bin classification by the compliance date is a treatment technique violation with a required Tier 2 public notice. This violation reflects the inability of the PWS to determine and comply with its *Cryptosporidium* treatment requirements under the rule and provide the appropriate level of public health protection. The violation ends when the State determines that the PWS is carrying out a monitoring plan that will lead to bin classification.

A PWS that has already provided a Tier 2 public notice for missing three sampling dates and is successfully meeting a State-approved sampling schedule is not required to issue another public notice for missing the bin classification date. Alternatively, the PWS can choose to provide the highest level of *Cryptosporidium* treatment required under the rule, which is 5.5-log for filtered PWSs and 3-log for unfiltered PWSs.

Requirements for grandfathering previously collected monitoring data in the rule based on the principle that to be eligible for grandfathering, previously collected data must be equivalent in quality to data that will be collected under the rule.

The Stage 2 M–DBP Advisory Committee recommended that EPA accept previously collected *Cryptosporidium* data that are equivalent in sample number, frequency, and data quality (volume analyzed, percent recovery) to data that would be collected under the long-term rule to determine bin classification in lieu of further monitoring.

Ongoing watershed assessment treatment requirements under the rule are based on source water quality. Consequently, the rule requires watershed assessment and, a second round of monitoring following initial bin classification to determine if source water quality has changed to the degree that the treatment level should be modified. States are allowed to use programs other than the

sanitary survey to assess changes in the watershed. The rule leverages the existing requirement for States to perform sanitary surveys on surface water PWSs. During the source water review in the sanitary survey, the rule requires States to determine if significant changes have occurred in the watershed that could lead to increased contamination by *Cryptosporidium*. The State can also choose to make this determination through an equivalent review of the source water under a program other than the sanitary survey, such as a Source Water Protection Assessment. If the State determines that significant changes have occurred, the State may specify that the PWS conduct additional source water monitoring or treat the potential contamination. This approach allows the PWS and State to respond to a significant change in source water quality prior to initiating a second round of monitoring or any time thereafter.

Second Round of Monitoring

A more rigorous reassessment of the source water occurs through a second round of monitoring that begins six years after initial bin classification. If EPA does not develop and finalize modifications to the rule prior to the date when PWSs must begin the second round of monitoring, then this second round must conform to the same requirements that applied to the initial round of monitoring. PWSs may be classified in a different treatment bin, depending on the results of the second round of monitoring.

Process Summary

Source water monitoring to determine additional treatment requirements for Cryptosporidium.

1. Sampling parameters and frequency, sampling location, sampling schedule, monitoring plants that operate only part-year, failing to monitor, providing treatment instead of monitoring, grandfathering previously collected data, ongoing source water assessment, second round of monitoring, and new source monitoring.

The Rule requires filtered PWSs using surface water or GWUDI sources to provide greater levels of treatment if their source waters have higher concentrations of *Cryptosporidium*. Filtered PWSs are classified in one of four treatment bins based on results from the source water monitoring. PWSs classified in the lowest concentration bin are subject to no additional treatment requirements, while PWSs assigned to higher concentration bins must reduce *Cryptosporidium* levels. All PWSs must continue to comply with the requirements of the SWTR, IESWTR, and LT1ESWTR, as applicable. This section addresses procedures for classifying filtered PWSs in *Cryptosporidium* treatment bins and the treatment requirements associated with each bin. Microbial toolbox that PWSs must use to meet additional Cryptosporidium treatment requirements.

- Bin classification-after completing initial source water monitoring, filtered PWSs must calculate a *Cryptosporidium* bin concentration for each treatment plant where *Cryptosporidium* monitoring is required. This *Cryptosporidium* bin concentration is used to classify filtration plants in one of the four treatment bins.

In general, the *Cryptosporidium* bin concentration is calculated by averaging individual sample results from one or more years of monitoring. Specific procedures vary, however, depending on the frequency and duration of monitoring. These procedures are as follows:

1. For PWSs that collect a total of at least 24 but not more than 47 *Cryptosporidium* samples over two or more years, the *Cryptosporidium* bin concentration is equal to the highest arithmetic mean of all sample concentrations in any 12 consecutive months of *Cryptosporidium* monitoring.
2. For PWSs that collect a total of at least 48 samples, the *Cryptosporidium* bin concentration is equal to the arithmetic mean of all sample concentrations.
3. For PWSs that serve fewer than 10,000 people and monitor for *Cryptosporidium* for only one year (collect 24 samples in 12 months), the *Cryptosporidium* bin concentration is equal to the arithmetic mean of all sample concentrations.
4. For PWSs with plants that operate only part-year that monitor for less than 12 months per year, the *Cryptosporidium* bin concentration is equal to the highest arithmetic mean of all sample concentrations during any year of *Cryptosporidium* monitoring.

In data sets with variable sampling frequency, PWSs must first calculate an arithmetic mean for each month of sampling and then apply one of these four procedures using the monthly mean concentrations. PWSs may grandfather previously collected *Cryptosporidium* data where the sampling frequency varies (one year of monthly sampling and one year of twice-per- month sampling). Filtered PWSs serving fewer than 10,000 people are not required to monitor for *Cryptosporidium* if they demonstrate a

mean E. *coli* concentration less than or equal to 10/ 100 mL for lake/reservoir sources or 50/ 100 mL for flowing stream sources or do not exceed an alternative State-approved indicator trigger. PWSs that meet this criterion are classified in Bin 1.

When determining the *Cryptosporidium* bin concentration, PWSs must calculate individual sample concentrations as the total number of oocysts counted, divided by the volume as saved. In samples where no oocysts are detected, the result is assigned a value of zero for the purpose of calculating the bin concentration. Sample analysis results are not adjusted for analytical method recovery or the percent of *Cryptosporidium* oocysts that are infectious. PWSs must report their treatment bin classification to the State for approval following initial source water monitoring. The report must include a summary of the data and calculation procedure used to determine the bin concentration. PWSs must recalculate their bin classification after completing the second round of monitoring and report the results to the State for approval. If the State does not respond to a PWS regarding its bin classification after either report, the PWS must comply with the *Cryptosporidium* treatment requirements of the rule based on the reported bin classification.

- Bin treatment requirements. All filtered PWSs must comply with the treatment requirements based on their bin classification.

The total *Cryptosporidium* treatment required for plants in Bins 2, 3, and 4 is 4.0-log, 5.0-log, and 5.5-log, respectively. Conventional treatment (including softening), slow sand, and diatomaceous earth filtration plants in compliance with the IESWTR or LT1ESWTR, as applicable, receive a prescribed 3.0-log *Cryptosporidium* treatment credit toward these total bin treatment requirements. Accordingly, these plant types must provide 1.0 to 2.5-log of additional treatment when classified in Bins 2–4, respectively. Direct filtration plants in compliance with existing regulations receive a prescribed 2.5-log treatment credit and, consequently, must achieve 0.5-log greater treatment to comply with Bins 2–4.

For PWSs using alternative filtration technologies, such as membranes, bag filters, or cartridge filters, no prescribed treatment credit is available because the performance of these processes is specific to individual products. Consequently, when PWSs using these processes are classified in Bins 2–4, the State must determine additional treatment requirements based on the credit the State awards to a particular technology. The additional treatment requirements must ensure that plants classified in Bins 2–4 achieve total *Cryptosporidium* reductions of 4.0- to 5.5-log, respectively. PWSs can achieve additional *Cryptosporidium* treatment credit through implementing pretreatment processes like pre-sedimentation or bank filtration, by developing a watershed control program, and by applying additional treatment steps like ozone, chlorine dioxide, UV, and membranes. In addition, PWSs can receive a higher level of credit for existing treatment processes through achieving very low filter effluent turbidity or through a demonstration of performance.

A combination of options from the microbial toolbox can be used to gather additional credit. PWSs in Bin 2 can meet additional *Cryptosporidium* treatment requirements by using any option or combination of options from the microbial toolbox. For Bins 3 and 4, PWSs must achieve at least 1-log of the additional treatment requirement by using ozone, chlorine dioxide, UV, membranes, bag filtration, cartridge filtration, or bank filtration.

- The rule increases protection against *Cryptosporidium* and other pathogens in PWSs with the highest source water contamination levels. This targeted approach builds upon existing regulations under which all filtered PWSs must provide the same level of treatment regardless of source water quality. The rule is to ensure that PWSs with higher risk source waters achieve public health protection commensurate with PWSs with less contaminated sources.

The rule establishes risk-targeted *Cryptosporidium* treatment requirements and sets specific bin concentration ranges and treatment requirements that apply to filtered PWSs. The IESWTR established a *Cryptosporidium* MCLG of zero and requires large filtered PWSs to achieve 2-log *Cryptosporidium* removal. The LT1ESWTR extended this requirement to small PWSs. After these rules were promulgated, advances were made in analytical methods and treatment for Cryptosporidium, and EPA collected new information on *Cryptosporidium* occurrence and infectivity. Consequently, EPA assessed the implications of these developments for further controlling Cryptosporidium to approach the zero MCLG. The risk-targeted approach for filtered PWSs in the rule stems from four general findings based on new information on *Cryptosporidium*:

1. New data on *Cryptosporidium* infectivity suggest that the risk associated with a particular level of *Cryptosporidium* is most likely higher than EPA estimated at the time of earlier rules.
2. New data on *Cryptosporidium* occurrence indicate that levels are relatively low in most water sources, but a subset of sources has substantially higher concentrations.

3. The finding that UV light can readily inactivate *Cryptosporidium*, as well as other technology developments, makes achieving high levels of treatment for *Cryptosporidium* feasible for PWSs of all sizes.
4. EPA Methods 1622 and 1623 are capable of assessing annual mean levels of *Cryptosporidium* in drinking water sources.

These findings led EPA to conclude that most filtered PWSs currently provide sufficient treatment for *Cryptosporidium*, but additional treatment is needed in those PWSs with the highest source water Cryptosporidium levels to protect public health. Further, PWSs can characterize *Cryptosporidium* levels in their source waters with available analytical methods and can provide higher levels of treatment with available technologies. Consequently, risk-targeted treatment requirements for *Cryptosporidium* based on source water contamination levels are appropriate and feasible to implement.

Basis for bin concentration ranges and treatment requirements. To establish the risk-targeted treatment requirements in today's rule, EPA had to determine the degree of treatment that should be required for different source water *Cryptosporidium* levels to protect public health. This determination involved addressing several questions:

1. What is the risk associated with *Cryptosporidium* in a drinking water source?
2. How much *Cryptosporidium* removal do filtration plants achieve?
3. What is the appropriate statistical measure for classifying PWSs into treatment bins?
4. What degree of additional treatment is needed for higher source water *Cryptosporidium* levels?
5. How should PWSs calculate their treatment bin classification?

The risk of infection from *Cryptosporidium* in drinking water is a function of exposure (the dose of oocysts ingested) and infectivity (likelihood of infection as a function of ingested dose). Primary (direct) exposure to *Cryptosporidium* depends on the concentration of oocysts in the source water, the fraction removed by the treatment plant, and the volume of water consumed (secondary exposure occurs through interactions with infected individuals). Thus, the daily risk of infection (DR) is as follows:

DR = (oocysts/L in source water) × (fraction remaining after treatment) × (liters consumed per day) × (likelihood of infection per oocyst dose). Assuming 350 days of consumption per year for people served by community water systems (CWSs), the annual risk (AR) of infection is as follows: AR = 1 ¥ (1 ¥ DR)350.

EPA has estimated the mean likelihood of infection from ingesting one *Cryptosporidium* oocyst to range from 4 to 16 percent. Median individual daily water consumption is estimated as 1.07 L/day.

Key Terms

- Cryptosporidium - a protozoan parasite that lives and reproduces entirely in one host; ingestion of *Cryptosporidium* can cause cryptosporidiosis, a gastrointestinal (GI) illness; cryptosporidium is excreted in feces.
- **Ground Water Rule (GWR)** – the purpose is to improve drinking water quality and provide protection from disease-causing microorganisms; water systems that have groundwater sources may be susceptible to fecal contamination; applies to public water systems that use ground water as a source of drinking water
- **Surface Water Treatment Rules (SWTRs)** – the purpose is to reduce illnesses caused by pathogens in drinking water, including *Legionella*, *Giardia lamblia*, and *Cryptosporidium*; the SWTRs requires water systems to filter and disinfect surface water sources.
- Total Coliform Rule (TCR) - a National Primary Drinking Water Regulation (NPDWR), published in 1989 and became effective in 1990; sets a health goal (Maximum Contaminant Level Goal (MCLG)) and legal limits (Maximum Contaminant Levels, MCLs)) for the presence of total coliforms in drinking water

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2.7.1: Review Questions

Review Questions

1. **What are the primary components of the Total Coliform Rule?**
2. **What is the basis of the Total Coliform Rule?**
3. **What is the primary requirement in the Groundwater Rule?**
4. **List four EAP approved laboratory methods for testing for coliforms.**

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2.7.2: Chapter Quiz

Chapter Quiz

1. Total coliforms are used as a(n) _____ of the possible presence of pathogens in drinking water. Total coliforms are used to determine the adequacy of water treatment and the integrity of the distribution system.

1. indicator
2. model
3. log removal
4. alternative

2. The Revised Total Coliform Rule establishes _____for E. coli and uses E. coli and total coliforms to initiate a find and fix approach to address fecal contamination that could enter into the distribution system.

1. a log removal
2. a maximum contaminant level (MCL)
3. a secondary maximum contaminant level (SMCL)
4. a model

3. Within 24 hours of learning of a Total Coliform positive routine sample result, at least ____ repeat samples must be collected and analyzed for total coliform.

1. 1
2. 2
3. 3
4. 4

4. States are required to conduct _____ of all groundwater systems in order to identify significant deficiencies, including deficiencies which may make a system susceptible to microbial contamination.

1. hydrologic studies
2. microbial examinations
3. a sanitary survey
4. laboratory studies

5. The Surface Water Treatment Rule requires water systems to _____ surface water sources.

1. filter and disinfect
2. conserve
3. aerate
4. disinfect

6. In order not to be subject to triggered source water monitoring under the Groundwater Rule, a groundwater system can notify the state that it provides at least _____ treatment of viruses using virus inactivation, or removal, before or at the first customer.

1. 2-log
2. 3-log
3. 4-log
4. 6-log

7. The Long-Term Surface Water Rule establishes risk-targeted treatment technique requirements to control _____ in PWSs using surface water or groundwater under the influence of surface water.

1. *E.coli*
2. *Giardiasis lambdia*
3. *Cryptosporidium*
4. Coliforms

8. What is the maximum allowable turbidity in the combined filter effluent?

1. 0.5 NTU
2. 1.0 NTU
3. 3.0 NTU
4. 5.0 NTU

9. EPA promulgated the Long-Term Surface Water Treatment Rule to reduce the public health risk associated with _____ in drinking water.

1. *Giardiasis lambdia*
2. *Cryptosporidium*
3. Coliforms
4. *E. coli*

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2.8: Total Coliform Rule

Learning Objectives

After reading this section, you should be able to:

- Describe biofilms
- Explain common microbiological techniques
- Outline and describe coliform bacterial analysis

Biofilms

Bacteria may grow and persist in the environment as free floating (planktonic) cells in liquids or attached to surfaces as biofilm. In 1683, Antoni van Leeuwenhoek observed and described biofilms by using his primitive microscope on matter from his own teeth. Biofilm form when bacteria adhere to environmental surfaces, especially those located in the presence of high moisture. Biofilm typically persist in a matrix containing slimy, glue-like substances (extracellular polymeric substances) which facilitate their attachment to many hard surfaces. The biofilm matrix provides embedded bacteria with protection from dehydration and other environmental stresses and may interfere with the action of chemical disinfectants.[1]

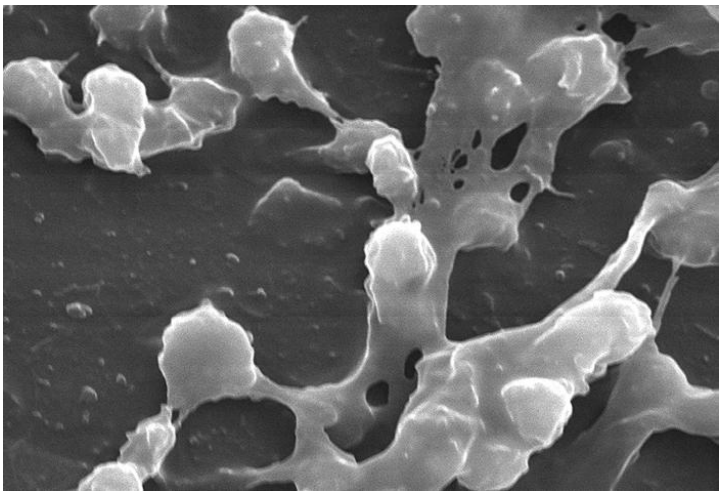


Figure **2.8.1**: Copy and Paste Caption here. (Copyright; Image by CDC is in the public domain)

A biofilm is considered to a hydrogel. According to Wang et. al (2020), hydrogels are "three-dimensional (3D) cross-linked polymer networks that can absorb and retain large amount of water. Because of their tunable properties as well as their versatile fabrication methods, hydrogel materials have been applied in a wide range of biomedical and engineering applications, ranging from tissue engineering and regenerative medicine to wastewater treatment…"[2]

Culture Media

Culture medium or growth medium is a liquid or gel designed to support the growth of microorganisms. There are different types of media suitable for growing different types of cells. Nutrient broths and agar plates are the most common growth media, although specialized media are sometimes required for microorganism and cell culture growth. Some organisms, termed fastidious organisms, need specialized environments due to complex nutritional requirements. Viruses, for example, are obligate intracellular parasites and require a growth medium containing living cells. Many human microbial pathogens also require the use of human cells or cell lysates to grow on a media. The most common growth media nutrient broths (liquid nutrient medium) or LB medium (Lysogeny Broth) are liquid. These are often mixed with agar and poured into Petri dishes to solidify. These agar plates provide a

solid medium on which microbes may be cultured. They remain solid, as very few bacteria are able to decompose agar. Many microbes can also be grown in liquid cultures comprised of liquid nutrient media without agar.

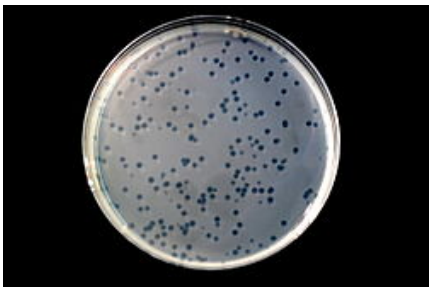


Figure **2.8.2**: Petri Dish #1. (Copyright; Image by Ninjatacoshell is licensed under CC BY-SA 3.0)



Figure **2.8.3**: Petri Dish #2. (Copyright; Image by NASA is in the public domain)

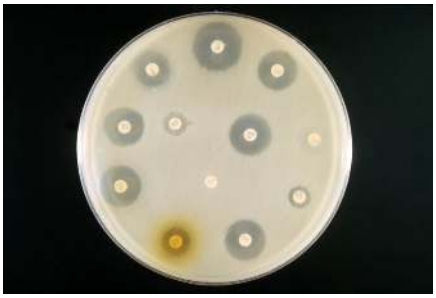


Figure **2.8.4**: Petri Dish #3. (Copyright; Image by the CDC is in the public domain)

Chemically Defined Medium

A *defined culture* medium will have known quantities of all ingredients. For microorganisms, it provides trace elements and vitamins required by the microbe and especially a defined carbon and nitrogen source. Glucose or glycerol are often used as carbon sources, and ammonium salts or nitrates as inorganic nitrogen sources. A chemically defined medium is entirely free of animal-derived components (including microbial derived components such as yeast extract) and represents the purest and most consistent cell culture environment.

Complex Undefined Media

An undefined medium has some complex ingredients, such as yeast extract or casein hydrolysate, which consist of a mixture of many, many chemical species in unknown proportions. Undefined media are sometimes chosen based on price and sometimes by necessity – some microorganisms have never been cultured on defined media. A defined medium (also known as chemically defined medium or synthetic medium) is a medium in which all the chemicals used are known, no yeast, animal, or plant tissue is present.

Anaerobic Growth Media and Methods

Quite a few human pathogens are strict **anaerobes**. One way to culture and grow anaerobes is the use of reduced media--media without oxygen. Thioglycollate broth has a reducing agent in it---the chemical thioglycollate---which binds any free oxygen within the medium. These tubes have screw caps, allowing a tight closure, to reduce oxygen entry. However, some oxygen will be in the tube between the cap and the broth and there is no way to get rid of it. So, there will be some diffusion of oxygen into the top portion of the broth, and that is where any aerobic bacteria may grow.

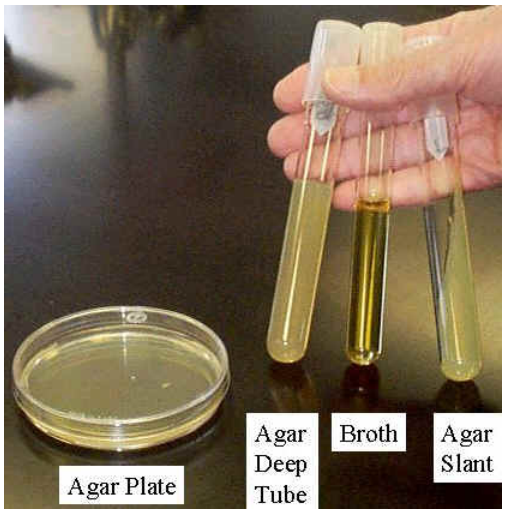


Figure 2.8.5: Nutrient Broth. (Image by LibreTexts is licensed under CC BY-SA 3.0.[8])

Special Culture Techniques

Microbes are incredibly varied in what they use as a food source, the environments they live in, and the danger levels they may have for humans and other organisms they may compete with. Therefore, they need special nutrient and growth environments that are not easily accommodated. For example, a microaerophile is a microorganism that requires oxygen to survive but requires environments containing lower levels of oxygen than are present in the atmosphere (~20% concentration). Many microphiles also require an elevated concentration of carbon dioxide. In the laboratory they can be easily cultivated in a candle jar. A candle jar is a container into which a lit candle is introduced before sealing the container's airtight lid. The candle's flame burns until extinguished by oxygen deprivation, which creates a carbon dioxide-rich, oxygen-poor atmosphere in the jar.

Pure Cultures

It is often essential to isolate a pure culture of microorganisms. A pure (or axenic) culture is a population of cells or multicellular organisms growing in the absence of other species or types. A pure culture may originate from a single cell or single organism, in which case the cells are genetic clones of one another. Microbiological cultures can be grown in petri dishes of differing sizes that have a thin layer of agar-based growth medium. Once the growth medium in the petri dish is inoculated with the desired bacteria, the plates are incubated at the best temperature for the growing of the selected bacteria.

But most bacteria samples contain a variety of different kinds and would be termed a mixed culture. However, it is possible to isolate specific bacteria by depositing the sample into a petri dish with agar with an inoculating loop or sterile cotton swab. using the streak plate method. If you swab a door handle, where bacteria are likely to be present, and then pass the swab across the surface of a petri plate, cells would be deposited onto the surface from the swab. Initially, the swab may have a fairly high concentration of cells and the area touched by it will have lots of different cell types placed close together. After these grow up, the cells' progeny will crowd together and overlap with other cells' progeny forming areas called confluent growth. As the swab moves across the agar leaving cells on the agar in a zig zag pattern as shown in Figure 8.6, regions touched later in the process will have fewer and fewer cells. Individual cells are far enough apart that each one would grow into a discrete isolated colony.



Figure **2.8.6**: Streak plate pure cultures. (Copyright;Image by Bill Branson is in the public domain.
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Coliform Bacterial Analysis

Municipal sewage contains human feces and water contaminated with these effluents may contain pathogenic (disease-causing) organisms and, consequently, may be hazardous to human health if used as drinking-water or in food preparation. Fecal contamination of water is routinely detected by microbiological analysis.

It is impractical to attempt the routine isolation of pathogens because they are present in relatively small numbers compared with other types of microorganism. Moreover, many types of pathogens exist, and each organism requires a unique microbiological isolation technique. The approach that has been adopted is to analyze samples for indicator organisms that inhabit the gut and are excreted in human feces. The presence of these indicator organisms in water is evidence that fecal contamination is present, and a risk exists that pathogens are present.

If indicator organisms are present in large numbers, the contamination is considered to be recent and/or severe. Bacteria in water are, in general, not present individually, but as clumps or in association with particulate matter. When enumerating bacteria in water it is not the number of individual bacteria present which are counted, but the number of clumps of bacteria or the particles and their associated bacteria. Each clump or particle may have many bacteria associated with it.

Total Coliforms

The term **total coliforms** refer to a large group of Gram-negative, rod-shaped bacteria that share several characteristics. The group includes heat-tolerant coliforms and bacteria of fecal origin, as well as some bacteria that may be isolated from environmental sources. The presence of total coliforms may or may not indicate fecal contamination. In extreme cases, a high count for the total coliform group may be associated with a low, or zero, count for thermos-tolerant coliforms. A result of this nature would not necessarily indicate the presence of fecal contamination. It might be caused by entry of soil or organic matter into the water or by conditions suitable for the growth of other types of coliform. In the laboratory total coliforms are grown in or on a medium containing lactose, at a temperature of 35 or 37 °C. They are provisionally identified by the production of acid and gas from the fermentation of lactose.

The term fecal coliform has been used in water microbiology to denote coliform organisms which grow at 44 or 44.5 C and ferment lactose to produce acid and gas. In practice, some organisms with these characteristics may not be of fecal origin and the term thermos-tolerant coliform is, therefore, more correct and is becoming more commonly used. Nevertheless, the presence of thermos-tolerant coliforms nearly always indicates fecal contamination.

Usually, more than 95 percent of thermos-tolerant coliforms isolated from water are the gut organism *Escherichia coli*, the presence of which is definitive proof of fecal contamination. As a result, it is often unnecessary to undertake further testing to confirm the

specific presence of *E. coli*.

The presence of fecal streptococci is evidence of fecal contamination. Fecal streptococci tend to persist longer in the environment than thermos-tolerant or total coliforms and are highly resistant to drying. It is, therefore, possible to isolate fecal streptococci from water that contains few or no thermos-tolerant coliforms as, for example, when the source of contamination is distant in time or space from the sampling point. Fecal streptococci grow in or on a medium containing sodium azide, at a temperature of 37-44°C. They are usually detected by the reduction of a dye (a tetrazolium-containing compound) or the hydrolysis of aesculin. Routine methods may give false positives and additional confirmatory tests may be required.

Key Terms

- **biofilm** – three-dimensional structures that create a matrix referred to commonly as a slime
- culture – the microbes that grow or multiply in or on a culture medium
- culture medium – a nutrient material prepared for the growth of microorganisms in a laboratory
- inoculum – microbes introduced into a culture medium to initiate growth
- streak plate method – an isolation method to achieve pure cultures by streaking a pattern over a surface of nutrient medium
- total coliform – a large group of Gram-negative, rod-shaped bacteria that share several characteristic and include heat-tolerant coliforms and bacteria of fecal origin, as well as some bacteria that may be isolated from environmental sources

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[1] (Efficacy Test Methods, Test Criteria, and Labeling Guidance for Antimicrobial Products with Claims Against Biofilm on Hard, Non-Porous Surfaces https://www.epa.gov/pesticide-analyt...eling-guidance)

[2] Wang, W., Narain, R., & Zeng, H. (2020). Hydrogels. Polymer Science and Nanotechnology, 203–244. https://doi.org/10.1016/b978-0-12-816806-6.00010-8

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2.8.1: Review Questions

Review Questions

1. **Describe a biofilm. Give two examples.**
2. **What does the term “coliforms” refer to? How are “coliforms” different than “fecal coliform”?**
3. **What is a culture medium?**

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2.8.2: Chapter Quiz

Chapter Quiz

1. A nutrient material prepared for the growth of microorganisms in a laboratory is called a _____.

1. enrichment medium
2. culture medium
3. selective media
4. complex media

2. Most investigations of microbes require a pure culture, or clones of bacteria. The isolation method used to achieve pure cultures is the _____.

1. selective selection
2. streak plate method
3. inoculation method
4. defined medium method

3. The term _____ refer(s) to a large group of Gram-negative, rod-shaped bacteria that share several characteristics. The group includes heat-tolerant bacteria of fecal origin.

1. virus
2. protozoan
3. parasite
4. total coliforms

4. _____ assume that each bacterium, clump of bacteria, or particle with bacteria attached, will give rise to a single visible colony. Each clump or particle is, therefore, a colony forming unit (cfu) and the results are expressed as colony forming units per unit volume.

1. Multiple Fermentation Tube Technique
2. Membrane Filter Technique
3. Heterotrophic Plate Count
4. Sabouraud

5. _____ count includes microorganisms that are capable of growing in or on a nutrient-rich solid agar medium.

1. Multiple Fermentation Tube Technique
2. Membrane Filter Technique
3. Heterotrophic Plate Count
4. Sabouraud

6. More than 95-percent of thermos-tolerant coliforms isolated from water are the gut organism, _____, the presence of which is definitive proof of fecal contamination.

1. Streptococcus
2. *E. coli*
3. Staphylococcus
4. Bacteroides

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2.9: Primary Standards

Learning Objectives

After reading this section, you should be able to:

- Define primary standards
- Describe the primary metal contaminants
- Describe the primary organic contaminants
- Describe the primary synthetic organic contaminants
- Describe sampling guidelines
- Describe the Radiologic Rule
- Describe the Total Coliform Rule

Federal (Environmental Protection Agency, EPA)

The process by which EPA sets drinking water standards is long and complicated. It involves deciding which contaminants may endanger public health, conducting studies of the effects of these contaminants, defining the maximum safe level of each contaminant, estimating the costs and benefits of regulation, proposing a standard or limit, listening to and evaluating public reactions to the proposed standard, revising the standard (if needed), proposing the standard in final form, seeking and evaluating additional public input, and finally, publishing the standard. The **primary standards** are referred to as the Maximum Contaminant Level (MCL). When the level of a contaminant is above the MCL, it is considered to be a health hazard. MCLs are enforceable by law.

The entire process by which a standard is proposed and promulgated is governed by strict procedural guidelines. It often takes three or more years to produce a standard.

Types of Contaminants

Five types of primary contaminants are considered to be of public health importance:

1. **Inorganic contaminants**, such as lead and mercury;
2. **Organic contaminants**, which include pesticides, herbicides, THMs, solvents, and other synthetic organic compounds;
3. **Turbidity**, such as small particles suspended in water that interfere with light penetration and disinfection;
4. **Microbial contaminants**, such as bacteria, viruses, and protozoa; and
5. **Radiologic contaminants**, which include natural and manmade sources of radiation.

Identifying Contaminants to Be Regulated

The 1986 Safe Drinking Water Act (SDWA) required EPA to establish a priority list of contaminants that may have adverse health effects and may require regulation. The 1996 SDWA amendments retained the list of 83 contaminants developed earlier but revised the process by which contaminants are selected for regulation. Before selecting a contaminant for regulation, the EPA must now consult with the scientific community, solicit public comments, and demonstrate that the contaminant actually occurs in public water systems. For this latter purpose, the 1996 amendments required EPA to establish an occurrence database by August 1999. The database contains information concerning regulated and unregulated contaminants and the information is available to the public.

To regulate a substance, EPA must demonstrate that the contaminant meets three criteria:

1. The contaminant has an adverse effect on human health;
2. It occurs, or is likely to occur, in public water systems at a frequency and concentration of significance to public health; and
3. Regulation of the contaminant offers a meaningful opportunity to reduce health risks for people served by public water systems.

In addition to meeting these three criteria, EPA must also weigh the relative health risks of various contaminants being considered for regulation, the risk reduction that regulation would accomplish, and the costs of implementing the regulations.

Working on a 5-year cycle, the EPA is required to select at least five contaminants from its Drinking Water Contaminant Candidate List (DWCCL) and decide whether there sufficient reason exists to regulate them. The first DWCCL included 50 chemicals and 10

microbial contaminants. In June 2002, the EPA announced a preliminary finding that their research revealed no need to regulate ten of the listed contaminants. Based on public comments and continued research and evaluation, EPA will make a final determination about regulating any of these contaminants and will begin to develop proposed regulations as necessary.

Unregulated Contaminants

EPA uses the Unregulated Contaminant Monitoring (UCM) program to collect data for contaminants suspected to be present in drinking water, although they do not have health-based standards set under the SDWA. Every 5 years, EPA reviews the list of contaminants, largely based on the Contaminant Candidate List.

The SDWA Amendments of 1996 provide for the following:

- Monitoring no more than 30 contaminants per 5-year cycle
- Monitoring only a representative sample of public water systems
- serving fewer than 10,000 people
- Storing analytical results in a National Contaminant Occurrence Database (NCOD)

The UCM program has progressed in several stages. Currently, EPA manages the program directly as specified in the Unregulated Contaminant Monitoring Regulation (UCMR). EPA has established a timeline and plans for monitoring unregulated contaminants through 2015.

Under the UCMR, community water systems and non-transient non-community water systems serving more than 10,000 people are required to monitor for unregulated contaminants; smaller systems may also have to conduct monitoring if required by the state. Transient water systems are not affected by the UCMR.

Always keep in mind that EPA's regulatory process is basically just a process. No list is permanent; regulations change frequently as new information becomes available. Water treatment plant operators must continually seek opportunities to learn about the regulations that affect the water industry. Also, operators should feel free to express their concerns regarding the regulations and the regulatory process to EPA.

Primary Standards

Inorganic chemicals are metals, salts, and other chemical compounds that do not contain carbon. The health concerns about inorganic chemicals are not centered on cancer, but rather on their suspected links to several different human disorders. For example, lead is suspected of contributing to mental retardation in children. Waters exceeding the MCL for these elements for short periods of time will pose no immediate threat to health. However, studies show that these substances must be controlled because consumption of drinking water that exceeds these standards over long periods of time may prove harmful.

Antimony

In the Code of Federal Regulations Reference: 40 CFR 721.1930, antimony is used in the production of ceramics, glassware, and pigments. Most exposures to antimony occur in industrial settings where workers may inhale dust containing particles of the metal.

Purpose of Regulating Antimony: To improve public health protection by reducing exposure to the amount of antimony in drinking water.

Public Health Benefit: Ingestion of antimony can alter cholesterol and glucose levels and may cause chromosome damage.

MCL/MCLG: 0.006 mg/L/0.006 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Arsenic

In the Code of Federal Regulations Reference: 40 CFR 141 Subpart B. arsenic occurs naturally in the environment, especially in the western United States, and it is used in insecticides. Arsenic is found in foods, tobacco, shellfish, drinking water, and in the air in some locations. Anyone who drinks water that continuously exceeds the national standard by a substantial amount over a lifetime may experience fatigue and loss of energy. Extremely high levels of arsenic can cause poisoning.

The regulation of arsenic has been vigorously debated. In 1997, EPA released a health effects study plan. Under this plan, EPA worked with the Water Research Foundation (WRF) and the Association of California Water Agencies to assess the health risks from exposure to low levels of arsenic. Based on the results of these studies, EPA proposed an MCL for arsenic in June 2000, and a final rule was issued January 22, 2001. Technologies available for removing arsenic include ion exchange, iron hydroxide coagulation followed by microfiltration, and activated alumina.

Purpose of Regulating Arsenic: To improve public health protection by reducing exposure to arsenic in drinking water.

Public Health Benefit: The avoidance of bladder and lung cancer, dental problems, and a reduction in the frequency of non-carcinogenic diseases.

MCL/MCLG: 0.010 mg/L/zero

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Asbestos

In the Code of Federal Regulations Reference: 40 CFR 141.62, the general term asbestos refers to a family of fibrous silicate minerals that have been widely used in the manufacture of commercial products. Some examples of products containing asbestos include floor and ceiling tiles, paper products, paint and caulking, plastics, brake linings, insulation, cement, and filters.

Asbestos in cement pipes is a potential source of contamination of drinking water. Deterioration of this material with age and exposure to corrosive water is thought to release asbestos particles. Mining for asbestos minerals has also contributed to the contamination of some drinking water sources throughout the United States. Scientific evidence on the harmful effects of asbestos consumed in drinking water is less conclusive than the evidence relating to inhaled asbestos.

Purpose of Regulating Asbestos: To improve public health protection by reducing exposure to asbestos in drinking water.

Public Health Benefit: To reduce the risk of developing benign intestinal polyps.

MCL/MCLG: 7 million fibers per liter (MFL)/7 MFL

Monitoring Requirements: Once every 9 years.

Barium

Code of Federal Regulations Reference: 40 CFR 141.62, although not as widespread as arsenic, this element also occurs naturally in the environment in some areas of the US. Barium can also enter water supplies through industrial waste discharges. Small doses of barium are not harmful. However, it is quite dangerous when consumed in large quantities and will bring on increased blood pressure, nerve damage, and death.

Purpose of Regulating Barium: To improve public health protection by reducing exposure to large quantities of barium in drinking water.

Public Health Benefit: To reduce the risk of high blood pressure.

MCL/MCLG: 2 mg/L/2 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Beryllium

In the Code of Federal Regulations Reference: 40 CFR 141.62, the major source of beryllium in the environment is the combustion of coal and oil. Airborne particulates containing beryllium can be inhaled or washed by precipitation into drinking water supplies. Animal studies show that when large doses of beryllium are ingested, it is carried by the bloodstream from the stomach to the liver; however, it is gradually transferred to the animal's bones.

Purpose of Regulating Beryllium: To improve public health protection by reducing exposure to large quantities of beryllium in drinking water.

Public Health Benefit: To reduce the risk of intestinal lesions.

MCL/MCLG: 0.004 mg/L/0.004 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Bromate

In the Code of Federal Regulations Reference: 40 CFR Parts 9, 141, and 142, bromate is formed as a byproduct of ozone disinfection of drinking water. Ozone reacts with the naturally occurring bromide ion in the water to form bromate. Bromate is an inorganic ion that is tasteless, colorless, and has a low volatility. Bromate dissolves easily in water and is fairly stable. Bromate is not typically derived from natural sources. It is commonly found in raw water supplies such as streams, lakes, and reservoirs.

Purpose of Regulating Bromate: To improve public health protection by reducing exposure to bromate in drinking water.

Public Health Benefit: To reduce the risk of cancer.

MCL/MCLG: 0.010 mg/L/zero

Monitoring Requirements: Monthly (ozone systems only).

Cadmium

In the Code of Federal Regulations Reference: 40 CFR 141.62, only extremely small amounts of cadmium are found in natural waters in the United States. Waste discharges from the electroplating, photography, insecticide, and metallurgy industries can increase cadmium levels. The most common source of cadmium in drinking water is from galvanized pipes and fixtures.

Purpose of Regulating Cadmium: To improve public health protection by reducing exposure to cadmium in drinking water.

Public Health Benefit: To prevent kidney damage.

MCL/MCLG: 0.005 mg/L/0.005 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Chlorite

In the Code of Federal Regulations Reference: 40 CFR Parts 9, 141,and 142, the main source of chlorite in drinking water is chlorine dioxide used for disinfection. Chlorite forms as the chlorine dioxide breaks down during the disinfection process. Chlorite is an inorganic ion that is colorless, odorless, tasteless, and dissolves easily in water. Chlorite is one of the two or three chemicals involved in the process of generating chlorine dioxide for water treatment. Chlorite is not typically derived from natural sources.

Purpose of Regulating Chlorite: To improve public health protection by reducing exposure to chlorite in drinking water, especially for infants and young children.

Public Health Benefit: To prevent adverse effects of the nervous system and anemia.

MCL/MCLG: 1.0 mg/L/0.8 mg/L

Monitoring Requirements: For systems that add chlorine dioxide, daily samples are required at distribution system entry points.

Chromium

In the Code of Federal Regulations Reference: 40 CFR 141.62, chromium is found in cigarettes, some foods, and the air. It is also discharged from steel and pulp mills and the erosion of natural deposits. Some studies suggest that in very small amounts, chromium may be essential to human beings, but it has not been proven.

Purpose of Regulating Chromium: To improve public health protection by reducing exposure to chromium in drinking water.

Public Health Benefit: To prevent allergic dermatitis.

MCL/MCLG: 0.1 mg/L/0.1 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Copper

In the Code of Federal Regulations Reference: 40 CFR 141.86, copper in drinking water usually results from the reaction of water on copper plumbing. Treatment of surface water in storage reservoirs to control algae may also cause high levels of copper. Copper is an essential nutrient; adults require 2 mg daily and children of preschool age require about 0.1 mg daily for normal growth.

The presence of copper in drinking water is also undesirable because of its aesthetic effects. At low levels (0.5 mg/L in soft waters) blue or blue-green staining of porcelain occurs. At higher levels (4 mg/L), it will stain clothing and blond hair. Concentrations greater than 1 mg/L can produce insoluble green curds when reacting with soap.

The primary standard for copper includes a treatment technique of the taps sampled exceed the action level (AL) of 1.3 mg/L.

> **Note**
>
> Action levels communicate health or physical hazards by categorizing these hazards into levels. Action levels are used by OSHA and NIOSH to determine how harmful a substance or activity is.**Purpose of Regulating Copper**: To improve public health protection by reducing water corrosivity.

Public Health Benefit: To prevent gastrointestinal, kidney, and liver problems.

MCL/MCLG: A treatment technique (TT) is triggered at AL = 1.3 mg/L/1.3 mg/L

Monitoring Requirements: Residential sample taken at the kitchen or bathroom sink tap. ALs must be met in 90 percent of the samples. Follow-up monitoring every 6 months after corrosion controls initiated or optimized. Reduced monitoring for systems consistently meeting AL.

Cyanide

In the Code of Federal Regulations Reference: 40 CFR 141.62, cyanide is a common ingredient of rat poisons, silver and metal polishes, and photo processing chemicals. The major source of cyanide in drinking water is discharge from industrial chemical factories.

Ingestion of even very small amounts of sodium cyanide or potassium cyanide can cause death within a few minutes to a few hours. Typical symptoms of cyanide poisoning include nausea without vomiting, anxiety, vertigo, lower jaw stiffness, convulsions, paralysis, irregular heartbeat, and coma.

Purpose of Regulating Cyanide: To improve public health protection by reducing long-term exposure to cyanide.

Public Health Benefit: To prevent thyroid/neurological damage.

MCL/MCLG: 0.2 mg/L/0.2 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Fluoride

In the Code of Federal Regulations Reference: 40 CFR 141.62, fluoride is a natural mineral and many sources of drinking water contain some fluoride. Fluoride produces two effects, depending on its concentration. EPA has set primary and secondary limits to regulate it. Many communities add fluoride to their drinking water to promote dental health. The decision to fluoridate a water supply is made by the state or local municipality, and is not mandated by EPA or any other federal entity.

However, EPA has completed and peer-reviewed a quantitative dose-response assessment based on the available data for severe dental fluorosis as recommended by the National Research Council (NRC). At levels of 6 to 8 mg/L, fluoride may cause brittle bones and stiffening of the joints. On the basis of this health hazard, fluoride has been added to the list of primary standards.

At levels of 2 mg/L and greater, fluoride may cause dental fluorosis, which is discoloration and mottling of the teeth, especially in children. EPA has reclassified dental fluorosis as a cosmetic effect, raised the primary drinking water standard from 1.4–2 mg/L to 4 mg/L, and established a secondary standard of 2 mg/L for fluoride.

Purpose of Regulating Fluoride: To improve public health protection by preventing long-term exposure to fluoride.

Public Health Benefit: To prevent bone disease.

MCL/MCLG: 4.0 mg/L/4.0 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Lead and Copper

In the Code of Federal Regulations Reference: 40 CFR 141 Subpart I, is concerned with the control of lead and copper. Basic Requirements of the Lead and Copper Rule (LCR) are:

1. Require water suppliers to optimize their treatment system to control corrosion in customers' plumbing.
2. Determine tap-water levels of lead and copper for customers who have lead service lines or lead-based solder in their plumbing system.
3. Rule out the source water as a source of significant lead levels.
4. If lead ALs are exceeded, require the suppliers to educate their customers about lead and suggest actions they can take to reduce their exposure to lead through public notices and public education programs. If a water system, after installing and optimizing corrosion control treatment, continues to fail to meet the lead AL, it must begin replacing the lead service lines under its ownership.

Revisions to the Lead and Copper Rule (LCR)—EPA is promulgating a rule that makes several targeted regulatory revisions to the existing national primary drinking water regulations

(NPDWRs) for lead and copper. The revisions to the LCR will do the following:

1. Enhance the implementation of the LCR in the areas of monitoring, treatment, customer awareness, and lead service line replacement
2. Improve compliance with the public education requirements of the LCR to ensure drinking water consumers receive meaningful, timely, and useful information needed to help them limit their exposure to lead in drinking water

Lead is a naturally occurring metal that was used regularly in a number of industrial capacities and commonly used in household plumbing materials and water service lines. Lead was used as a component of paint, piping, solder, brass, and as a gasoline additive until the 1980s. The greatest exposure to lead is swallowing or breathing it in lead paint chips and dust. Research has confirmed that lead is highly toxic.

Lead is rarely found in source water. Mostly, lead contamination occurs after water has left the treatment plant due to corrosion of plumbing materials. Since water is naturally corrosive, it corrodes the pipes and plumbing through which it passes. Homes built before 1986 are more likely to have lead pipes, fixtures, and solder. However, new homes are also at risk because even legally lead-free plumbing may contain up to 8-percent lead. Grounding of electrical circuits in homes to water pipes and galvanic action between two dissimilar metals may increase corrosion that could cause lead to leach into the water.

Purpose of Regulating Lead: To protect public health by minimizing lead levels in drinking water, primarily by reducing water corrosivity.

Public Health Benefit: To prevent kidney problems, high blood pressure, and delays in physical and mental development in infants and children.

MCL/MCLG: A TT is triggered at AL = 0.015 mg/L/zero

Monitoring Requirements/Comments: Residential samples taken at the kitchen or bathroom sink tap. ALs must be met in 90 percent of the samples. Follow-up monitoring every 6 months after corrosion controls initiated or optimized. Reduced monitoring requirements for systems consistently meeting the AL. An AL exceedance is not a violation but can trigger other requirements that include monitoring for the following water quality indicators: pH, corrosion, control treatment, source water monitoring/treatment, public education, and lead service line replacement.

Copper is a metal found in natural deposits such as ores containing other elements. Copper is widely used in household plumbing materials.

Purpose of Regulating Copper: To protect public health by minimizing the risk of ingesting copper in drinking water, primarily from the corrosion of pipes.

Public Health Benefit: To prevent gastrointestinal distress due to short-term exposure and to prevent liver or kidney damage from long-term exposure.

MCL/MCLG: A TT is triggered at AL = 1.3 mg/L/1.3 mg/L

Monitoring Requirements/Comments: Residential samples taken at the kitchen or bathroom sink tap. ALs must be met in 90 percent of the samples. Follow-up monitoring every 6 months after corrosion controls initiated or optimized. There are reduced monitoring requirements for systems consistently meeting the AL. An AL exceedance is not a violation but can trigger other requirements that include monitoring for the following water quality indicators: pH, corrosion control treatment, source water monitoring/treatment, public education, and lead service line replacement.

All water systems are required to optimize corrosion control; that is to say, they must do the best they can to control corrosion. Small- and medium-sized systems are considered to have optimized corrosion control if they meet the lead and copper action levels during each of two consecutive six-month sampling periods. Large systems have optimized corrosion control if the difference between the source water lead level and the 90th percentile tap-water lead level is less than 0.005 mg/L, and the 90th percentile copper concentration is less than or equal to half the copper action level (0.65 mg/L) for two consecutive six-month periods.

Any system that is achieving optimal corrosion control and meeting the action limits is permitted to reduce monitoring and reporting frequencies. Large water systems that do not meet the guidelines for optimal corrosion control are required to conduct studies of various types of corrosion control treatment and then submit to the state a plan that would adequately control corrosion in their distribution system.

Small- and medium-sized systems exceeding the action levels must make a written recommendation to the state for a proposed treatment method, but may also be required to conduct similar studies before the state makes a final determination.

Once the state directs a water supplier to install treatment, the agency has 24 months to install the specified treatment and 12 months to collect follow-up samples to determine if the system is working. The state will also determine maximum acceptable levels for pH, alkalinity, calcium (if carbonate stabilization is used), orthophosphate (if an inhibitor with a phosphate compound is used), and silica (if an inhibitor with a silicate compound is used). The system must then continue to operate within these water quality guidelines.

If corrosion control methods fail to reduce lead and copper concentrations below the action levels, the water supplier must collect and analyze source water samples. Data from this sampling is sent to the state along with the water agency's recommended treatment plan for reducing contaminant levels. The state may accept the agency's recommended plan or may require some alternative treatment such as ion exchange, reverse osmosis, lime softening, or coagulation-filtration.

When required to install source water treatment, the agency is allowed 24 months for installation and 12 months to collect follow-up samples of specific water quality indicators. Based on the results of the follow-up sampling, the state determines the maximum allowable source water lead and copper concentrations and the water system is required to meet these state limits on an ongoing basis.

Water systems that continue to exceed the lead action level after installing optimal corrosion control treatment and source water treatment will have to begin a program to replace lead service lines within a maximum of 15 years.

Sampling Guidelines

The sampling required by the Lead and Copper Rule includes tap-water sampling at the consumer's faucet and distribution system sampling. Tap-water samples for initial and routine lead and copper monitoring must be collected at high-risk locations, which are defined as homes with lead solder installed after 1982, homes with lead pipes, and homes with lead service lines.

Tap-water samples for water quality indicators should be taken from representative taps throughout the distribution system. The representative taps can be the same as total coliform sampling sites. These samples will be analyzed for water quality indicator levels to identify optimal treatment and monitor compliance with the rule.

The rule calls for first-draw or first-flush samples, which are water samples taken after the water stands motionless in the plumbing pipes for at least six hours. This rule usually means taking a sample early in the day before water is used in the kitchen or bathroom. The rule permits water utilities to instruct consumers in sampling techniques so that they may collect the samples.

One-liter samples are needed.

Distribution system sampling conducted in connection with corrosion control studies requires samples from representative taps throughout the system as well as samples from entry points to the distribution system.

Initial and Base Monitoring Sample Sites

Compliance with the Lead and Copper Rule depends on meeting the action levels during two consecutive six-month monitoring periods. All public water systems are required to collect one sample for lead and copper analysis from a number of sites depending on population during each six-month monitoring period.

If a system meets the lead and copper action levels or maintains optimal corrosion control treatment for two consecutive six-month periods, tap-water sampling for lead and copper can be reduced to once per year and half the number of sites. After three consecutive years of acceptable performance, tap-water sampling can be reduced to once every three years at the reduced number of sites listed above.

Water Quality Indicator Frequency

All large systems (more than 50,000 persons) and any small- or medium-sized system that exceeds the lead or copper action level will be required to monitor for the following water quality indicators: pH, alkalinity, calcium, conductivity, orthophosphate, silica, and water temperature. Samples must be taken from representative taps throughout the system and at entry points to the distribution system. Two tap-water samples must be collected for each applicable water quality indicator.

In addition to the sampling from representative taps, one sample must be collected every two weeks for each applicable water quality indicator at each entry point to the distribution system.

All large water systems and any small- and medium-sized system that exceed the lead or copper action levels after installing optimal corrosion control treatment must continue to collect samples as follows:

1. 2 samples for each applicable water quality indicator at each of the sampling sites (taps) every 6 months.
2. 1 sample for each applicable water quality indicator at each entry point to the distribution system every 2 weeks.
3. After meeting water quality guidelines for 2 consecutive 6-month monitoring periods, systems may reduce the number of tap samples collected, and after 3 consecutive years of acceptable performance they will be permitted to collect annual samples at the reduced number of sampling points.

Calculation of the 90th Percentile

The action levels that trigger implementation of treatment techniques to reduce lead and copper concentrations are based on the principle that no more than 10 percent of the samples should exceed the limit. To determine whether a system meets this test, it is necessary to figure out the lead or copper concentration on the sample that falls at the 90th percentile.

To calculate the 90th percentile value, write down the results from a set of samples arranging them in order of increasing or decreasing concentration. Number each sample beginning with the number 1 for the smallest concentration. Multiply the total number of samples (which will be the same as the number assigned to the highest concentration) by 0.9. Then, use the value from this calculation to identify the sample with the same number.

The concentration of the sample whose number matches the calculated value is the 90th percentile and is used in determining compliance with the action level. For systems serving fewer than 100 people, the 90th percentile is the average of the highest concentration and the second highest concentration.

Public Education

A public education program developed by the EPA must be delivered to water system customers within 60 days whenever the system exceeds the lead or copper action levels. The information describes the harmful effects of lead in drinking water and tells customers what they can do to reduce their exposure. The education program should continue as long as the system fails to meet the lead or copper action levels. In conjunction with the public education program, the water system must offer to sample a

customer's water if asked to do so. However, the water system is not required to pay for the sampling and analysis and is not required to collect and analyze the sample.

Lead Service Line Replacement

Any water system that continues to exceed the lead and copper action levels even after optimizing corrosion control and installing source water treatment will be required to replace its lead distribution pipes within a maximum of 15 years. A lead pipeline qualifies for replacement if it contributes more than 15 parts per billion to the total tap-water lead levels. Seven percent of the lines meeting this standard must be replaced annually. Customers must be notified 45 days before replacing the lines.

Mercury

In the Code of Federal Regulations Reference: 40 CFR 141.62, mercury is found naturally throughout the environment. Large increases in mercury levels in water can be caused by industrial and agricultural use. The health risk from mercury is greater from mercury in fish than simply from waterborne mercury.

Mercury poisoning may have an acute health effect in large doses, or a chronic health effect in lower doses taken over an extended time period.

Purpose of Regulating Mercury: To improve public health protection and reduce ingestion of mercury.

Public Health Benefit: To prevent kidney damage.

MCL/MCLG: 0.002 mg/L/0.002 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Nitrate

In the Code of Federal Regulations Reference: 40 CFR 141.62, nitrate (as N) in drinking water above the national standard of 10 mg/L poses an immediate threat to children under three months of age. In some infants, excessive levels of nitrate have been known to react with intestinal bacteria that change nitrate to nitrite. It is often difficult to pinpoint sources of nitrate because so many possibilities exist.

Sources of nitrogen may include runoff or seepage from fertilized agricultural lands, municipal and industrial wastewater, refuse dumps, animal feedlots, septic tanks and private sewage disposal systems, urban drainage, and decaying plant debris.

Purpose of Regulating Nitrate: To improve public health protection.

Public Health Benefit: To prevent methemoglobinemia (blue baby syndrome)/diuresis.

MCL/MCLG: 10 mg/L/10 mg/L

Monitoring Requirements: Groundwater annually; surface water quarterly initially, then annually.

Nitrite

Code of Federal Regulations Reference: 40 CFR 141.62, nitrite reacts with hemoglobin in the blood. This reaction will reduce the oxygen-carrying ability of the blood and produce an anemic condition commonly known as blue baby syndrome. Sources of nitrite may include runoff or seepage from fertilized agricultural lands, municipal and industrial wastewater, refuse dumps, animal feedlots, septic tanks and private sewage disposal systems, urban drainage, and decaying plant debris.

Purpose of Regulating Nitrite: To improve public health protection.

Public Health Benefit: To prevent methemoglobinemia (blue baby syndrome)/diuresis.

MCL/MCLG: 1 mg/L/1 mg/L

Monitoring Requirements: One sample during first 3-year compliance period. Repeat frequency determined by state.

Selenium

In the Code of Federal Regulations Reference: 40 CFR 141.62, this mineral occurs naturally in soil and plants, especially in western states. Selenium is found in meat and other foods. Although it is believed to be essential in the diet, indications exist that

excessive amounts of selenium may be toxic.

Studies are underway to determine the amount required for good nutrition and the amount that may be harmful. If a person's intake of selenium came only from drinking water, it would take an amount many times greater than the standard to produce any ill effects.

Purpose of Regulating Selenium: To improve public health protection.

Public Health Benefit: To prevent hair or fingernail loss, numbness of fingers or toes, and circulatory problems.

MCL/MCLG: 0.05 mg/L/0.05 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Thalliumo[48]

In the Code of Federal Regulations Reference: 40 CFR 141.62, thallium is a metal found in natural deposits such as ores containing other elements. An average of 23 ppb of thallium in surface water and 11 ppb in groundwater have been found at hazardous waste sites. Since thallium compounds mix easily in water, you can be exposed if you live near a chemical waste site where thallium emissions have contaminated the water.

The greatest use of thallium is in specialized electronic research equipment. It is also used for production of optical lenses, jewelry, semiconductors, dyes, and pigments. The most common source of thallium poisoning is ingestion of rat poisons and insecticides.

Purpose of Regulating Thallium: To improve public health protection.

Public Health Benefit: To protect nervous system, lung/heart/kidney/liver/intestinal problems.

MCL/MCLG: 0.002 mg/L/0.0005 mg/L

Monitoring Requirements: Once a year for surface water; once every 3 years for groundwater. To minimize monitoring costs, use historical data, waivers, susceptibility waivers, or make composite samples.

Organic Standards

Organic chemicals are either natural or synthetic chemical compounds that contain carbon. Synthetic organic chemicals (SOCs) are manmade compounds and are used throughout the world as pesticides, paints, dyes, solvents, plastics, and food additives. **Volatile organic chemicals (VOCs)** are a subcategory of organic chemicals. These chemicals are termed volatile because they evaporate easily.

The most commonly found VOCs are THMs, trichloroethylene (TCE), tetrachloroethylene, and 1,1-dichloroethylene. THMs were the first regulated VOCs when EPA finalized regulations in 1979. The most common sources of organic contamination of drinking water are pesticides and herbicides, industrial solvents, and DBPs (THMs and haloacetic acids).

Millions of pounds of pesticides are used on croplands, forests, lawns, and gardens in the United States each year. They drain off into surface waters or seep into underground water supplies. Spills, poor storage, improper application, and haphazard disposal of organic chemicals have resulted in widespread groundwater contamination. A critical problem occurs once groundwater is contaminated, it may remain that way for a long time. Many organic chemicals pose health problems if they get into drinking water and the water is not properly treated.

In 2011, EPA decided to address up to 16 volatile organic compounds (VOCs) as a group that may cause cancer. The agency determined that they represent a near-term opportunity and it is likely that the public health goal for all VOCs would likely be set at zero because they may cause cancer. A preliminary evaluation of occurrence indicates that some of these VOCs may co-occur. This group will include trichloroethylene (TCE) and tetrachloroethylene (PCE).

EPA determined in March 2010 that the drinking water standards for TCE and PCE need to be revised. Addressing these VOCs as a group will help reduce exposure to these contaminants.

Trichloroethylene (TCE)

In the Code of Federal Regulations Reference: 40 CFR 141.50, although the use of TCE is declining because of stringent regulations, it was, for many years, a common ingredient in household products (spot removers, rug cleaners, and air fresheners), dry cleaning agents, industrial metal cleaners and polishes, refrigerants, and even anesthetics. Its wide range of use is perhaps why TCE is the organic contaminant most frequently encountered in groundwater.

Purpose of Regulating Trichloroethylene: To improve public health protection.

Public Health Benefit: To prevent cancer risks; liver problems.

MCL/MCLG: 0.005 mg/L/zero

Monitoring Requirements: Four consecutive quarterly samples during first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems. These requirements apply to community and non-community water systems.

1,1-Dichloroethylene

In the Code of Federal Regulations Reference: 40 CFR 141.50, this solvent is used in manufacturing plastics and, more recently, in the production of 1,1,1-trichloroethane.

Purpose of Regulating 1,1-Dichloroethylene: To improve public health protection.

Public Health Benefit: To prevent impacts to the liver, kidneys, heart, and central nervous system

MCL/MCLG: 0.007 mg/L/0.007 mg/L

Monitoring Requirements/Comments: For VOCs: Four consecutive quarterly samples during first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems.

With the completion of source water assessments, primacy agencies are allowed to develop alternative monitoring requirements. Applies to community water systems and non-transient

Non-community water systems.

Vinyl Chloride

In the Code of Federal Regulations Reference: 40 CFR 141.50, billions of pounds of this solvent are used annually in the United States to produce polyvinyl chloride (PVC), the most widely used ingredient for manufacturing plastics throughout the world. Also, evidence exists that vinyl chloride may be a biodegradation end-product of TCE and PCE under certain environmental conditions.

Purpose of Regulating Vinyl Chloride: To improve public health protection.

Public Health Benefit: To prevent cancer in humans.

MCL/MCLG: 0.002 mg/L/zero

Monitoring Requirements/Comments: For VOCs: Four consecutive quarterly samples during first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems.

With the completion of source water assessments, primacy agencies are allowed to develop alternative monitoring requirements. Applies to community water systems and non-transient non-community water systems.

Carbon Tetrachloride

In the Code of Federal Regulations Reference: 40 CFR 141.50, carbon tetrachloride was once a popular household solvent, a frequently used dry cleaning agent, and a charging agent for fire extinguishers. Since 1970, however, carbon tetrachloride has been banned from all use in consumer goods in the United States.

In 1978, carbon tetrachloride was banned as an aerosol propellant. Currently, its principal use is in the manufacture of fluorocarbons, which are used as refrigerants.

Purpose of Regulating Carbon Tetrachloride: To improve public health protection.

Public Health Benefit: To prevent liver problems and cancer.

MCL/MCLG: 0.005 mg/L/zero

Monitoring Requirements: Four consecutive quarterly samples during first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems. These requirements apply to community and non-community water systems.

Benzene

In the Code of Federal Regulations Reference: 40 CFR 141.50, benzene is used primarily in the synthesis of styrene (for plastics), phenol (for resins), and cyclohexane (for nylon). Other uses include the production of detergents, drugs, dyes, and insecticides. Benzene is still being used as a solvent and as a component of gasoline. It is also discharged from factories and leaches from gas storage tanks and landfills.

Purpose of Regulating Benzene: To improve public health protection.

Public Health Benefit: To prevent anemia, a decrease in blood platelets, and cancer.

MCL/MCLG: 0.005 mg/L/zero

Monitoring Requirements: Four consecutive quarterly samples during first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems. These requirements apply to community and non-community water systems.

Para-Dichlorobenzene (p-Dichlorobenzene)[2]

In the Code of Federal Regulations Reference: 40 CFR 141.50, the principal uses of p-dichlorobenzene are in moth control (moth balls and powders) and as lavatory deodorants. It is also used as an insecticide and fungicide on crops; in the manufacture of other organic chemicals; and in plastics, dyes, and pharmaceuticals.

The major source of p-dichlorobenzene in drinking water is from surface water sources. Low levels at best since it does not dissolve easily in water and quickly evaporate into the air.

Purpose of Regulating Para-Dichlorobenzene (p-Dichlorobenzene): To improve public health protection.

Public Health Benefit: To prevent kidney/liver/spleen/circulatory system problems.

MCL/MCLG: 0.075 mg/L/0.075 mg/L

Monitoring Requirements: Four consecutive quarterly samples during the first compliance period. Compliance is based on annual average of quarterly samples. If no detections are found during the initial round, two quarterly samples are required each year for systems serving greater than 3,300; one sample is required every 3 years for smaller systems. These requirements apply to community and non-community water systems.

Disinfection By-Products[3]

Disinfection of drinking water by the addition of chlorine has long been considered a highly effective yet relatively low-cost method of preventing widespread outbreaks of waterborne diseases. In addition to reacting with disease-causing organisms in water, however, chlorine also reacts with many other types of organic materials.

The EPA has published information on scientific research which indicates that certain byproducts of water disinfection are linked to increases cancer incidence. In some cases, the research results are contradictory, showing no adverse health effects. EPA regulators weigh the public health benefits of disinfection against the risks of potentially harmful disinfection byproducts and continue to

conduct research. They have adopted enforceable regulations to limit occurrence of disinfection byproducts in drinking water for a group of four total trihalomethanes (TTHMs) and the individual byproducts chlorite and bromate.

THMs are an example of a compound formed by the reaction of chlorine with organic matter in water. THMs are suspected of being carcinogenic and have been regulated by EPA in the 1996 SDWA amendments. The MCL for TTHMs is 0.080 milligram per liter or 80 micrograms per liter.

In May 1996, EPA published the Information Collection Rule (ICR). This rule required large public water systems to undertake extensive monitoring of microbial contaminants and DBPs in their water systems. Also, some water systems conducted studies on the use of granular activated carbon and membrane processes. The data reported under the ICR were used by EPA to study the risks and tradeoffs involved in disinfecting drinking water and adopt additional regulations if necessary. The ICR data form the scientific basis for EPA's development of the Enhanced Surface Water Treatment Rule and the Disinfectants and Disinfection Byproducts Rule.

EPA issued the Stage 1 DBPR on December 16, 1998 (Federal Register 63, No. 241). This rule set new MCLGs and MCLs for TTHMs, HAA5, bromate, and chlorite. Maximum residual disinfectant level goals (MRDLGs) and maximum residual disinfectant levels (MRDLs) have also been set for chlorine, chloramine, and chlorine dioxide.

The Stage 1 DBPR attempts to further reduce potential formation of harmful DBPs by requiring the removal of THM precursors. A treatment technique of enhanced coagulation, enhanced softening, or use of granular activated carbon (GAC) applies to conventional filtration systems. In most cases, systems must reduce total organic carbon (TOC) levels based on specific source water quality factors.

For large systems (serving more than 10,000 persons) that use surface water or groundwater under the direct influence of surface water, the compliance date for the Stage 1 DBPR was January 1, 2002. Small systems (serving fewer than 10,000) that use surface water or groundwater under the direct influence of surface water and all groundwater systems must have complied by January 1, 2004.

The Stage 1 DBPR has very specific laboratory and monitoring requirements. The routine monitoring requirements include the following regulated contaminants/disinfectants:

1. TTHM/HAA5
2. Bromate
3. Chlorite
4. Chlorine/chloramines
5. Chlorine dioxide
6. DBP precursors (TOC/alkalinity/specific UV absorbance)

Also, the Stage 1 DBPR specifies the monitoring coverage in terms of surface water, groundwater, and groundwater under direct influence (GWUDI), population served, and the type of filtration system and disinfection system. Monitoring frequency depends on the type of source water, population served, and type of treatment and disinfection system. The routine monitoring requirements are based on the regulated contaminants/disinfectants and include the MCL, MRDL, analytical method, preservation/quenching agent, holding time for sample/extract, and sample container size and type.

On December 15, 2005, EPA promulgated the Stage 2 DBPR. This rule reduces potential cancer and reproductive and developmental health risks from DBPs in drinking water, which form when disinfectants are used to control microbial pathogens. This final rule strengthens public health protection for consumers by tightening compliance monitoring requirements for two groups of DBPs: TTHMs and HAA5.

The rule targets systems with the greatest risk and builds incrementally on existing rules. This regulation reduces DBP exposure and related potential health risks and provides more equitable public health protection. The Stage 2 DBPR was promulgated simultaneously with the Long Term 2 Enhanced Surface Water Treatment Rule to address concerns about risk tradeoffs between pathogens and DBPs.

Under the Stage 2 DBPR, systems will conduct an evaluation of their distribution systems, known as an Initial Distribution System Evaluation (IDSE), to identify the locations with high DBP concentrations. These locations are used by the systems as the sampling sites for Stage 2 DBPR compliance monitoring.

Compliance with the maximum contaminant levels for two groups of DBPs (TTHMs and HAA5) is calculated for each monitoring location in the distribution system. This approach,

referred to as the locational running annual average (LRAA), differs from previous requirements, which determine compliance by calculating the running annual average of samples from all monitoring locations across the system.

The Stage 2 DBPR also requires each system to determine if they have exceeded an operational evaluation level, which is identified using their compliance monitoring results. The operational evaluation level provides an early warning of possible future MCL violations, which allows the system to take proactive steps to remain in compliance. A system that exceeds an operational evaluation level is required to review their operational practices and submit a report to their state that identifies actions that may be taken to mitigate future high DBP levels; particularly, those levels that may jeopardize their compliance with the DBP MCLs.

Radionucleotide Standards

EPA promulgated the Radionuclides Rule on December 7, 2000. The purpose of the Radionuclides Rule is to reduce the exposure to radionuclides in drinking water, which reduces the risk of cancer. This rule also improves public health protection by reducing exposure to all radionuclides. The rule applies to all community water systems.

The public health benefits from the rule include reduced exposure to uranium, which can cause toxic kidney effects and cancer.

In the Code of Federal Regulations Reference: 40 CFR 141.24, radioactivity is the only contaminant that has been shown to cause cancer for which standards have been set. Three radioactive elements, radon, radium, and uranium, occur naturally in the ground and dissolve into groundwater supplies. However, the possible exposure to radiation in drinking water is only a fraction of the exposure from all natural sources. The main source of radioactive material in surface water is fallout from nuclear testing. Other sources could be nuclear power plants, nuclear fuel processing plants, and uranium mines. Those sources are monitored constantly and no great risk of contamination exists, barring accidents.

Alpha and radium radioactivity occur naturally in groundwater in parts of the West, Midwest, and Northeast. Standards for those types of radioactivity and for manmade, or beta radiation, have been set at levels of safety comparable to other contaminants. The MCLs for radiological contaminants are divided into two categories: natural radioactivity that results from well water passing through deposits of naturally occurring radioactive materials and manmade radioactivity such as that which might result from industrial wastes, hospitals, or research laboratories.

A pCi/L, picoCurie per Liter, is a measure of radioactivity. One picoCurie of radioactivity is equivalent to 0.037 nuclear disintegrations per second. For surface water systems serving more than 100,000 persons and systems determined by the state to be vulnerable. Monitoring for natural radioactivity contamination is required every four years for surface water and groundwater community systems. Routine monitoring procedures to follow

are:

1. Test for gross alpha activity; if gross alpha exceeds 5 pCi/L, then
2. Test for radium 226; if radium 226 exceeds 3 pCi/L, then
3. Test for radium 228.

The MCL for gross beta particle activity is 4 mrem/yr for water systems using surface water and serving more than 100,000 people, and for any other community system determined by the state to be vulnerable to this type of contamination. After the initial monitoring period, beta radiation must be monitored every 4 years unless the MCL is exceeded or the state determines that more frequent monitoring is appropriate.

Regulation of radon continues to be a source of considerable debate. EPA proposed a maximum contaminant level in 1991 and then withdrew the proposed MCL in 1997 in response to the 1996 SDWA amendments. EPA published a proposed regulation for radon in 1999, but the final MCL has not been published.

The final Radionuclides Rule was published in 2000. The rule retains the current standards for radium 226 and 228, gross alpha activity, and gross beta particle activity, but establishes a new MCL 30 µg/L for uranium. The EPA has indicated that it will continue to review the standard for beta particle activity and may revise the MCL in the future. EPA must base its new rules on a scientific risk assessment and an analysis of the amount of health risk reduction that will be achieved and the cost of implementing the new rules.

Microbial Standards

Microbial contamination of drinking water can pose a potential public health risk in terms of acute outbreaks of disease. Bacteria, viruses, and other organisms have long been recognized as serious contaminants of drinking water. Organisms such as *Giardia*, *Cryptosporidium*, and *E. coli* (a type of coliform bacteria) cause almost immediate gastrointestinal illness when people consume them in water. Waterborne diseases such as typhoid, cholera, infectious hepatitis, and dysentery have been traced to improperly disinfected drinking water.

In most communities, drinking water is treated to remove contaminants before being piped to consumers, and bacterial contamination of municipal water supplies has been largely eliminated by adding chlorine or applying other forms of disinfection to drinking water to prevent waterborne diseases. By treating drinking water and wastewater, diseases such as typhoid and cholera have been virtually eliminated.

Many types of coliform bacteria from human and animal wastes may be found in drinking water if the water is not properly treated. Often, the bacteria do not cause diseases transmitted by water, although certain coliforms have been identified as the cause of traveler's diarrhea. In general, however, the presence of coliform bacteria indicates that other harmful organisms may be present in the water.

Throughout the early 1990s, chemical contaminants in drinking water were the focus of EPA's regulatory efforts. With passage of the 1996 SDWA amendments, Congress directed EPA to focus on microbial contaminants and to promulgate a series of new regulations to improve treatment effectiveness. Significant new regulations of the microbial contaminant *Cryptosporidium* were promulgated in December 1998. The new regulations consist of mandatory treatment techniques similar to the current regulations for *Giardia* and coliform bacteria. Filtration and disinfection requirements for surface water systems are currently in place and the final Ground Water Rule was signed in 2006. These regulations significantly affect the water treatment processes of most water suppliers.

Total Coliform Rule

In the Code of Federal Regulations Reference: 40 CFR 141 Subpart C, coliforms are bacteria that are always present in the digestive tracts of animals, including humans, and are found in their wastes. They are also found in plant and soil material. The most basic test for bacterial contamination of a water supply is the test for total coliform bacteria. Total coliform counts give a general indication of the sanitary condition of a water supply.

Coliforms include the following:

1. Total coliforms—include bacteria that are found in the soil, in water that has been influenced by surface water, and in human or animal waste.
2. Fecal coliforms—are the group of the total coliforms that are considered to be present specifically in the gut and feces of warm-blooded animals. Because the origins of fecal coliforms are more specific than the origins of the more general total coliform group of bacteria, fecal coliforms are considered a more accurate indication of animal or human waste than the total coliforms.

Escherichia coli (*E. coli*) is the major species in the fecal coliform group. Of the five general groups of bacteria that comprise the total coliforms, only *E. coli* is generally not found growing and reproducing in the environment. Consequently, *E. coli* is considered to be the species of coliform bacteria that is the best indicator of fecal pollution and the possible presence of pathogens.

2012 Revised Total Coliform Rule (RTCR)

EPA has revised the Total Coliform Rule so that public water systems in the US take steps to ensure the integrity of the drinking water distribution system and monitoring for the presence of microbial contamination. Public water systems and the state and local agencies that oversee them must comply with the RTCR beginning April 1, 2016. The final RTCR requires the following:

1. Public water systems are to notify the public if a test exceeds the MCL for *E. coli* in drinking water
2. Public water systems that are at risk and therefore vulnerable to microbial contamination are required to identify and fix the problems, including the potential sources and the pathways of contamination
3. Criteria will be used for public water systems that are well operated to qualify for and stay on reduced monitoring, which could reduce water system burden
4. Provide incentives for better system operation, in particular small systems

5. Require additional monitoring requirements for seasonal systems such as campgrounds and state and national parks

The RTCR establishes an MCLG and an MCL for *E. coli* and eliminates the MCLG and MCL for total coliforms, replacing them with treatment techniques for coliforms that require assessment and corrective action. EPA has established an MCLG of zero for *E. coli*, which is a more specific indicator of fecal contamination and those pathogens that are potentially more harmful than total coliform. EPA has removed the 1989 MCLG and MCL for total coliforms, although the acute total coliform MCL violation under the 1989 TCR has been maintained as the MCL for *E. coli* under the RTCR.

Under the new treatment technique, total coliforms serve as the indicator of a potential pathway of contamination into the system's distribution system. Public water supplies that exceed a specified frequency of total coliform occurrence must conduct an assessment to determine if any sanitary deficiencies exist; if found, they must be corrected. A public water system that experiences an *E. coli* MCL violation must conduct an assessment and correct any sanitary defects that are identified.

Monthly notification requirements based only on the presence of total coliforms will no longer be required. Instead, the RTCR will require public notification when an *E. coli* MCL violation occurs, indicating a potential health threat or when a water system fails to assess and take corrective action.

Sanitary Survey

In the Code of Federal Regulations Reference: 40 CFR 141.2, sanitary surveys are conducted to identify possible health risks that may not be discovered by routine coliform sampling. The

Total Coliform Rule requires community water systems serving fewer than 4,100 persons to complete an initial sanitary survey by June 1994 and to conduct subsequent surveys every 5 years.

Non-community water systems are required to complete an initial sanitary survey by June 1999 and subsequent surveys every 5 years with the exception of those systems with protected and disinfected groundwater sources, which are allowed 10 years for subsequent surveys.

A sanitary survey requires detailed planning, a thorough system survey, and reporting of the results. The planning portion involves a review of water quality records for compliance with applicable microbial, inorganic chemical, organic chemical, and radiological contaminant MCLs as well as the records of compliance with the monitoring requirements for those contaminants.

The actual field survey is a detailed evaluation and inspection of the source of the water supply and all conveyances, storage, treatment, and distribution facilities to ensure protection from all pollution sources.

The final report includes the date(s) of the survey, who was present during the survey, the survey findings, the recommended improvements to correct identified problems, and the target dates of completion for any improvements.

Sampling Plan

The Total Coliform Rule requires each water supply system to develop and follow a written sampling plan. Each plan must specifically identify sampling points throughout the distribution system. Sampling plans must be approved by the state regulatory agency, and it is necessary to check with the state agency to determine the details of their review process and what documents need to be submitted.

Laboratory Procedures

In the Code of Federal Regulations Reference: 40 CFR 141.21 and 40 CFR 141 Subpart C, with regard to coliform testing methodology, EPA maintains a current list of analytical methods that are approved for monitoring drinking water supplies that is published and updated in 40 CFR 141. Examples of the acceptable analytical methods for determining total coliforms include the following:

1. Multiple-tube fermentation technique (MTF)
2. Membrane filter technique (MF)
3. Presence-absence coliform test (P-A)
4. Colilert™ system (ONPG-MUG test)
5. Colisure test

Regardless of the method used, the standard sample volume for total coliform testing is now 100 ml. This volume is an increase over the past testing method using 50 mL for the MTF technique.

The multiple-tube fermentation method of testing for coliforms determines the presence or absence of coliforms by the multiple-tube dilution method. This test is a process whereby equal portions of a sample (100 mL) are added to 10 tubes containing a culture medium and an inverted vial. If gas accumulates in the inverted vial, it indicates presumptive evidence of coliform organisms and the sample is considered coliform-positive. If no gas forms in any of the vials, the sample is coliform-negative.

The membrane filter method provides for filtering a 100 mL water sample through a thin, porous, cellulose membrane filter under a partial vacuum. The filter is placed in a sterile container and incubated in contact with a special liquid called a culture medium, which the bacteria use as a food source. Colonies of bacteria then grow on the media. The coliform colonies are visually identified, counted, and recorded as the number of coliform colonies per 100 mL of sample.

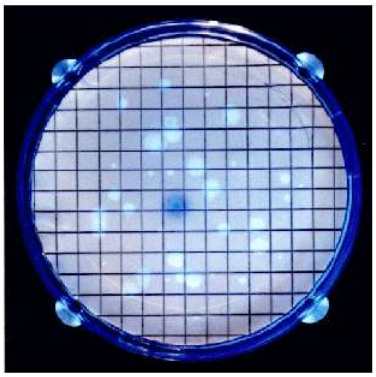


Figure 2.9.1: Membrane filter test for coliforms.. (Copyright;[4] Image by the EPA is in the public domain)

The presence-absence (P-A) test for the coliform group is a simple modification of the multiple-tube procedure. Even though this simplified test uses only one large test portion (100 mL) in a single culture bottle, the results still indicate the presence or absence of coliform bacteria and thus meet the testing requirements.

The Colilert™ system is a privately developed version of the ONPG-MUG test procedure that meets the EPA's laboratory methods requirements. The ONPG-MUG test indicates the presence or absence of coliform bacteria within 24 hours. Although the Colilert™ method can yield presence-absence results within 24 hours and is easier to perform than the Membrane Filtration (MF) method, operators should be aware of the limitations of these tests in evaluating samples for regulatory purposes. The results for the Colilert™ and MF tests are not always comparable, which may be due to the following:

1. Interferences in the sample that may suppress or mask bacterial growth
2. Greater sensitivity of the Colilert™ media
3. Added stress to organisms related to filtering
4. The fact that different media may obtain better growth for some bacteria

These test methods are approved by the EPA for reporting under the Safe Drinking Water Program. When these tests produce conflicting results, however, the safest course of action is to increase monitoring and treatment efforts until the results for each test is negative.

The Colisure test is a presence-absence test for coliform bacteria. A sample of water is added to a dehydrated medium and, after 24 to 48 hours, the medium is examined for the presence of coliforms.

Table 2.9.1: Total Coliform Indicator Color Chart

Positive Test	Negative Test
• Many gas bubbles present • Gel rises to surface • Liquid below gel is cloudy • Indicator turns yellow	• Liquid above gel is clear • Indicator remains red or turns yellow with no gas bubbles • Gel remains at bottom of tube

Water supply systems may contain various other types of bacteria besides coliforms. These organisms are nonpathogenic bacteria and are sometimes referred to as heterotrophic bacteria. During the analyses of water samples for coliforms, heterotrophic bacteria sometimes interfere with the test causing one of the following reactions:

1. MTF technique: a turbid culture with no gas production
2. P-A test: a turbid culture in the absence of an acid reaction
3. MF technique: confluent growth or a coliform colony number too numerous to count

The sample being tested can be considered invalid if any of these situations occurs and total coliforms are not detected. A replacement sample must be taken from the same location within 24 hours of receiving the laboratory results. If the replacement sample also shows heterotrophic interference but tests positive for total coliforms, the sample is considered valid.

Monitoring Frequency

The routine monitoring frequency for community water systems is based on the population served. Routine monitoring frequencies for non-community systems are based on the source of supply and, in some cases, the population served. Whenever a routine sample tests positive for total coliform, two provisions of the Total Coliform Rule take effect: repeat samples (formerly referred to as check samples) must be taken and the original coliform-positive sample must be tested for the presence of fecal coliforms or *E. coli* to determine whether an actual or potential violation of the coliform MCL exists.

The reason repeat samples are required is to investigate whether the original coliform-positive sample was caused by a contamination problem that exists throughout the distribution system or if it is a localized problem that exists only at that one sampling point. With this information, appropriate corrective action can be taken to eliminate the problem as quickly as possible.

The Total Coliform Rule specifies how many repeat samples must be taken, when, and from what locations. It also directs the water utility to collect a specific number of samples the following month, based on the number of routine samples ordinarily collected.

Non-community systems serving more than 1,000 people have the same requirements as community water systems. Non-community systems serving fewer than 1,000 people are required to collect one routine sample per quarter. When the routine sample tests positive, four repeat samples are required in the same quarter and five samples are required the following quarter.

Whenever a routine or repeat sample tests positive for total coliform, the water agency must collect a set of three or four repeat samples within 24 hours of receiving the laboratory results. At least one of the repeat samples must be taken from the same tap as the original coliform-positive sample; the remaining repeat samples in the set must be collected at nearby taps (within five service connections of the original sampling point), upstream and downstream of the original.

Repeat samples must be taken until no coliforms are detected or until the MCL is exceeded and the state is notified.

Determining Compliance

The MCLG for total coliforms (including fecal coliforms and *E. coli*) is zero. The MCL, based on the presence-absence concept, is as follows:

1. For water systems analyzing at least 40 samples per month, no more than 5.0 percent of the samples (including routine and repeat samples) may be positive for total coliforms.
2. For water systems analyzing fewer than 40 samples per month, no more than one sample per month may be positive for total coliforms.

The Revised Total Coliform Rule makes another significant change in the way compliance is calculated. All valid coliform-positive samples, routine and repeat samples, must be counted when calculating compliance with the monthly MCL. Under previous regulations, check or repeat samples were not included in the monthly MCL calculation. On a case-by-case basis, the state may declare a sample invalid for one of several reasons, including interference by heterotrophic bacteria during laboratory analysis, as previously discussed.

Total-coliform-positive samples may be invalidated by the state under any of the following conditions:

1. The analytical laboratory acknowledges that improper sample analysis caused the positive result
2. The state determines that the contamination is a local plumbing problem

3. The state has substantial grounds to believe that the positive result was unrelated to the quality of drinking water in the distribution system

Reporting and Notification Requirements

Reporting frequencies for coliform test results increase in step with the urgency of the problem. A water agency must report the results of monthly coliform testing to the state regulatory agency within the first 10 days of the following month.

Any time a water agency fails to collect a sample as required, the state must be notified within 10 days after the system learns of the violation. An invalid sample result is considered a failure to monitor and must be reported.

If the MCL is exceeded, the state must be notified no later than the end of the next business day and the public within 14 days. This requirement could occur when the water agency exceeds its monthly coliform-positive limit or when test results show the presence of fecal coliforms or *E. coli* in any sample.

The most critical situation exists when either of two situations occurs:

1. A routine sample tests positive for total coliforms and for fecal coliforms or *E. coli*, and any repeat sample tests positive for total coliforms.
2. A routine sample tests positive for total coliforms and negative for fecal coliforms or *E. coli*, and any repeat sample tests positive for fecal coliforms or *E. coli*.

These situations are considered an acute risk to health. This occurrence is a Tier 1 violation, which requires that the state and the public be notified within 24 hours.

Key Terms

- **Inorganic contaminants** – non-Carbon-based contaminants, such as lead and mercury;
- **Microbial contaminants** - bacteria, viruses, and protozoa
- **Organic contaminants** – Carbon-based contaminants, which include pesticides, herbicides, THMs, solvents, and other synthetic organic compounds
- **Primary standards – federal** and state standards of contaminants with health effects; the Maximum Contaminant Level (MCL) for a contaminant
- **Secondary standards –** federal and state standards for contaminants that affect the aesthetic qualities relating to the public acceptance of drinking water
- **Radiologic contaminants** - natural and manmade sources of radiation, including uranium
- **Volatile organic compounds –** a subcategory of organic chemicals. These chemicals are termed volatile because they evaporate easily.
- **Turbidity**, such as small particles suspended in water that interfere with light penetration and disinfection

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[1] Agency for Toxic Substances and Disease Registry (ATSDR). 1992 Toxicological profile for thallium. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

[2] https://www.atsdr.cdc.gov/toxfaqs/tfacts10.pdf

[3] https://www.epa.gov/sites/default/files/2015-09/documents/why_are_disinfection_byproducts_a_public_health_concern.pdf

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2.9.1: Review Questions

Review Questions

1. **List the metals in the Safe Drinking Water Act that are considered to be primary contaminants.**

Contaminant	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water

2. **List the radiologic contaminants that drinking water plants are required to be tested for in the Safe Drinking Water Act.**
3. **What is the action level for lead and copper in the Safe Drinking Water Act?**
4. **What is the MCL for nitrate in drinking water?**
5. **Which contaminant has a primary and secondary contaminant limit?**
6. **List the disinfection by-products that are monitored and controlled in the Safe Drinking Water Act?**
7. **Describe a Sanitary Survey.**

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2.9.2: Chapter Quiz

Chapter Quiz

1. In the Code of Federal Regulations, 40CFR 141.2, a sanitary survey should be conducted every _____.

1. one per year
2. every two years
3. every five years
4. every six years

2. EPA uses the _____ to collect data for contaminants suspected to be present in drinking water, although they do not have health-based standards set under the Safe Drinking Water Act.

1. Maximum Contaminant Level
2. Maximum Contaminant Level Goal
3. Unregulated Contaminant Monitoring
4. Secondary Maximum Contaminant Level

3. Which of the primary contaminants has an action level rather than an MCL?

1. THMs and HAA5s
2. Arsenic
3. Mercury
4. Lead and Copper

4. In the Code of Federal Regulations Reference: 40 CFR 141.62, the amounts of cadmium that are found in natural waters in the United States is small. Waste discharges from the electroplating, photography, insecticide, and metallurgy industries can increase cadmium levels. The most common source of cadmium in drinking water is from galvanized pipes and fixtures. What is the MCL and MCLG for Cadmium?

1. 5 ppb
2. 50 ppb
3. 5 ppm
4. 50 ppm

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2.10: Secondary Standards

Learning Objectives

After reading this section, you should be able to:

- Describe the secondary standards
- Outline the secondary contaminants
- Explain physical standards
- Outline levels of violations

Enforcement of Regulations

The National Secondary Drinking Water Regulations control contaminants in drinking water that primarily affect the aesthetic qualities relating to the public acceptance of drinking water. These regulations are called **secondary standards**. At considerably higher concentrations of these contaminants, health implications may also exist as well as aesthetic (or appearance) degradation. These regulations are not federally enforceable; however, some states have passed laws requiring the state health agency to enforce the regulations.

Secondary Maximum Contaminant Levels

Secondary Maximum Contaminant Levels (SMCLs) apply to public water systems and, in the judgment of the EPA Administrator, are necessary to protect the public welfare or for public acceptance of the drinking water. The SMCL means the maximum permissible level of a contaminant that is delivered to the free-flowing outlet of the ultimate user of a public water system.

Contaminants added to the water under circumstances controlled by the user, except those contaminants resulting from corrosion of piping and plumbing caused by water quality, are excluded by definition. The only exceptions are those resulting from corrosion of piping and plumbing caused by water quality. Currently, 15 secondary standards exist. States may establish higher or lower levels depending on local conditions, providing that public health and welfare are adequately protected.

Aesthetic qualities are important factors in public acceptance and confidence in a public water system. States are encouraged to implement SMCLs so that the public will not be driven to obtain drinking water from potentially lower-quality, higher risk sources. Many states have chosen to enforce Primary and SMCLs to ensure that the consumer is provided with the best quality water available.

Monitoring

In order to monitor, you must collect samples for secondary contaminants at a free-flowing outlet of water being delivered to the consumer. Monitor contaminants in these regulations at least as often as the monitoring performed for inorganic chemical contaminants listed in the Primary Drinking Water Regulations as applicable to community water systems. For surface water systems, the rule means yearly monitoring is required; for groundwater systems, monitor at least once every three years. Collect monthly distribution system physical water quality monitoring samples for color and odors. More frequent monitoring would be appropriate for specific contaminants such as pH, color, odor, or others, under certain circumstances as directed by the state.

Secondary Contaminants

Aluminum

Until relatively recently, most environmental aluminum was found in forms that did not greatly affect humans and other animals. Acid rain, however, has caused a significant increase in aluminum exposure. The average daily intake of aluminum in the general population is about 20 milligrams per day; the SMCL is 0.05 to 0.2 mg/L. Although aluminum is regulated as a secondary contaminant because precipitates of the metal can cause cloudy-looking water, aluminum compounds may also interfere with absorption of fluoride in the gastrointestinal tract and may decrease the absorption of calcium, iron, and cholesterol. Many over-the-counter antacids contain aluminum and use of these products frequently causes constipation, which is thought to be the result of the gastrointestinal effects.

Chloride

The SMCL for chloride is 250 mg/L.

Undesirable Effects

- Objectionable salty taste in water
- Corrosion of the pipes in hot water systems and other pipelines

Studies Concerning the Mineralization Effects of Water Indicate

- Major taste effects are produced by anions (where TDS was studied).
- Chloride produces a taste effect somewhere between the milder sulfate and the stronger carbonate.
- Laxative effects are caused by highly mineralized waters.

Mineralized waters often contain chloride as well as high levels of sodium and magnesium sulfate.

Corrosion Effects

- Studies indicate that corrosion depends on concentration of TDS (TDS may contain 50 percent chloride ions).
- Domestic plumbing, water heaters, and municipal waterworks equipment will deteriorate when high concentrations of chloride ions are present.

Example

Where the TDS = 200 mg/L (Chloride = 100 mg/L), water heater life will range from 10 to 13 years. Water heater life declines uniformly as a function of TDS-1 year shortened life per 200 mg/L additional TDS.

Color

The SMCL for color is 15 color units. The level of this water quality indicator is not known to be a measure of the safety of water. However, high color content may indicate the following:

- High organic chemical contamination
- Inadequate treatment
- High disinfectant demand and the potential for production of excess amounts of DBPs

Color may be caused by:

- Natural color-causing solids such as aromatic, polyhydroxy, methoxy, and carboxylic acids
- Fulvic and humic acid fractions
- Presence of metals such as copper, iron, and manganese

Rapid changes in color levels may provoke more citizen complaints than relatively high, constant color levels.

Copper

The SMCL for copper is 1.0 mg/L. Soft water containing a low level (0.5 mg/L) of copper may cause blue or blue-green staining of porcelain. Higher levels (4 mg/L) of copper will stain clothing and blond hair. When soap is used with water having a copper concentration greater than 1 mg/L, insoluble green curds will form.

Corrosivity

The corrosivity of water indicates the rate at which water causes the gradual decomposition or destruction of a material (such as a metal or cement lining). The severity and type of corrosivity are dependent on the chemical and physical characteristics of the water and the material.

Corrosivity causes materials to deteriorate and go into solution (be carried by the water). Corrosion of toxic metal pipe materials such as lead can create a serious health hazard. Corrosion of iron may produce a flood of unpleasant telephone calls from consumers complaining about rusty water, stained laundry, and bad tastes.

Corrosivity can cause the reduction of the carrying capacity of a water main. This reduced carrying capacity can cause an increase in pump energy costs and may reduce distribution system pressures. Leaks in water mains due to corrosivity may eventually require replacement of a water main.

Fluoride

Fluoride produces two effects, depending on its concentration. At levels of 6 to 8 mg/L, fluoride may cause skeletal fluorosis (the bones become brittle) and stiffening of the joints. For this reason, fluoride has been added to the list of primary standards (having health effects).

At levels of 2 mg/L and greater, fluoride may cause dental fluorosis, which is discoloration and mottling of the teeth, especially in children. EPA has recently reclassified dental fluorosis as a cosmetic effect, raised the primary drinking water standard from 1.4 to 2 mg/L to 4 mg/L, and established a secondary standard of 2 mg/L for fluoride.

Foaming Agents

The SMCL for foaming agents is 0.5 mg/L.

Undesirable Effects

1. Causes frothing and foaming, which are associated with contamination (greater than mg/L).
2. Imparts an unpleasant taste (oily, fishy, perfume-like) (less than 1.0 mg/L).

Information

1. Because no convenient foamability test exists and because surfactants are one major class of substances that cause foaming, this property is determined indirectly by measuring the anionic surfactant (MBAS) concentration in the water.
2. Surfactants are synthetic organic chemicals and are the principal ingredient of household detergents.
3. The requirement for biodegradability led to the widespread use of linear alkylbenzene sulfonate (LAS), an anionic surfactant.
4. Concentrations of anionic surfactants found in drinking waters range from 0 to 2.6 mg/L in well supplies and 0 to 5 mg/L in surface water supplies.
5. LAS is essentially odorless. The odor and taste characteristics are likely to arise from the degradation of waste products rather than the detergents.
6. If water contains an average concentration of 10 mg/L surfactants, the water is likely to be entirely of wastewater origin.
7. From a toxicological standpoint, an MCL of 0.5 mg/L, assuming a daily adult human water intake of 2 liters, would give a safety factor of 15,000.

Iron and Manganese

1. Iron and manganese are frequently found together in natural waters and produce similar adverse environmental effects and color problems. Excessive amounts of iron and manganese are usually found in groundwater and in surface water contaminated by industrial waste discharges.
2. Before 1962, these elements were covered by a single recommended limit.
3. In 1962, the US Public Health Service recommended separate limits for iron and manganese to reflect more accurately the levels at which adverse effects occur for each.
4. Each are highly objectionable in large amounts in water supplies for domestic and industrial use.
5. Each element imparts color to laundered goods and plumbing fixtures.
6. Taste thresholds in drinking water are considerably higher than the levels that produce staining effects.
7. Each element is part of the daily nutritional requirements; however, these requirements are not met by the consumption of drinking water.

Iron

The SMCL for iron is 0.3 mg/L.

Undesirable Effects

1. At levels greater than 0.05 mg/L some color may develop, staining of fixtures may occur, and precipitates may form.
2. The magnitude of the staining effect is directly proportional to the concentration.
3. Depending on the sensitivity of taste perception, a bitter, astringent taste can be detected from 0.1 mg/L to 1.0 mg/L.
4. Precipitates that are formed create not only color problems but also lead to bacterial growth of slimes and of the iron loving bacteria, *Crenothrix*, in wells and distribution piping.

Nutritional Requirements

1. Daily requirement is 1 to 2 mg; however, intake of larger quantities is required as a result of poor absorption.
2. The limited amount of iron permitted in water (because of objectionable taste or staining effects) constitutes only a small fraction of the amount normally consumed and does not have toxicologic (poisonous) significance.

Manganese

The SMCL for manganese is 0.05 mg/L.

Undesirable Effects

1. A concentration of more than 0.02 mg/L may cause buildup of coatings in distribution piping.
2. If these coatings slough off, they can cause brown blotches in laundry items and black precipitates.
3. Manganese imparts a taste to water above 0.15 mg/L.
3. The application of chlorine, even at low levels, increases the likelihood of precipitation of manganese at low levels.
4. Unless the precipitate is removed, precipitates reaching pipelines will promote bacterial growth.

Toxic Effects

1. Toxic effects are reported as a result of inhalation of manganese dust or fumes. Liver cirrhosis has arisen in controlled feeding of rats.
2. Neurological effects have been suggested; however, these effects have not been scientifically confirmed.

Nutritional Requirements

1. Daily intake of manganese from a normal diet is about 10 mg.
2. Manganese is essential for proper nutrition.
3. Diets deficient in manganese will interfere with growth, blood and bone formation, and reproduction.

Odor

The SMCL for odor is a Threshold Odor Number (TON) of 3.

Important facts to remember when dealing with odors include:

1. Taste and odor go hand-in-hand.
2. Absence of taste and odor helps to maintain the consumers' confidence in the quality of their water, even though it does not guarantee that the water is safe.
3. Research indicates that there are only four true taste sensations: sour, sweet, salty, and bitter.
4. All other sensations ascribed to the sense of taste are actually odors, even though the sensation is not noticed until the material is taken into the mouth.
5. Odor tests are less fatiguing to people than taste tests when testing for tastes and odors.
6. Taste and odor tests are useful:

1. As a check on the quality of raw10 and treated water
2. To help control odor throughout the plant

7. Odor is a useful test:

1. For determining the effectiveness of different kinds of treatment
2. As a means for tracing the source of contaminants

8. Hydrogen sulfide is included under the odor SMCL.

pH

The SMCL for pH is defined as pH values beyond the acceptable range from 6.5 to 8.5. A wide range of pH values in drinking water can be tolerated by consumers.

Undesirable Effects

1. When the pH increases, the disinfection activity of chlorine falls significantly.

2. High pH may cause increased halogen reactions, which produce chloroform and other THMs during chlorination.
3. Both excessively high and low pHs may cause increased corrosivity, which can, in turn, create taste problems, staining problems, and significant health hazards.
4. Metallic piping in contact with low-pH water will impart a metallic taste.
5. If the piping is iron or copper, high pH will cause oxide and carbonate compounds to be deposited, leaving red or green stains on fixtures and laundry.
6. At a high pH, drinking water acquires a bitter taste.
7. The high degree of mineralization often associated with basic waters results in encrustation of water pipes and water-using appliances.

Silver

Silver is a nonessential element, providing no beneficial effects from its ingestion in trace amounts. Chronic toxicity causes an unsightly blue-gray discoloration of the skin, mucous membranes, and eyes. Apparently, beside cosmetic changes, no physiologic effects are known. Ingestion of trace amounts of silver or silver salts results in its accumulation in the body, particularly the skin and eyes. Some evidence exists that changes to the kidneys, liver, and spleen can occur.

The SMCL for silver is 0.10 mg/L.

Sulfate

The SMCL for sulfate is 250 mg/L.

Undesirable Effects

1. Tends to form hard scales in boilers and heat exchangers.
2. Causes taste effects.
3. Causes a laxative effect. This effect is commonly noted by newcomers or casual or intermittent users of water high in sulfate. Water containing more than 750 mg/L of sulfate usually produces the laxative effect while water with less than 600 mg/L sulfate usually does not. An individual can adjust to sulfate in drinking water.
4. Sodium sulfate and magnesium sulfate are more active as laxatives, whereas calcium sulfate is less active.
5. When the magnesium sulfate content is 200 mg/L, the most sensitive person will feel the laxative effect; however, magnesium sulfate levels between 500 mg/L and 1,000 mg/L will induce diarrhea in most individuals.
6. Tastes may sometimes be detected at 200 mg/L of sulfate, but generally are detected in the range of 300 to 400 mg/L.

Total Dissolved Solids (TDS)

The SMCL for total dissolved solids is 500 mg/L.

Undesirable Effects

1. TDS imparts adverse taste effects at greater than 500 mg/L.
2. Highly mineralized water influences the deterioration of distribution systems as well as domestic plumbing and appliances (the life of a water heater will decrease one year with each additional 200 mg/L of TDS above a typical 200 mg/L value).
3. Mineralization can also cause precipitates to form in boilers and other heating units, sludge in freezing processes, rings on utensils, and precipitates in food being cooked.
4. There may be a great difference between a detectable concentration and an objectionable concentration of the neutral salts. Many people can become accustomed to high levels.
5. Studies show that the temperature of mineralized waters influences their acceptability to the public.

Zinc

The SMCL for zinc is 5 mg/L.

Undesirable Effects

1. High concentrations of zinc produce adverse physiological effects.
2. Zinc imparts a bitter, astringent taste that is distinguishable at 4 mg/L. Also, at 4 mg/L a metallic taste will exist.
3. Zinc will cause a milky appearance in water at 30 mg/L.
4. Zinc may increase lead and cadmium concentrations.

5. The activity of several enzymes is dependent on zinc. Enzymes are proteins that catalyze chemical reactions. Zinc is an essential enzyme growth element in terms of nutrition at low doses (zinc must be present) and is toxic to enzymes at high doses.
6. Cadmium and lead are common contaminants of zinc used in galvanizing steel pipe.

Physiological Effects

1. A concentration of 30 mg/L can cause nausea and fainting.
2. Zinc salts act as gastrointestinal irritants. This symptom of illness is acute and transitory.
3. The vomiting concentration range is 675 to 2,280 mg/L.
4. A wide margin of safety exists between normal food intake and concentrations in water high enough to cause oral toxicity.

Dietary Requirements

1. The daily requirement for preschool children is 0.3 mg Zn/ kg of weight.
2. Total zinc in an adult human body averages two grams.
3. Zinc most likely concentrates in the retina of the eye and in the prostate.
4. Zinc deficiency in animals leads to growth retardation.

Key Terms

- **Secondary standards –** federal and state standards for contaminants that affect the aesthetic qualities relating to the public acceptance of drinking water
- **Secondary Maximum Contaminant Level –** levels that apply to public water systems and are necessary to protect public welfare or for public acceptance of the drinking water

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2.10.1: Review Questions

Review Questions

1. **Explain the Secondary Maximum Contaminant Levels found in the Safe Drinking Water Act.**
2. **What is the SMCL for chloride?**
3. **What is the SMCL for color?**
4. **What is the MCL and the SMCL for fluoride?**
5. **What is the SMCL for TDS (total dissolved solids)?**

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2.10.2: Chapter Quiz

Chapter Quiz

1. _____ apply to public water systems and, in the judgment of the EPA, are necessary to protect the public welfare or for public acceptance of the drinking water. The rule means the maximum permissible level of a contaminant that is delivered to the free-flowing outlet of the ultimate user of a public water system. This maximum is not enforceable under EPA, but recommended: however, in some states, these levels are enforceable by law.

1. Maximum Contaminant Levels
2. Maximum Contaminant Level Goals
3. Secondary Maximum Contaminant Levels
4. Unregulated Contaminant Levels

2. _____ are important factors in public acceptance and confidence in a public water system. States are encouraged to implement SMCLs so that the public will not be driven to obtain drinking water from potentially lower-quality, higher risk sources. Many states have chosen to enforce Primary and Secondary Contaminant Levels to ensure that the consumer is provided with the best quality water available.

1. Biological contaminants
2. Chemical contaminants
3. Aesthetic qualities
4. Radiologic contaminants

3. Although _____ is regulated as a secondary contaminant because precipitates of the metal can cause cloudy-looking water, this contaminant may interfere with absorption of fluoride in the gastrointestinal tract and may decrease the absorption of calcium, iron, and cholesterol.

1. aluminum
2. zinc
3. silver
4. manganese

4. _____may be caused by aromatic, polyhydroxy, methoxy, and carboxylic acids, as well as fulvic and humic acid fractions, and the presence of metals such as copper, iron, and manganese. Changes to these levels may provoke citizen complaints.

1. Taste
2. Odor
3. Color
4. Laxative effects

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2.11: Distribution System Water Quality

Learning Objectives

After reading this section, you should be able to:

- Describe sampling procedures
- Describe water quality parameters
- Explain the causes behind water degradation in the distribution system
- Explain the risks of cross-connection
- Explain corrosion
- Describe data reporting
- Outline problem resolution

Sampling

All of the drinking water regulations apply to all public water systems.



Figure **2.11.1**: An Irrigation Ditch. (Copyright; Image by Bob White is licensed under CC BY-NC-ND 2.0)

Any water system that provides services for fewer connections or persons than these rules outline are not covered by the Safe Drinking Water Act. Certain other individuals and residences also are excluded, such as those whose water is supplied by an irrigation, mining, or industrial water system. However, regardless of size, all operators must strive to provide consumers with potable drinking water.

Drinking water regulations also consider the type of population served by the system and classify water systems as community or non-community systems. EPA defines a **public water system** as one which provides water for human consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of at least 25 people for at least 60 days a year. A public water system may be publicly or privately owned.

EPA further classifies public water systems according to the number of people they serve, the source of their water, and whether they serve the same customers year-round or on an occasional basis. EPA has defined three types of water systems[1]:

Community Water System: A public water system that supplies water to the same population year-round.

Non-Transient Non-Community Water System: A public water system that regularly supplies water to at least 25 of the same people at least six months per year. A small school would be an example of this.

Transient Non-Community Water System: A public water system that provides water in a place such as a gas station, or campground where people do not remain for long periods of time.



Figure **2.11.2**: Gros Ventre Campground.(Copyright; Image by the NPS is in the public domain)

Any water system that provides services for fewer connections or persons than these rules outline are not covered by the Safe Drinking Water Act. Certain other individuals and residences also are excluded, such as those whose water is supplied by an irrigation, mining, or industrial water system. However, regardless of size, all operators must strive to provide consumers with potable drinking water.

EPA has revised the Total Coliform Rule so that public water systems in the US take steps to ensure the integrity of the drinking water distribution system and monitoring for the presence of microbial contamination. Public water systems and the state and local agencies that oversee them must comply with the Revised Total Coliform Rule (RTCR) beginning April 1, 2016. The final RTCR requires the following:

1. Public water systems are to notify the public if a test exceeds the MCL for *E. coli* in drinking water
2. Public water systems that are at risk and therefore vulnerable to microbial contamination are required to identify and fix the problems, including the potential sources and the pathways of contamination
3. Criteria will be used for public water systems that are well operated to qualify for and stay on reduced monitoring, which could reduce water system burden
4. Provide incentives for better system operation, in particular small systems
5. Require additional monitoring requirements for seasonal systems such as campgrounds and state and national parks

The RTCR establishes an MCLG and an MCL for *E. coli* and eliminates the MCLG and MCL for total coliforms, replacing them with treatment techniques for coliforms that require assessment and corrective action. EPA has established an MCLG of zero for *E. coli*, which is a more specific indicator of fecal contamination and those pathogens that are potentially more harmful than total coliform. EPA has removed the 1989 MCLG and MCL for total coliforms, although the acute total coliform MCL violation under the 1989 TCR has been maintained as the MCL for *E. coli* under the RTCR.

Under the new treatment technique, total coliforms serve as the indicator of a potential pathway of contamination into the system's distribution system. Public water supplies that exceed a specified frequency of total coliform occurrence must conduct an assessment to determine if any sanitary deficiencies exist; if found, they must be corrected. A public water system that experiences an *E. coli* MCL violation must conduct an assessment and correct any sanitary defects that are identified.

Monthly notification requirements based only on the presence of total coliforms will no longer be required. Instead, the RTCR will require public notification when an *E. coli* MCL violation occurs, indicating a potential health threat or when a water system fails to assess and take corrective action.

Sampling Plan

The Total Coliform Rule requires each water supply system to develop and follow a written sampling plan. Each plan must specifically identify sampling points throughout the distribution system. Sampling plans must be approved by the state regulatory agency and it is necessary to check with the state agency to determine the details of their review process and what documents need to be submitted.

Data and Reporting

Monitoring Frequency

The routine monitoring frequency for community water systems is based on the population served. Routine monitoring frequencies for non-community systems are based on the source of supply and, in some cases, the population served. Whenever a routine sample tests positive for total coliform, two provisions of the Total Coliform Rule take effect: repeat samples (formerly referred to as check samples) must be taken and the original coliform-positive sample must be tested for the presence of fecal coliforms or *E. coli* to determine whether an actual or potential violation of the coliform MCL exists.

The reason repeat samples are required is to investigate whether the original coliform-positive sample was caused by a contamination problem that exists throughout the distribution system or if it is a localized problem that exists only at that one sampling point. With this information, appropriate corrective action can be taken to eliminate the problem as quickly as possible.

The Total Coliform Rule specifies how many repeat samples must be taken, when, and from what locations. It also directs the water utility to collect a specific number of samples the following month, based on the number of routine samples ordinarily collected.

Non-community systems serving more than 1,000 people have the same requirements as community water systems. Non-community systems serving fewer than 1,000 people are required to collect one routine sample per quarter. When the routine sample tests positive, four repeat samples are required in the same quarter and five samples are required the following quarter.

Whenever a routine or repeat sample tests positive for total coliform, the water agency must collect a set of three or four repeat samples within 24 hours of receiving the laboratory results. At least one of the repeat samples must be taken from the same tap as the original coliform-positive sample; the remaining repeat samples in the set must be collected at nearby taps (within five service connections of the original sampling point), upstream and downstream of the original.

Repeat samples will be taken until no coliforms are detected or until the MCL is exceeded and the state is notified.

Determining Compliance

The MCLG for total coliforms (including fecal coliforms and *E. coli*) is zero. The MCL, based on the presence-absence concept, is as follows:

1. For water systems analyzing at least 40 samples per month, no more than 5.0 percent of the samples (including routine and repeat samples) may be positive for total coliforms.
2. For water systems analyzing fewer than 40 samples per month, no more than one sample per month may be positive for total coliforms.

The Total Coliform Rule makes another significant change in the way compliance is calculated. All valid coliform-positive samples, routine and repeat samples, must be counted when calculating compliance with the monthly MCL. Under previous regulations, check or repeat samples were not included in the monthly MCL calculation. On a case-by-case basis, the state may declare a sample invalid for one of several reasons, including interference by heterotrophic bacteria during laboratory analysis, as previously discussed.

Total-coliform-positive samples may be invalidated by the state under any of the following conditions:

1. The analytical laboratory acknowledges that improper sample analysis caused the positive result
2. The state determines that the contamination is a local plumbing problem

3. The state has substantial grounds to believe that the positive result was unrelated to the quality of drinking water in the distribution system

Reporting and Notification Requirements

Reporting frequencies for coliform test results increase in step with the urgency of the problem. A water agency must report the results of monthly coliform testing to the state regulatory agency within the first 10 days of the following month.

Any time a water agency fails to collect a sample as required; the state must be notified within 10 days after the system learns of the violation. An invalid sample result is considered a failure to monitor and must be reported.

If the MCL is exceeded, the state must be notified no later than the end of the next business day and the public within 14 days. This requirement could occur when the water agency exceeds its monthly coliform-positive limit or when test results show the presence of fecal coliforms or *E. coli* in any sample.

The most critical situation exists when either of two situations occurs:

1. A routine sample tests positive for total coliforms and for fecal coliforms or *E. coli*,

and any repeat sample tests positive for total coliforms.

2. A routine sample tests positive for total coliforms and negative for fecal coliforms or *E. coli*, and any repeat sample tests positive for fecal coliforms or *E. coli*.

These situations are considered an acute risk to health. This occurrence is a Tier 1 violation, which requires that the state and the public be notified within 24 hours.

Water Quality

Section 304 (a)of the Clean Water Act directed EPA to develop water quality criteria not only for human health, but also aquatic life criteria, biological criteria, and microbial/recreational criteria. But they all point towards protecting public health.

Water agencies and utilities utilize local or imported surface water and groundwater sources and then convey it to treatment plants and distribution systems composed pipes, pumps, and storage reservoirs. Sometimes the storage reservoirs are small impoundments to large lakes with recreation. In all cases, primary standards set by the Federal, State, and tribal governments must be met. This extends to monitoring the health of aquatic life, water bodies in terms of the kinds of organisms present as well as bacteria and other pathogens. It is quite a responsibility. And it is a dynamic process. Regulations may become more stringent, and it will be the responsibility of engineers, scientists, and operators to ensure that a safe supply of water is always maintained for the public and environment.

Furthermore, the drinking water public judges the quality of their drinking water from Secondary (aesthetic) standards. You may be providing a safe supply of water to a customer, but if it slightly discolored from natural minerals in a groundwater supply, no one is going to trust it.

The quality of treated water put into the water distribution system from finished water treatment plants is high. The most pervasive water quality problem that affects most American communities results from the deterioration of water quality within water distribution conveyance systems.

Distribution Systems

Conditions exist in the distribution system that could result in degradation of water quality in the distribution system. The system operator must be aware of them and take corrective or protective measures where possible.

Consider how water is delivered to most of Southern California. Surface water is conveyed hundreds of miles in an aqueduct system, possibly blended with a groundwater supply, treated, and then delivered to a retail customer. The biggest threat to water quality degradation is typically in the last several miles of the distribution system pipeline conveyance system from the treatment plant.

Distribution System Integrity[2]

There are three components to distribution system integrity.

1. Physical Integrity of the system – the maintenance and isolation of the infrastructure (pipes, pumps, various valves including air release and blowoff valves, tanks) from the external environment

2. Hydraulic Integrity – the maintenance of a desirable water flow, and pressure

3. Water quality integrity – the maintenance of water age and disinfection residual in the system to prevent internally derived contamination. This involves routine continual water quality monitoring at various locations in the distribution system, particularly at unique and vulnerable locations such as area of lower flows and dead ends times. This will be discussed in the next section.

The causes of water quality degradation are due to breaches in distribution system integrity. It should be noted that minor water quality changes such as fluctuations in temperature, pH, alkalinity, or disinfectant residual are quite normal in the day-to-day operation of a well maintained distribution system and treatment plant.

Causes of Quality Degradation to Distribution System

Breaches to distribution system integrity were discussed in an EPA issue paper on the Total Coliform Rule. Various causes of major water quality degradation requiring an assessment and improvement in operations and maintenance procedures include:

Water main breaks, repairs, installation

Water distribution systems under pressure are susceptible to contamination if a break occurs. It is quite common for utilities like natural gas and sewer lines to share common corridors (rights of way) such as streets, A major break, particularly in those areas, create a pathway of contamination to the distribution system.

Contamination from sediment and high groundwater during repair or new installation is always a concern. Maintenance of the systems requires it to be properly, isolated, disinfected and flushed before the line is placed back into service.

Operation and Maintenance Deficiencies

Pipeline flushing is a routine maintenance practice often conducted within the distribution system to address consumer complaints and to reduce the retention time of water to improve water quality. Utilities have typically manually flushed water from the system using fire hydrants or flushing hydrants to control microbial growth.[2]

These practices can affect distribution system water quality in a negative manner if not conducted properly. Improper flushing can result in moving a contaminant further into the distribution system. The amount of time (age) water stays in a distribution system can affect its disinfectant residual and lead to bacterial growth. Stagnant water can occur in **dead-end pipes** or storage facilities that are over-sized or have periods of limited use.

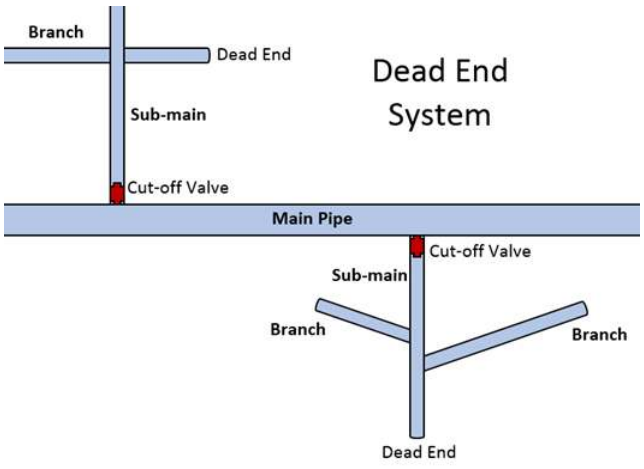


Figure **2.11.3**: Dead end in distribution system. (Copyright; Image by COC OER is licensed under CC BY 4.0)

Stagnant water provides an opportunity for suspended particulates to settle into pipe sediments, for biofilm to develop, and for biologically mediated corrosion to accelerate (Brandt et al., 2004). Long-term water storage in finished water reservoirs (lasting

weeks or several months) can result in waterborne heterotrophic bacteria growing in sediments, attaching to inner walls, and spreading a biofilm over surfaces (Geldreich, 1996). Long retention time can also result in reduction in disinfectant residual and cause the release of ammonia through the decay of chloramines (Brandt et al., 2004). Loose deposits are susceptible to entrainment and suspension under normal hydraulic scenarios, such as flow reversals and velocity changes (Friedman et al., 2004a). Sudden flow increases (USEPA, 1992) or hydraulic disturbances (USEPA and CA DHS, 1989) can cause accumulated biofilm, scales, sediment, or tubercles to shear or slough, resulting in release to the water column. Also, if the distribution system is fed by multiple sources with varying water quality, the release of biofilms, scales, or sediments may occur at the interface between the sources.

Permeation

Non-metallic pipelines may be susceptible to contaminants passing through the pipeline walls from the exterior. This is referred to as permeation. Modern PVC pipes exhibit lower permeation, but some organic solvents are capable of permeating through plastic pipe.

Storage tanks for treated water

Storage tanks without screens for vents, or any hatch or opening that is not locked is a pathway for contamination. Storage tank walls must be properly lined (coated) on the inside as well.

Cross-connections

A cross-connection is typically defined as a connection between the drinking water distribution and another connection with different source water, or any other source. It is not uncommon for water agencies to share cross connections in the event of an emergency. But if the disinfection methods are different, or one source is not treated, then a pathway for contamination exists.

Backflow is the “undesirable reversal of flow of water or mixtures of water and other liquids, gases or other substances in the distribution pipes of the potable water supply from any source or sources.”[3] Backflow occurs when a pressure differential exists between the cross connection and the distribution because of a hydraulic change in the distribution. If the pressure in a water users connection becomes greater than the pressure in the distribution system, backflow will occur.

Enforceable regulations requiring back flow prevention devices for service connections have been adopted by State and Federal agencies.

Significant pressure reduction can occur in the event of line break. Backflow in this case is often referred to as backsiphonage.

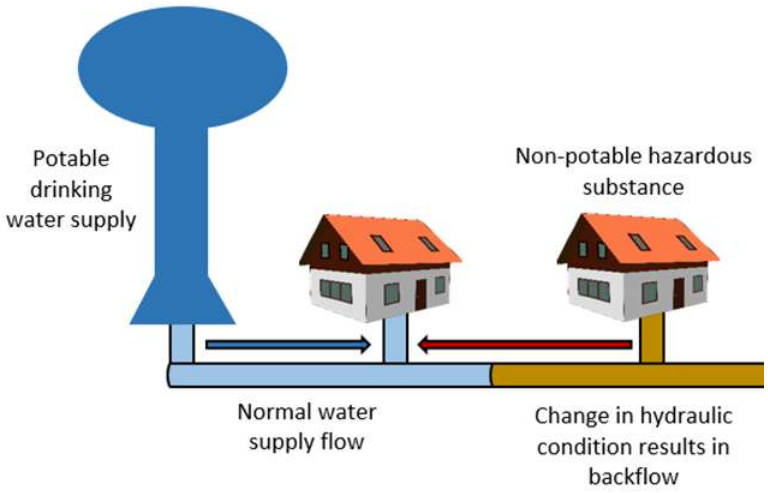


Figure **2.11.4**: Cross-connection in distribution system. (Copyright: Image by Machovka is licensed under CC0 1.0 modified by COC OER)

Backsiphonage is a form of backflow caused by a negative or below atmospheric pressure within the water supply piping. Backsiphonage can develop from such causes as main breaks, an inadequate source of supply capacity, undersized mains, unusual water demands, planned shutdowns for maintenance or repair, or the use of on-line booster pumps. Backflow caused by back pressure can occur when the user’s water system is at a higher pressure than the public water system.

Chemical and microbial contamination from cross connections and backsiphonage have been responsible for many distribution system related illnesses. [4]

Corrosion and leaching

Corrosion is the gradual deterioration of metal pipe, metal fixtures, cement mortar lining in pipe, or other substances because of a reaction with the water.[5] Corrosion can be the result of physical actions that erode the coating of a pipe, chemical dissolution that leaches a pipe's lining or wall material, or electrochemical reactions that remove metal from the wall of the pipe.[6 Corrosion can result in the leaching of certain metals, such as lead and copper.

Biological growth within the distribution system can also cause corrosion by providing an environment in which physical and chemical interaction can occur. Leaching is defined as the dissolution of metals, solids, and chemicals into drinking water (Symons et al., 2000). Some of the factors that influence corrosion and leaching are water velocity, pipe material, and water quality within the distribution system, such as pH, alkalinity, temperature, chlorine residual, and hardness of the water.



Figure 2.11.5:Pipe with corrosion . (Copyright: Image by Mr pantswearer is licensed under CC BY-SA 4.0.)

Contaminants from pipe linings, tank coatings, fittings, or other materials can sometimes leach into the drinking water, causing contamination. Cement-lined pipes and storage tanks can leach calcium carbonate into the water, which may significantly increase the alkalinity and pH of the water. This is especially true when the cement lined material is new, but also depends on the type of cement used, the contact time between the water and cement material, and the diameter of the pipe.

BiofilmBiofilms were introduced in Chapter 8. Contaminants, including total coliforms and some pathogens, may attach to or become enmeshed in biofilms on pipe walls in distribution systems. Many pathogens have been found to survive, if not grow, in these pipe biofilms where they are protected from disinfectants. Over time, coliform bacteria may detach or slough from the biofilm, causing persistent total coliform detections. Pathogens may also be included in the detached material and may result in waterborne disease. The biofilm can result in total coliform positive detections and other contamination events if disturbed. Organisms that have been found in biofilms include bacteria, viruses, protozoa, invertebrates, algae, and fungi.[7] Less efficient treatment of source water during runoff or changing water quality conditions may cause a change in the organic matter of treated water, which in turn may enable increased biofilm growth in the distribution system [8]

Key Terms

- **appurtenances –** small (but important) parts of a water distribution system, such as valves or meters, which help control flow
- **Community Water System –** a public water system that has at least 15 regular service connections and regularly serves at least 25 all year residents

- **Cross connection** - an unprotected connection between a part of a water system used or intended to be used to supply water for drinking purposes and any source or system containing water or a substance that is not or cannot be approved as safe drinking water. It is a connection between a regulated and approved drinking source and an unregulated drinking water source.
- **Public Water System (PWS)** – any system with at least 15 connections and regularly serves an average of 25 individuals daily at least 60 days out of the year

[1] https://www.epa.gov/sites/default/files/2021-05/documents/issuepaper_tcr_indicators_posted.pdf

[2] Brandt, M., J. Clement, J. Powell, R. Casey, D. Holt, N. Harris, and C. Ta. 2004. *Managing Distribution Retention Time to Improve Water Quality - Phase I*. AwwaRF. Denver, CO.).+

[3] USC-FCCCHR (University of Southern California Foundation for Cross-Connection Control and Hydraulic Research). 1993. *Manual of Cross-Connection Control, Ninth Edition*. University of Southern California. Los Angeles, CA.

[4] Craun, G. F. and R. L. Calderon. 2001. Waterborne Disease Outbreaks Caused by Distribution System Deficiencies. Journal *AWWA* 93:9:64-75

[5] AWWA. 1999a. *Water Quality and Treatment, Fifth Edition*. McGraw-Hill, Inc. New York, NY.

[6] AWWA. 2000. *Water Distribution Systems Handbook*. McGraw-Hill, Inc. New York, NY.

[7] AWWA. 2000. *Water Distribution Systems Handbook*. McGraw-Hill, Inc. New York, NY.

[8] USEPA, 2002. Health Risks from Microbial Growth and Biofilms in Drinking Water Distribution Systems.

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2.11.1: Review Questions

Review Questions

1. **What is a cross-connection?**
2. **How can backflow occur in a drinking water distribution system?**
3. **Define backsiphonage.**
4. **Define backflow.**
5. **Name the common situations that can result in a cross connection in the drinking water distribution system.**
6. **Describe corrosion as a process in a drinking water distribution system.**
7. **Describe the problems associated with dead ends in the distribution system.**

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2.11.2: Chapter Quiz

Chapter Quiz[67]

1. A _____ is defined as any system that has at least 15 service connections and regularly serves an average of at least 25 individuals daily at least 60 days out of the year.

1. public water system (PWS)
2. community water system (CWS)
3. transient water system
4. non-transient non-community water system

2. A system that has at least 15 service connections used by all-year residents and regularly serves at least 25 all-year residents is defined as a _____.

1. public water system (PWS)
2. community water system (CWS)
3. transient water system
4. non-transient non-community water system

3. EPA identifies some systems as _____ if they regularly serve at least 25 of the same persons over 6 months per year.

1. public water system (PWS)
2. community water system (CWS)
3. transient water system
4. non-transient non-community systems

4. The routine monitoring frequency for community water systems is based on the _____.

1. past history of coliforms being present in the sampling
2. population served
3. type of treatment
4. raw water source being surface water or ground water

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2.12: Water Treatment for Contaminant Removal

Learning Objectives

After reading this section, you should be able to:

- Describe water quality characteristics
- Describe disinfection processes
- Describe the classes of water quality
- Explain water quality characteristics

Water Quality Characteristics

Water functions as a solvent due to its polarity and small molecular size. It has the ability to form hydrogen bonds which allows it to dissolve many types of molecules. It is often referred to as a "universal solvent". Microorganisms rely on water in order to grow. As such, pathogens which cause human illness are found in untreated surface water and groundwater. Waterborne diseases include typhoid fever, cholera, giardia, dysentery, E coli., hepatitis A, cryptosporidium, and Salmonella.

Public water system treatment plants use a combination of different treatment methods to remove or inactivate all disease-causing organisms and viruses. The process is referred to as a **multi-barrier treatment** approach. The final step in this approach involves chemical disinfection using chlorine or chloramines. Complete sterilization like the process used in hospitals is not necessary in water treatment.

Factors Influencing Disinfection

Several physical characteristics of a microorganism and chemical factors can influence the disinfection of water and include:

pH

Worldwide, many agencies have historically limited the range of pH values of distributed water between 6.5 and 8.5.[1] Although this range is not a regulatory limit, many jurisdictions have used it as one. The antimicrobial activity of chlorine is optimal at a neutral pH of 7.0. But an increase in pH will reduce its efficacy (pH over 8.0).

Temperature

The activity of most disinfectants will increase as the temperature increases. Chlorine is very effective at temperatures above 65 . Temperature measurements for calculating treatment contact times is important.

Turbidity

Turbidity is the measure of the relative clarity of a liquid. Cloudy (turbid) water would be due

To the presence of clay, silt, tiny inorganic and organic matter and other microorganisms.[2] This would definitely interfere with the disinfection process and is why a multi-barrier treatment approach with filtration precedes disinfection.

Organic Matter

A disinfectant like chlorine or bromine will react with natural organic residue found in water. This reduces the amount of disinfectant available. But more importantly the formation of chemical disinfection by-products called trihalomethanes (THMs) also occurs.[3] These compounds are regulated by the EPA. Consequently, most water agencies in California now use chloramines instead of chlorine as a primary disinfectant.

Inorganic Matter

Inorganic compounds found in residual silts or a compound such as ammonia (NH_3) in water will reduce the amount of disinfectant.

Reducing Agents

A reducing agent loses electrons and is oxidized in a chemical reaction. Examples of reducing agents include earth metals, formic acid, and sulfite compounds.[4] Chlorine combines with reducing agents, thereby affecting the amount of chlorine available to disinfect. Examples of reducing agents in water include hydrogen sulfide (H_2S), ferrous ion (Fe^{+2}), manganous ion (Mn^{+2}), ammonia (NH_3), and nitrite (NO_2^-).

Microorganisms

The physical characteristics of a microorganism can influence the disinfection process for example, spores are resistant to disinfectants because the spore coat and cortex act as a barrier. But most microorganisms can be filtered or settled out prior to disinfection.

Removal Processes[5]

A multi-barrier approach is used to remove pathogens before they are killed or inactivated (if a virus) by chemical disinfection.

1. **Coagulation.** Coagulation is often the first step in water treatment. During coagulation, chemicals with a positive charge are added to the water (floc). The positive charge neutralizes the negative charge of dirt and other dissolved particles in the water. When this occurs, the particles bind with the chemicals to form slightly larger particles. Common chemicals used in this step include specific types of salts, aluminum, or iron. In an international report published in 1998, it was found that coagulation and sedimentation alone can remove between 27 and 84 percent of viruses and between 32 and 87 percent of bacteria. Usually, the pathogens that are removed from the water are removed because they are attached to the dissolved substances that are removed by coagulation.[6]
2. **Sedimentation.** This refers to one of the steps water treatment plants use to separate out solids from the water. During sedimentation, flocs settle to the bottom because they are heavier than water.
3. **Filtration.** Once the flocs have settled to the bottom of the water, the clear water on top is filtered to separate additional solids from the water. During filtration, the clear water passes through filters that have different pore sizes and are made of different materials (such as sand, gravel, and charcoal). These filters remove dissolved particles and germs, such as dust, chemicals, parasites, bacteria, and viruses. Activated carbon filters also remove any bad odors.

Disinfection Process

After the water has been filtered, water treatment plants may add one or more chemical disinfectants (such as chlorine, chloramine, or chlorine dioxide) to kill any remaining parasites, bacteria, or viruses. To help keep water safe as it travels to homes and businesses, water treatment plants will make sure the water has low levels of the chemical disinfectant when it leaves the treatment plant. This remaining disinfectant kills pathogens living in the pipes between the water treatment plant and your tap.

In addition to or instead of adding chlorine, chloramine, or chlorine dioxide, water treatment plants can also disinfect water using UV light and ozone. They work well to disinfect water in the treatment plant, but these disinfection methods do not continue killing germs as water travels through the pipes between the treatment plant and your tap (no disinfection residual).

Ultraviolet Rays

Advances in UV disinfection have been made in recent years. An Ultraviolet (UV) disinfection system transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA). When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. UV radiation, generated by an electrical discharge through mercury vapor, penetrates the genetic material of microorganisms and retards their ability to reproduce. Unfortunately, this method leaves no disinfectant residual and is expensive.[7]

Heat

Primarily used in emergencies, heating water to a boil for 5 minutes will kill all microorganisms which may have breached the distribution system. From a practical perspective, it is an expensive and inefficient way to disinfect water for a public water system.

Chemical Disinfection

Iodine

Iodine is a good disinfectant and has been utilized for potable water treatment since the early 1900's in concentrations between 2.5 – 7 ppm. The US Army continues to issue iodine-based tablets to field soldiers and other personnel to disinfect water in emergencies. It is expensive and is also not recommended for use as a primary disinfectant due to lack of knowledge on long-term toxic effects.[8]

Bromine

Bromine is primarily used as an alternative disinfectant for swimming pools, spas and cooling tower water, but not for municipal drinking-water, partly due to cost and partly to concerns about the formation of brominated DBPs.[9]

Ozone

Ozone is used to disinfect water along with reducing taste and odors. Drawbacks of ozone for disinfection include a high cost, big physical footprint, lack of residual, difficulty in storing, and maintenance requirements.

Ozone has its advantages and disadvantages. Ozone treatment has the ability to achieve higher levels of disinfection than chlorine or UV, however, the capital costs as well as maintenance expenditures are not competitive with available alternatives.[10]

Chlorine

At room temperature, chlorine is a yellow-green gas that is heavier than air and has a strong irritating odor. It can be converted to a liquid under pressure or cold temperatures. Chlorine is mainly used as bleach in the manufacture of paper and cloth and to make a wide variety of products. Chlorine appears as a greenish yellow gas with a pungent suffocating odor. Chlorine does not burn but, like oxygen, supports combustion. Long-term inhalation of low concentrations or short-term inhalation of high concentrations has ill effects. Vapors are much heavier than air and tend to settle in low areas.[11]

Disinfection Action

Chlorine destroys organisms by oxidizing their cellular material. It is extremely effective for inactivating pathogens with one exception, Cryptosporidium. Leaving chemistry out of this discussion, let's consider what happens if 1 mg of chlorine gas is added to 1 liter of pure distilled water. Chemical reactions will occur to form two chlorine species which are referred to as free chlorine. That free chlorine "residual" is 1 mg/liter and has the ability to disinfect. Now consider 1 liter of water as it exists in nature. Let's also say there are no pathogens in the water. It will still contain natural organic compounds, non-organic elements like iron and manganese, and other compounds found in nature like nitrites, ammonia, and hydrogen sulfide. Chlorine will also react with them to form other compounds but won't have the ability to disinfect. Consequently, you won't have 1mg/liter of free chlorine residual. It will be less. You would need to add more chlorine gas to get back to 1mg/liter.

Chlorine Reactions in Water

Chlorine and water will react to form hypochlorous acid HOCL and hydrochloric acid HCl. These are weak compounds and HOCL will dissociate further into the hypochlorite ion OCL^-. Hypochlorous acid and the hypochlorite ion are what make up the free chlorine residual. As a disinfectant, the hypochlorite ion is only 1% as effective as hypochlorous acid.

These reactions are reversible and pH dependent.

- between pH 3.5 and 5.5, HOCl is the predominant species.
- between about pH 5.5 and 9.5, both HOCl and OCl^- species exist in various proportions.
- above pH 8, OCl^- predominates.

Reactions with Substances in Water

Chlorine will react with natural organic and inorganic compounds. This will reduce the free chlorine residual for disinfection purposes and necessitate the addition of additional chlorine gas. Hydrogen sulfide is a common compound found in groundwater. It has an unpleasant smell and is responsible for many taste and odor complaints from retail customers who may be served with groundwater sources of supply. Chlorine is very effective at removing it.

When chlorine reacts with natural organic matter, a group of disinfection byproducts, known as THM's or trihalomethanes may form. They may be harmful to certain segments of the population and are listed as a contaminant and regulated by the EPA.

Consequently, many water agencies have switched from using the direct use of chlorine gas as a primary disinfectant.

Chloramination

Chloramines have been used as a disinfectant in water systems for many years, primarily to control taste and odor. They can maintain a detectable disinfectant residual in a distribution system. But chloramine is a weaker disinfectant than chlorine. Consequently, higher chloramine doses and longer contact times are required to achieve the same level of disinfectant effectiveness as chlorine. A big advantage of using chloramines is to significantly reduce trihalomethane (THM) levels in order to meet the regulatory requirements of the Surface Water Treatment Rule.

Chloramines are formed when chlorine reacts with ammonia. They will form when natural untreated water contains ammonia. To maintain very low THM levels but maintain effective disinfection residuals, treatment plant operators will apply chlorine gas with ammonia concurrently in the treatment plant influent, or sequentially at a different downstream location in order to create a high chorine residual in part of the treatment process.

Hypochlorite

Rather than use chlorine gas, hypochlorite is available as calcium hypochlorite or sodium hypochlorite. They are a good alternative to supplying chlorine. Calcium hypochlorite is available as a solid. Sodium hypochlorite is available in solution.

Chlorine Dioxide

Chlorine dioxide (ClO_2) is an effective disinfectant. Chlorine dioxide does not form THM's like chlorine gas. It is more costly, and more hazardous to use. Chlorine dioxide is highly reactive and flammable.

UV Disinfection and Treatment of Water

Ultraviolet (UV) rays are part of the light that comes from the sun. The UV spectrum is higher in frequency than visible light and lower in frequency compared to x-rays. The UV spectrum has a larger wavelength than x-rays and a smaller wavelength than visible light and the order of energy, from low to high, is visible light, UV, and x-rays.

UV is known to be an effective disinfectant due to its strong germicidal (inactivating) ability. UV disinfects water containing bacteria and viruses and can be effective against protozoans, such as *Giardia lamblia* cysts or *Cryptosporidium* oocysts. UV is used in the pharmaceutical, cosmetic, beverage, and electronics industries. In the United States, it is used for drinking water disinfection; however, high operating costs compared to disinfection by chlorination has limited its usage.

Because of safety issues associated with the reliance of chlorination and improvements in UV technology, UV has experienced increased acceptance in municipal water systems. Two classes of disinfection systems are certified and classified by the NSF under Standard 55, Class A and Class B Units.

1. Class A These ultraviolet water treatment systems must have an intensity and saturation rating of at least 40,000 uw-sec/cm^2 and possess designs that will allow them to disinfect and/or remove microorganisms from contaminated water. Affected contaminants should include bacteria and viruses. Class A point-of-entry and point-of-use systems covered by this standard are designed to inactivate and/or remove microorganisms, including bacteria, viruses, and *Cryptosporidium* oocyst and *Giardia* cysts from contaminated water. Systems covered by this standard are not intended for the treatment of water that has obvious contamination or intentional source contamination, such as raw sewage, nor are these systems intended to convert wastewater to drinking water. These systems are intended to be installed on visually clear water.
2. Class B These ultraviolet water treatment systems must have an intensity and saturation rating of at least 16,000 uw-sec/cm^2 and possess designs that will allow them to provide supplemental bactericidal treatment of water already deemed safe, such that no elevated levels of *E. coli* or a standard plate count of less than 500 colonies per 1 ml exists. NSF Standard 55 suggests Class B UV systems are designed to operate at a minimum dosage and are intended to reduce normally occurring non-pathogenic or nuisance microorganisms only. The Class B or similar non-rated UV systems are not intended for the disinfection of microbiologically unsafe water.

The type of unit depends on the situation for use, source of water, and water quality. Transmitted UV light dosage is affected by water clarity. Water treatment devices are dependent on the quality of the raw water. When turbidity is 5 NTU or greater and/or

total suspended solids are greater than 10 ppm, pre-filtration of the water is highly recommended. Normally, it is advisable to install a 5 to 20 micron filter prior to a UV disinfection system.

UV disinfection is based on the principles associated with wave lengths of light that damage the nucleic acids of water borne pathogens. UV radiation has three wavelength zones, UV-A, UV-B, and UV-C, and it is the last region, the shortwave UV-C, that has germicidal properties for disinfection. A low-pressure mercury arc lamp resembling a fluorescent lamp produces the UV light in the range of 254 manometers (nm). These lamps contain elemental mercury and an inert gas, such as argon, in a UV-transmitting tube, usually quartz. Traditionally, most mercury arc UV lamps have been the low-pressure type because they operate at a relatively low partial pressure of mercury, low overall vapor pressure (about 2 mbar), low external temperature (50-100° C), and low power. These lamps emit nearly monochromatic UV radiation at a wavelength of 254 nm, which is in the optimum range for UV energy absorption by nucleic acids (about 240-280 nm).

In recent years, medium pressure UV lamps that operate at much higher pressures, temperatures, and power levels have been installed. They emit a broad spectrum of higher UV energy between 200 and 320 nm.

An essential requirement for UV disinfection with lamp systems is an available and reliable source of electricity. While the power requirements of low-pressure mercury UV lamp disinfection systems are modest, they are essential for lamp operation to disinfect water. Since most microorganisms are affected by radiation around 260 nm, UV radiation is in the appropriate range for germicidal activity. UV lamps are available that produce radiation in the range of 185 nm, and they are effective in reducing microorganisms as well. They will also reduce the total organic carbon (TOC) content of the water.

For typical UV systems, approximately 95-percent of the radiation passes through a quartz glass sleeve and into the untreated water. The water is flowing as a thin film over the lamp. The glass sleeve is designed to keep the lamp at an ideal temperature of approximately 104° F.

UV radiation affects microorganisms by altering the DNA in the cells and impeding reproduction. UV treatment does not remove organisms from the water. It inactivates them. The effectiveness of this process is related to exposure time and lamp intensity, as well as general water quality parameters.

The exposure time is reported as microwatt-seconds per square centimeter (uwatt-sec/cm^2), and the U.S. Department of Health and Human Services has established a minimum exposure of 16,000 µwatt-sec/cm^2 for UV disinfection systems. Most manufacturers provide a lamp intensity of 30,000-50,000µwatt-sec/cm^2. In general, coliform bacteria are destroyed at 7,000 µwatt-sec/cm^2.

Since lamp intensity decreases over time with use, lamp replacement and proper pretreatment are key to the success of UV disinfection. In addition, UV systems should be equipped with a warning device to alert operators when lamp intensity falls below the germicidal range.

Used alone, UV radiation does not improve the taste, odor, or clarity of water. UV light is a very effective disinfectant, although the disinfection can only occur inside the unit. No residual disinfection in the water exists to inactivate bacteria that may survive or may be introduced after the water passes by the light source. The percentage of microorganisms destroyed depends on the intensity of the UV light, the contact time, raw water quality, and proper maintenance of the equipment.

If material builds up on the glass sleeve or the particle load is high, the light intensity and the effectiveness of treatment are reduced. At sufficiently high doses, all waterborne enteric pathogens are inactivated by UV radiation. The general order of microbial resistance (from least to most) and corresponding UV doses for extensive (>99.9%) inactivation are vegetative bacteria and the protozoan parasites *Cryptosporidium parvum* and *Giardia lamblia* at low doses (1-10 mJ/cm^2) and enteric viruses and bacterial spores at high doses (30-150 mJ/cm^2).

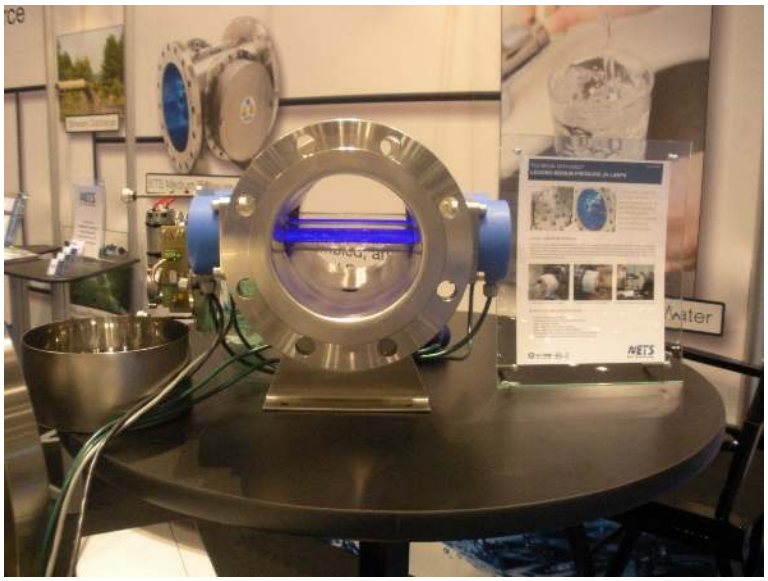


Figure **2.12.1**: UV light used for disinfection in water treatment. (Copyright; mage by Pam Broviak is licensed under CC BY-SA 2.0)

Most low-pressure mercury lamp UV disinfection systems can readily achieve UV radiation doses of 50-150 mJ/cm^2 in high quality water; and therefore, efficiently disinfect waterborne pathogens. However, dissolved organic matter, such as natural organic matter, certain inorganic solutes such as iron, sulfites and nitrites, and suspended matter (particulates or turbidity) will absorb UV radiation or shield microbes from UV radiation, resulting in lower delivered UV doses and reduced microbial disinfection. Another concern surrounding disinfecting microbes with lower doses of UV radiation is the ability of bacteria and other cellular microbes to repair UV-induced damage and restore pathogenicity, which is a phenomenon known as reactivation.

UV inactivates microbes primarily by chemically altering nucleic acids. However, the UV-induced chemical lesions can be repaired by cellular enzymatic mechanisms, some enzymes act independent of light (dark repair) and other enzymes require visible light (photo-repair or photo-reactivation). Therefore, achieving optimum UV disinfection of water requires delivering a sufficient UV dose to induce greater levels of nucleic acid damage; and thereby, overcome DNA repair mechanisms.

UV units have a maximum flowrate capacity and some equipment have minimum flowrates. If the flow is too high, water will pass through without enough UV exposure. If the flow is too low, heat may build up which can damage the UV lamp. A UV unit with minimum flow requirements should not be placed on the water line supplying pressure stations in a non-recirculating system. UV units are most often used in constant flow systems.

UV lamps do not burn out as normal florescent lamps do. Instead, the UV lamps will solarize, which reduce their intensity to about 60% of a new lamp after about one year of continuous use. When lamps are new, they will generate a dosage level near 60,000 µW-s/cm^2. When the dosage drops to 30,000 µW-s/cm^2, the minimum dosage needed to effectively kill bacteria, lamps should be replaced. Lamp life will be shortened significantly if the lamp is turned on and off more frequently than once every eight hours.

Water should be sampled and tested for bacteria counts regularly. Sample before and after the UV unit to test its performance. Water should also be sampled in the distribution since bacterial regrowth can occur downstream of the UV unit.

As water passes through the UV unit, minerals, debris, and other material in the water will deposit onto the quartz or Teflon sleeve. This activity will limit the penetration of UV rays through the sleeve and into the water. To maintain high clarity, the glass around the lamp must be cleaned regularly. Cleaning frequency depends on the water quality and will be minimal with RO treatment upstream.

UV light intensity meters are available which indicate the penetration of UV light through the glass sleeve and the water. Low intensity means the UV dose is too low to provide adequate disinfection. This meter will indicate when cleaning or lamp replacement is needed.

Ozone

Ozone is one of the most powerful water treatment compounds available to system managers today. It is a technology that has been in continual commercial use for over 100 years and has distinct properties that allow disinfection of even heavily compromised water streams. With the 1996 reauthorization of the Safe Drinking Water Act, ozone was named as among the best available technologies for water system compliance with National Primary Drinking Water Regulations as overseen by the US Environmental Protection Agency.

Ozone (O_3) is formed when oxygen molecules are exposed to electron flow. Ozone molecules are unstable and will lose the third oxygen atom over time. Ozone is formation characterization:

1. Ozone generators provide an electron flow between dielectric and SS tubes.
2. Oxygen is passed through the gap between dielectrics resulting in ozone generation.
3. Oxygen feed gas must be dry and free of particles.
4. Ozone generators must be cooled, and cooling water removes .90 percent of the heat that is generated.

Ozone is a powerful oxidant with high disinfectant capacity. Ozone residuals between 0.3 to 2.0 mg/L inactivate viruses. Inactivation rates range from >3.9-log to >6-log, and occur within very short contact periods, 5 seconds. Microorganisms in natural waters are very sensitive to ozone. *Giardia* and enteric viruses are inactivated by ozone, as a primary disinfectant, with 5 minutes of contact time. Ozone residuals of 0.5 to 0.6 mg/L result in 3-log and 4-log removals, respectively. When ozone is used as a primary treatment, the criterion for its use is based on ozone residuals, competing ozone demands, and a minimum contact time to meet the required cyst and viral inactivation requirements.

Ozone is the strongest oxidant and strongest disinfectant available for potable water treatment. This unique material can be utilized for a number of specific water treatment applications, including disinfection, taste and odor control, color removal, iron and manganese oxidation, hydrogen sulfide removal, nitrite and cyanide destruction, oxidation of organics such as phenols, pesticides, and some detergents, algae destruction and removal, and as a coagulant aid. Even though ozone is the strongest chemical disinfectant available for water treatment, some refractory organics are not oxidized, or oxidize too slowly. In such cases, ozone can be combined with UV radiation and/or hydrogen peroxide to produce hydroxyl free radicals, HO^-, which is a stronger oxidant than molecular ozone, O_3. Deliberate production of hydroxyl free radicals starting with ozone has been termed ozone advanced oxidation. Groundwater that is contaminated with chlorinated organic solvents and some refractory hydrocarbons are being treated successfully with ozone advanced oxidation techniques.

At ambient temperatures, ozone is an unstable gas, partially soluble in water; generally, more soluble than oxygen. Due to its instability, ozone quickly reverts to oxygen. Ozone cannot be produced at a central manufacturing site, bottled, shipped, and stored prior to use. It must be generated and applied on-site. The installation of an ozone production plant requires storage of pure oxygen on-site as the feed gas. Ozone is generated for commercial uses using corona discharge or ultraviolet radiation. The UV technique produces low concentrations of ozone, whereas corona discharge produces ozone concentrations in the range of 1 – 4.5 % when dry air is fed to the ozone generator. When concentrated oxygen is used as the feed gas, gas phase ozone concentrations of up to 14 to 18% can be produced. Since ozone is only partially soluble in water, once it has been generated it must be contacted with the water to be treated in such a manner as to maximize the transfer of ozone from the gas phase into water. For this purpose, many types of ozone contactors have been developed. However, as higher concentrations of ozone gas are employed, contacting system designs become more critical because of the lower gas to liquid ratios.

The use of oxygen as the feed gas can result in oxygen super saturation of the treated water causing operational problems and corrosion in the distribution system. Ozone contacting system options include atmospheric tall towers or pressurized gas to liquid mass transfer processes. Fine bubble diffusers, static mixers, or venturi injectors can be used to mix the gas with the water to be treated in full flow or side stream configurations. Once dissolved in water, ozone is available to act on water contaminants to accomplish its intended purposes of disinfection and/or oxidation. At pH levels of 3-6, ozone is present primarily in its molecular form (O_3). However, as the pH rises, the decomposition of ozone to produce the hydroxyl free radical (HO^-) becomes increasingly rapid. At pH 7 about 50% of the ozone transferred into water produces HO^-. At pH >10, the conversion of molecular O_3 to HO^- is virtually instantaneous.

Because ozone is such a powerful oxidant/disinfectant, the trick to applying it to solve water treatment problems is to do so in a manner that is effective for water treatment, yet at the same safe for the people in the vicinity. Ozone safety issues are handled

easily by using proper ambient ozone monitoring, tank venting, and ozone destruction. In the case of systems driven solely by a pumping/injector system, ozone may be produced under vacuum, which ensures no leakage of ozone into the operating environment.

The five basic components of an ozone system include:

1. Gas preparation–either drying gas to a suitable dew point or using oxygen concentrators
2. A suitable electrical power supply
3. A properly sized ozone generator(s)
4. An ozone contacting system
5. Ozone off-gas destruction or suitable venting system

Moisture in the feed gas causes two operating problems:

1. The amount of ozone produced by application of a given electrical energy level is lowered as relative humidity rises. Consequently, it is usually cost-effective to dry the air to a recommended dew point of minus 65’C (-65’C or -76’F) or lower.
2. Ozone generated using air in the presence of moisture allows small amounts of nitrogen oxides to react with the moisture to produce nitric acid. In this instance, gas condensation at the cooling/heat transfer surfaces produces a corrosive compound which can cause corrosion problems in the ozone generation equipment with concomitant increases in equipment maintenance requirements.

Because of the high oxidative qualities of gas-phase ozone and the chance of moisture from a failing feed gas unit, system managers must take extra care to make certain that all components in the ozone generator, ozone supply line, ozone gas to liquid mass transfer equipment and the contact vessel are ozone-compatible.

For large scale ozone systems, the equipment for cleaning and drying feed gases can become quite complex. For example, effective air drying can involve multiple treatment steps including air filtration, compression, cooling, desiccation, and final filtration prior to passage into an operating corona discharge ozone generator.

A need exists for efficient ozone contacting and destruction of excess ozone in contactor off-gases. Absent an effective ozone off-gas destruct unit, excess ozone would be present for people in the vicinity to breathe, which is not recommended because of its strong oxidizing nature. Additionally, ozone is heavier than ambient air, and can settle in the vicinity, and attack oxidizable materials. Destruction of contactor off-gas ozone is readily accomplished thermally (370’C), catalytically, thermal-catalytically, and by passing the off-gas through granular activated carbon. Care should be exercised in selecting an ozone destruct method whenever very high concentrations of ozone are encountered.

Ozone is a critical process for non-reverse osmosis purification. It is usually coupled with biologic activated carbon filtration. The process reduces TOC and trace chemical pollutants, removes protozoans, kills viruses, and is a flocculation aid. Ozone treatment is an oxidation process used as a disinfection and oxidant prior to biologic activated carbon filtration.

Instrumentation and controls for ensuring effective and safe operation of ozone systems are concerned with applying ozone effectively and affordably. System processes control ozone generation, oxygen usage, drying, ozone injection and diffusing, and ozone destruction.

The instrumentation monitors each step, and each step has an alarm associated with the process.

Key Terms

- **Coagulation –** a process that is followed by sedimentation and filtration will remove 90 to 95-percent of the pathogenic organisms depending on which chemicals are used; alum usage in coagulation can increase virus removals up to 99-percent.
- **Disinfection –** a process that destroys harmful organisms physically or chemically
- **Filtration** – a process through granular filters is an effective means of removing pathogenic and other organisms form water; removal rates vary from 20 to 99-percent, depending on the coarseness of the filter media and the type of effectiveness of pretreatment.
- **Sedimentation** – a process through which pathogenic organisms settle out by gravity, assisted by chemical floc; proper design of sedimentation processes can effectively remove 20 to 70-percent of the pathogenic microorganisms

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2.12.1: Review Questions

Review Questions

1. **List the factors that affect chlorination of drinking water?**
2. **Describe disinfection as a process in drinking water treatment.**
3. **What is the purpose of chloramination in drinking water?**
4. **What is ozonation of drinking water?**
5. **How does UV light effect microorganisms?**
6. **Describe the primary reason that chlorine may not be used for drinking water disinfection at a particular drinking water facility.**

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2.12.2: Chapter Quiz

Chapter Quiz

1. _____ is the process designed to kill or inactivate most microorganisms in water, including essentially all pathogenic (disease-causing) bacteria.

1. Sterilization
2. UV treatment
3. Application of chlorine
4. Disinfection

2. Which of the diseases listed is not caused by a waterborne pathogenic organism?

1. Gastrointestinal anthrax
2. Shigellosis
3. Polio
4. All of these are water borne diseases

3. Hypochlorous Acid and hypochlorite when considered together are also known as the _____.

1. chlorine dose
2. chlorine demand
3. free chlorine
4. chlorine residual

4. _____ is a gas that does not form carcinogenic compounds like those compounds formed by chlorine disinfection. It also is not affected by ammonia, and it is a very effective disinfectant at higher pH levels. It is also used to diminish taste and odor problems in the distribution system. It is especially useful in inhibiting *Legionella*.

1. Chloramination
2. Chlorine dioxide
3.
4.

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2.13: Customer Questions, Complaints, and Investigation

Learning Objectives

After reading this section, you should be able to:

- Outline common customer questions and complaints
- Explain recording keeping
- Explain response process to customer inquiries and complaints

Questions and Issues

Water agencies rely on customer inquiries or complaints for effective monitoring water quality in a distribution system. Most customer questions are regarding secondary or aesthetic concerns:

- Why does my water look this way?
- Why does it taste this way?
- Why does it have this smell?

Many of these questions can be answered without launching a full investigation. But water quality complaints at times may provide an early warning of a more serious water quality incident. As such, well run agencies have established effective customer complaint monitoring and communication programs.

EPA designed a Water Quality Surveillance and Response System, in 2017, which includes a customer complaint component. It was designed for the water resource professional and is flexible and adaptable based on a water utility's goals.[1] It is based on a "Funnel, Filter and Focus" approach whereby utilities can quickly identify which complaints may identify an actual water quality incident.

Water utility customer service departments typically follow this approach:

1. **Collect Data.** (Funnel and Filter) Customer contact is directed to a central location to representatives who are trained to collect and filter information based on the type of complaint, including the customer's contact information, description of the problem, and dates that it started (and ended, if it did).
2. **Investigate.** (Focus) Forward the complaint to the proper department or person for evaluation, if necessary. Then the relevant department should initiate an investigation, consider potential causes, gather additional data from the customer and other sources such as operations records of the plant or distributions system, laboratory, or field testing results on water samples, and distribution system inspection results, such as cross connections and proper valve operation. Water quality staff will determine if the complaint could indicate contamination and take corrective action if necessary.
3. **Communicate.** Keep the customer informed of the results of the complaint investigation. If it is an actual water quality incident, notification rules to the public and other agencies may be required.

Open, positive, and transparent communication with the public cannot be overstated. All utility employees should be provided with training by the water utility they represent. Customer service representatives should be able to respond to billing or meter reading concerns and general water quality complaints related to minor issues such as taste and odor changes when switching from chloramine to free chlorine. All water operators should have the knowledge and basic understanding of all aspects of their source water, distribution system, and treatment plant. They will likely encounter regulators from other agencies in the course of their career.

Social media is a major resource employed by well-run agencies to reach customers, address complaints and manage water quality issues. Social media platforms like "Facebook" and community based "Nextdoor" are presently used by many agencies. The irony is that the public will judge its water supply on secondary standards (cloudy, rust colored, musty smell) and not primary standards. Social media can go a long way towards explaining what is taking place when these nuisance water quality issues arise.



Figure 2.13.1: A water utility customer service department. (Copyright; [1] of SCV Water)

Pin It! Misconception Alert
It's easy to dismiss customer concerns, particularly if they are vocalized loudly or rudely. All complaints should be treated as legitimate.

It is important for customers to know how to communicate complaints to their utility and that all complaints are captured and funneled into one location regardless of how they are received. The near real-time acquisition of this information is invaluable in the event of a real emergency.

Agencies have used their Consumer Confidence Reports to clearly explain how to report water quality issues. They include examples of the type of information the customer should provide (taste, odor, appearance of the water).

Records

Written records should be kept on all facilities in the distribution system. These records should describe the facility, its construction, date installed, repairs and maintenance work completed, manufacture, and condition during the latest inspection.

As new facilities are installed, they should be included in the existing record system. Records should also note those facilities retired from service. Other types of records that should be kept are:

1. Results of water quality monitoring
2. Cross-connection control
3. Main flushing
4. Main cleaning
5. Consumer questions, complaints and conservation programs participated in
6. Disinfection
7. Pressure surveys
8. Leaks
9. Engineering reports
10. Any operations done in compliance with the request of the health department
11. A daily log kept on any and all unusual events occurring, such as equipment malfunction, unusual weather conditions, and natural or manmade disasters.

Each public water system is required by the primary Drinking Water Regulations to maintain records of water quality analyses, written reports, variances or exemptions, and actions taken to correct violations of the regulations.

Complaints

Customer complaints may vary based on geographic region. Within the southwestern United States, complaints about hard water are very common. Customers may complain about the water containing “floating objects,” which are often calcium or magnesium. These are minerals that are naturally occurring in groundwater, but may cause customers to think the water is not safe to drink. It is not common for many customers to utilize water softener services and under sink filtration and reverse osmosis treatment systems.

Many water quality complaints originate within the customers own plumbing system downstream from their retail service connection. There may be low pressure problems or rusty colored water incidents due to the customer’s valves or water lines. It is not uncommon for a utility to dispatch an employee to take a water quality sample at the customer’s residence and report back with the results.

Water utilities will also receive complaints about illnesses in a home due to the drinking water. The customer should also be referred to city or county public health agencies while the utility is performing its own investigation.

Surveys

Most utilities go directly to their customers to find out how the customers feel about the system and its operations. The process is part of an overall plan by utility to self-evaluate and collect customer opinions. Follow-up after a survey with consumers, and develop an improvement program to address the issues that were uncovered in the questionnaire. The questionnaires should be designed to ask questions that a layperson could understand, and it may be advantageous to field test the survey before wide distribution. Problems can be identified, and priorities can be designated as to which problems can be solved soon and which must wait for solutions at some later date. Again, social media can be a valuable platform for this.

When customers or stakeholders complain about an aspect of the drinking water or service, document the complaints. Maintain a data file of all complaints that are received and use it to monitor underlying symptoms of problems that are larger than the immediate issue raised. The data file should be such that it can be searched for any patterns that could surface from the complaints. Importantly, the utility should use the complaints as a tool for early detection of potential problems.

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[1] USEPA, Designing Customer Complaint Surveillance For Water Quality Surveillance and Response Systems https://www.epa.gov/sites/default/files/2018-02/documents/customer_complaint_surveillance_design_guidance.pdf)

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2.13.1: Review Questions

Review Questions

1. **Outline the steps that should be implemented when responding to customer complaints concerning drinking water quality.**
2. **What is a common consumer complaint that is received by the drinking water treatment plant?**
3. **Why should complaint logs and responses to customer complaints be reviewed periodically?**

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2.13.2: Chapter Quiz

Chapter Quiz

1. The _____ of a utility are responsible for customer relations and for positive customer communication.

1. customer service personnel
2. employees (all)
3. public relations officer
4. operators

2. Which of the following is not included in the process of dealing with a consumer complaint?

1. Collect as much information from the consumer as possible
2. Direct the complaint to the proper department or person for evaluation, if necessary
3. Consider different potential causes of the problem and methods of testing
4. Correcting the complaint and having as little public contact as possible is the goal

3. When presented with a complaint, _____ should show concern, listen carefully, and calmly offer to look into the complaint. Help correct any problems that are found within the system and answer questions or obtain answers to questions.

1. customer service personnel
2. employees (all)
3. public relations officer
4. operators

4. Sometimes, it is through _____ that a water utility learns the service being provided is not satisfactory.

1. complaints
2. award applications
3. records
4. surveys

5. A customer may complain about a lack of _____in the home which is typically due to valving problems in the home's plumbing.

1. pressure
2. red water or dirty water
3. illness resulting from drinking water
4. too much chlorine

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3: Safety

Student Learning Outcomes

After reading this chapter, you should be able to:

- Describe the difference between acute and chronic health effects as they relate to safety
- List the various types of safety practices of a water utility
- Explain the importance of proper record keeping related to safety

Safety in the workplace is something that transcends all industries. Each profession has their own set of safe work practices as it pertains to their specific job functions. For example, construction workers might be exposed to excessive heat. Therefore, these employees should be given the proper training and equipment to help prevent things like heat stroke. People working on an assembly line might be exposed to repetitive motions, which can lead to things like carpal tunnel syndrome. Their employer must provide the right work conditions in order to protect against strains and conditions associated with this type of activity. Another example might be someone working on a loading dock and is required to lift heavy objects. In this case, they must receive the proper instructions on how to lift properly and provided about what to do in the case where something is too heavy to lift.

These are just a few examples of safety-related items workers encounter in various industries. The water utility industry is no different. In fact, a professional water worker might be exposed to many different safety-related issues compared to employees in other industries. In addition, since many water utility operators are required to work around the public, there is an aspect of protecting the public from injuries related to the work they do. This text will attempt to analyze and address many of the safety items water workers might encounter.

Various Types of Safety

We will break the different types of safety into three (3) main categories. These are organizational safety, fleet safety, and public safety. Each of these categories is defined below:

- Organizational Safety—This is the most universal type of safety businesses (organizations) are faced with. It is the overall prevention of injury to employees. This prevention of injury is for employees both on and off the job. You might ask why an employer should be concerned with an employee's personal safety when they are not working. The main reason organizations should instill the value of safety for employees both on and off the job is two-fold. First, any injury can result in lost time. This means if an employee gets injured at home, they may not be able to report to work. This results in inefficiency in the workplace and sometimes results in a loss of revenue for the employer. The second reason and maybe more importantly is creating a culture where safety is a value within the organization. Valuing safe work practices both on and off the job will result in a safer work environment and less loss time and money for organizations.
- Fleet Safety—Water utility workers work within a community. They are required to operate equipment and drive vehicles. This can result in traffic accidents and equipment-related accidents. Fleet safety is designed to help prevent these types of accidents.
- Public Safety—Put simply, public safety is the prevention of injury to the general public. Water utilities have facilities throughout a community and it is important these facilities do not pose a safety hazard to the general public. An example of this might be something simple like a meter box lid. If the lid is missing or broken, it could present a tripping hazard to someone walking along a sidewalk. Water utility workers also work in public streets. This not only presents a safety hazard to the employee but blocking off portions of a street can lead to traffic accidents and exposes the public to potential safety hazards.

Organizing a Safety Program

Each utility should designate an individual responsible for safety. Unfortunately in smaller agencies this is usually someone in middle management. A full-time safety officer is important in order to have one single person looking after health and safety for the entire organization. When safety is assigned to someone with other responsibilities, safety sometimes gets overlooked. Regardless who is tasked with overseeing the program, it is important that staff, management, and the entire organization look at safety as a core value. Each individual is ultimately responsible for their own safety, but they also need the correct tools and equipment to do their job safely.

A designated safety's main responsibility is to help staff and primarily supervisors. They are not tasked with providing all the training and equipment. They are to assess safety work practices and help implement safety programs. They determine the safety needs of an organization. They plan, develop, and recommend safety plans and programs. A safety officer should evaluate the effectiveness of safety plans and programs and make adjustments and corrections as necessary. Generating safety information and conducting meetings with employees and supervisors is also a function of a safety officer. Investigating accidents and injuries is also part of the responsibility of a safety officer as well as maintain records and reports covering all aspects of the safety program. These are some of the more critical responsibilities and additional tasks may be required as necessary.

Management also plays a large role in regards to safety. Without management's "buy-in", staff sometimes feels disenfranchised. Management needs to establish an overall safety policy for the organization. They appoint the safety officer (or coordinator) and assign responsibility for accident prevention. Management establishes goals, revises as needed, and evaluates results of the overall program.

Supervisors set the patterns for safety and should lead by example. No employee likes the "do as I say, not as I do" attitude. Since supervisors have direct control over employees, they should instill safety as a core value and provide the proper tools, equipment, and safety items needed to do tasks in a safe manner. They should instruct and council staff on safe work habits and review work for compliance with the safety program and regulations.

Employees are the front line workers of an organization. Therefore they are typically exposed to the majority of safety hazards. They must perform their work in accordance with the appropriate safety procedures and actively participate in the safety program. All injuries and hazards should be reported. At no time should an employee work in an unsafe manner or condition. If an employee feels a job is unsafe they are to report these findings to a supervisor.

The following is an example policy safety statement:

- The organization's recognition of the need for safety in order to stimulate efficiency, improve service, build employee morale, and promote better public relations
- The organization's interest in the employee - to provide proper equipment and working conditions, and to promote safety and the expectation that the individual employee will maintain safe work practices
- The fact that the human factor rather than the mechanical is most significant cause of accidents, thus emphasizing the employee's responsibility to perform the job safely
- That an essential part of the supervisor's job is responsibility for development of safe work practices and their environment

Safety Regulatory Requirements

The federal Occupational Safety and Health Administration (OSHA) is responsible for assuring safe and healthful working conditions by setting and enforcing standards and by providing training, outreach, education, and assistance. OSHA is part of the United States Department of Labor. Safe work practices can eliminate and reduce suffering, injury, and death. Safe work practices also reduce lost time, medical costs, and legal judgments. Proper safe work practices save time and money for companies too.

OSHA has established minimum health and safety standards that are applicable to every industry. The mandate that every employer furnish employees with a workplace that is free from recognized hazards that are likely to cause death or serious physical harm.

Causes of Accidents

Unsafe acts and unsafe conditions are two of the most common results in accidents and injuries. Lack of experience or improper training commonly results in unsafe acts. Some employees have an indifference to safety and can result in excess accidents and injuries. Poor work habits or cutting corners, working too fast and impatience results in unnecessary accidents and injuries. It is also important for employees to be well-rested and in good physical condition. There are usually specific condition requirements for some jobs. For example, a job requiring the operation of heavy equipment or strenuous labor may require certain licenses and regular physical fitness testing. Drug and alcohol testing may also be required for certain jobs. Impaired employees pose a danger to themselves and to other co-workers. Below are examples of unsafe acts:

- Ignorance—It is not that employees are ignorant. It is when they lack the experience or training to do their job safely
- Indifference—Some employees and in some instances employers are "indifferent" or do not care about safe work practices

- Poor work habits—Many times employees develop bad habits if they don't understand how to perform task correctly in the first place
- Laziness—Sometimes employees do not want to or are unable to provide the required effort
- Haste—Working too fast can contribute to unsafe work conditions
- Poor physical condition—Employees need to have proper rest and for some tasks must be physically fit
- Temper—Impatience and anger can cloud judgment and result in accidents

Reading through the list above you might have thought that most if not all of these are preventable. If so, you would be right. Most unsafe acts and conditions are preventable. That is not to say all accidents can be avoided, but many can by simply avoiding the list above.

Safety Training Topics

One of the most important aspects of a safety program is training the workforce. Some training topics are required to be completed by employees on a routine basis. Standard training requirements are found in Occupational Safety and Health Administration (OSHA) regulations. Some safety requirements are under General Industry standards while others are specific based on the type of industry. The following safety training topics are general in nature, required throughout the water industry, and provide a high level of understanding.

Hazard Communication

Any industry where chemicals are used, annual training explaining the hazards associated with exposure to these chemicals in the workplace must be conducted. Employers should provide employees with training prior to initial assignment to their work area. Hazard communication (HazComm) training should identify the activities and locations of the chemicals in the workplace and the health hazards associated with exposure to the chemicals. Additional topics covered in the training include but are not limited to steps employees can take to protect themselves, labeling criteria of the chemicals. And clean up procedures.

As part of hazard communication training, an inventory list of chemicals needs to be provided and available to all employees. The details of which chemicals are required to be covered in training are beyond the details provided in this text. The example we will use is one of the more common chemicals used in the water industry. Chlorine is one of the most widespread chemicals used in drinking water distribution and treatment. In addition, chlorine is hazardous to health.

Several different types of chlorine related compounds are used in the disinfection of drinking water. Calcium hypochlorite is corrosive in water and can support combustion. Sodium hypochlorite is a very strong base on its own and becomes an acid in water. Operators should wear goggles and gloves when working with hypochlorites.

The most common disinfectant in drinking water is chlorine, which is a greenish/yellow gas. Since chlorine gas is two and half times heavier than air, ventilation is required in chlorine rooms. The ventilation vents should be twelve (12) inches above the floor. Since chlorine is a compressed gas and stored in cylinders, it should not be filled more than eighty-five (85) percent to allow for expansion. Another safety feature of chlorine gas cylinders is a fusible plug. One (1) ton cylinders have two (2) valves for removing either gas or liquid and six (6) fusible plugs. A one hundred fifty (150) pound cylinder has one of each. Fusible plugs are designed to melt between the temperatures of one hundred fifty-eight (158) and one hundred sixty-five (165) degrees Fahrenheit. If there are chlorine leaks in a cylinder, an ammonia-soaked rag can be used to help detect the leak. By waving an ammonia-soaked rag a white cloud would appear. High levels of chlorine in the air affect respiration and the immediately dangerous to life and health (IDLH) level is 10 parts per million (ppm).

This example is just one of many where chemicals are used in the workplace and employees need to be properly trained on the hazards associated with working with and around these chemicals. In 2003, the United Nations adopted the Globally Harmonized System of Classification and Labeling of Chemicals (GHS). In 2009, OSHA published regulations to align their Hazard Communication standard (HCS) with the GHS. There are five (5) mandatory components of OSHA's HCS, one of which includes an update to what was previously known as Material Safety Data S, which sheets. The revised standard refers to Safety Data Sheets (STS) and sixteen (16) required sections with information about each chemical. If there is no relevant information under one of the subject headings, then the SDS must clearly indicate that no applicable information is available.

Personal Protective Equipment

One of the sections on an SDS must reference personal protection from exposure to chemicals. In addition, personal protective equipment (PPE) has its own regulatory standards regarding training, what types of working conditions might require PPE, and how to Don, Doff, and care for PPE.

Each employee is responsible to maintain their own PPE and notify their supervisor whenever it needs replacing. It is the management's responsibility to provide the training and required PPE needed by the employees. The following PPE examples are just some common types of personal protective equipment.

- Hard hats—Any time there is a potential for head injuries including low headroom working conditions or overhead items, which can fall on an employee, hard hats are required. Metal or plastic hard hats can be used, but metal hard hats should not be used where there are electrical hazards.
- Gloves—If there are pinching, cutting, crushing, or other hand-related injuries, then gloves should be worn. In addition, gloves may also be required when working with or around chemicals.
- Respiratory—When surrounding air contains dust, fumes, mists, or any other particulates, which can be inhaled, then respiratory protection is required. Respiratory protection can be as simple as a dust mask or as complex as a self-contained breathing apparatus.
- Eye Protection—Goggles, face shields, safety glasses are all forms of eye protection. Dust and debris can cause irritation is they get into someone's eyes. Any kind of object, including chemicals, can all cause damage to the eye.
- Steel-toed boats—It is prudent to wear foot protection in any construction-related industry. Therefore, steel-toed boats are often required.
- Hearing Protection—Earplugs provide ear protection from loud noises and sounds. Earmuffs can also be used to protect ears.

Understanding how to don and doff PPE is an important aspect of PPE training and all employees should understand the proper way to wear the appropriate equipment.

Slips Trips and Falls

Sometimes, the simplest and most common hazards can result in personal injury. Slips, trips, and falls should always be avoidable. Often times, it is a matter of good housekeeping. Making sure floors and walking surfaces are clear of debris and any kind of slipping or tripping hazards. Walking areas should have slip-resistant surfaces and proper handrails should be provided on stairways, catwalks, and areas where walking can be difficult. Fall protection also needs to be provided on elevated surfaces.

Back Safety

Back injuries are one of the most common injuries in the workplace. Improper lifting, twisting, pulling, and pushing are all aspects of back safety. Whenever lifting something heavy, workers should always bend at the knees and keep their back straight. One person should never lift large and heavy loads. When carrying something heavy, you should always turn with your legs and not at your waist. Equipment should also be used when appropriate to help lift and/or move heavy objects.

Trench Safety

Trenching is a method of digging into the ground to install things such as pipes. Whenever work is done inside a trench, special precautions need to be made in order to protect workers from the possibility of a cave-in. There are specific requirements based on the depth of the trench. If trenches are shallow (less than five (5) feet) then the danger is not as great as it is with deeper trenches. However, workers can still get trapped in shallow trenches. When trenches are five (5) feet or deeper, special protection is required. This protection is referred to as shoring, shielding, or sloping. If there is enough room, then sloping is allowed. Sloping is the process of reducing the depth of a trench by removing soil and opening the width of a trench to prevent the trench walls from collapsing. Shoring and shielding is the process of using equipment placed up against trench walls. The dirt being excavated (referred to as spoils) should be placed at least two (2) feet away from the trench edge and on the side opposite of the pipe being installed. If trenches are long, then ladders should be placed within twenty-five (25) feet of workers. Another important aspect of trench safety is proper supervision. Special training must be provided to individuals overseeing trenching activities. These individuals providing supervision are referred to as a "Competent Person".

Confined Spaces

A confined space is defined, as a workspace, which has limited or restricted means of entry or exit, is large enough for an employee to enter and perform work, and is not designed for continuous work or occupancy. Confined spaces are defined as “permit-required” and “non-permit required” confined spaces. In order for a confined space to be classified as a permit-required confined space, it must meet the following conditions:

- Contains or has the potential to contain a hazardous atmosphere
- Contains a material that has the potential for engulfing an entrant
- Has an internal configuration such that an entrant could be trapped or asphyxiated by inwardly converging walls or by a floor that slopes downward and tapers to a smaller cross-section
- Contains any other recognized serious safety or health hazard

The internal atmosphere of a confined space must be tested for oxygen content, flammable gases, and vapors, potentially toxic air contaminants, hydrogen sulfide, and methane. Ventilation equipment should be used to provide acceptable air conditions. Three (3) or more workers should be involved with permit-required confined spaces. One (1) or more workers inside the confined space, one (1) worker in communication with the worker(s), and one (1) worker to respond and retrieve emergency personnel if needed.

Respiratory Safety

As previously mentioned, it is important to provide workers with respiratory protection if the surrounding atmosphere is not adequate for a working environment. Respiratory hazards include, but are not limited:

- Dust from rock, cement, coal, and wood
- Dust from toxic materials such as lead, arsenic, and asbestos
- Mists and fumes from chemicals and heated materials
- Vapors and gases from chemicals such as chlorine, ammonia, and carbon monoxide
- Oxygen deficient environments

Respiratory problems can range from very mild irritation causing coughing and wheezing, to death. Respirators can be broken down into two main types, air purifying and atmosphere supplying.

Air-purifying—These types of respirators use cartridges, filters, or canisters to remove contaminants from the air. In order to remove vapors and gases, a granular porous material referred to as an absorbent needs to be used. The type of filter, cartridge, or canister is dependent on the type and amount of the airborne contaminate. For example, a particulate filter would not necessarily remove vapors or gases. Therefore the employer must identify the contaminant(s) and provide employees the proper protection against dust, fumes, mists, and solid particulate matter.

Atmosphere-supplying—In certain circumstances, the surrounding atmosphere is not suitable for breathing and purifying the air may not be sufficient. Therefore, a respirator where clean air is provided should be used. A common situation where this might occur is when the surrounding atmosphere lacks adequate oxygen levels or is considered oxygen deficient. At this point, atmosphere-supplying respirators are required.

There are a number of various other safety topics, which should be considered if potential hazards exist. Some of these topics include, but are not limited to hand and power tool safety, electrical, head, body, and extremity protection.

Traffic Control

Utility workers often work in roadways. Whenever work is performed in traffic areas, the Manual on Uniform Traffic Control Devices for Streets and Highways should be used. This manual is published by the US Department of Transportation (USDOT) and specifies approved traffic control devices and procedures. Some states have their own traffic control reference manuals and those should also be reviewed before working in the street. If improper traffic control is set up, the utility can be held liable for damage from accidents. Often times special permits, such as encroachment permits are required as well as special traffic control plans need to be submitted to the governing agency. Traffic control devices such as cones, pylons, and other systems are used to channel the flow of traffic to designated areas. There are five (5) zones within a construction worksite in roadways:

- Advanced Warning Zone—This area is a warning to drivers letting them know what to expect. This advanced warning can be as simple as a single flashing light to a series of signs and notifications prior to the temporary construction work and change in the flow of traffic.
- Transition Zone—Whenever the redirection of the normal flow of traffic is required, a transition area is needed. Traffic must be channelized from the normal flow to the new path in order to avoid the construction area.
- Buffer Zone—While not required, it is an important area for the protection of workers. It is an area between the flow of oncoming traffic and the area where employees are working.
- Work Zone—This is the area where the work is being performed. Workers and equipment are within this area. By the time traffic reaches this area, it should be completely redirected out of this zone.
- Termination Zone—As with the transition zone, the termination zone is redirecting traffic. Except in this zone, traffic is being returned to its normal flow path.

The taper lengths and buffer zones have specific distances in relation to traffic speed. More traffic control devices, longer taper lengths, and larger buffer zones are needed as the speed of traffic increases.

Occupational Injuries

All injuries in the workplace should be reported immediately. This early reporting not only helps the utility determine if the injury occurred at work and it also speeds up the process for the employee to start any type of worker's compensation. An occupation injury is defined as any personal injury sustained by an employee during the course of work. Employees should report their injury to their supervisor or to the organization's safety representative. Utilities typically have injury report forms. These forms should be simple but informative. They should contain information from both the employee and supervisor. The employee is responsible for reporting the injury and the supervisor and safety representative are responsible for making sure the report form is completed correctly.

All injuries should be investigated. Accident and injury investigations provide an opportunity for the safety professional to speak with the employee and any witnesses. It allows for feedback on the cause of the incident and give the safety professional the opportunity to provide feedback on the necessity of exercising care and caution. It also presents the opportunity to identify any unsafe work practices or conditions and allows for recommendations on workplace improvements.

Safety professionals should prepare and review a variety of reports associated with workplace accidents and injuries. These include, but are not limited:

- Number of lost-time injuries—any injuries resulting employees missing time from work
- Number of injuries requiring first aid—first aid kits should be provided at each workplace and with workers who work in remote locations
- Number of injuries requiring medical attention—any injury where an employee receives assistance from a medical professional
- Number of lost time days—when employees miss work due to an injury, this is referred to as lost time

There are also OSHA related performance measures safety professionals use to track and interpret the prevalence of workplace-related injuries. These include:

- Incidence Rate—This is based on the number of injuries requiring more than first aid per 200,000 hours worked
- Frequency Rate—This is the number of lost time accidents per million employee hours worked
- Severity Rate—This is the number of days lost or charged per million employee hours worked

OSHA has specific reporting requirements related to workplace injuries. Most organizations are required to maintain an OSHA Form 300 Log. This log lists all recordable workplace injury and illness. OSHA defines a recordable injury or illness as:

- Any work-related fatality
- Any work-related injury or illness that results in loss of consciousness, days away from work, restricted work, or transfer to another job
- Any work-related injury or illness requiring medical treatment beyond first aid
- Any work-related diagnosed case of cancer, chronic irreversible diseases, fractured or cracked bones or teeth, and punctured eardrums

In addition to these definitions, there are also special recording criteria for work-related cases involving: needle sticks and sharps injuries; medical removal; hearing loss; and tuberculosis. In general, minor injuries and injuries requiring first aid treatment do not need to be recorded. All employers are also required to notify OSHA directly when an employee is killed on the job or suffers a work-related hospitalization, amputation, or loss of an eye. Fatalities must be reported within eight (8) hours and in-patient hospitalization, amputation, or eye loss must be reported within twenty-four (24) hours.

Safety is a very important aspect for all occupations. Water utility operations are no exception. It is important for safety to be supported from the top executives all the way down throughout the organization. Ultimately, the primary person responsible for safety is…YOU!

Sample Questions

1. When symptoms develop rapidly within a person it is considered _____.
    1. A chronic health effect
    2. An acute health effect
    3. A disease
    4. Both 1 and 3
2. What is the primary responsibility of the safety officer?
    1. Should be a line function
    2. Should be a staff function
    3. Should provide all the training
    4. All of the above
3. Traffic control should be set up in the following order:
    1. Buffer Zone, Transition Zone, Work Zone, Termination Zone, Advanced Warning
    2. Advanced Warning, Buffer Zone, Work Zone, Transition Zone, Termination Zone
    3. Advanced Warning, Transition Zone, Buffer Zone, Termination Zone, Work Zone
    4. Advanced Warning, Transition Zone, Buffer Zone, Work Zone, Termination Zone
4. Fusible plugs are designed to _____.
    1. Melt, preventing combustion
    2. Melt between 158°F - 165°F
    3. Fuse the valve connection to the hose
    4. Only 1 and 2
5. A 1-ton chlorine cylinder has _____.
    1. 2 fusible plugs and 6 valves
    2. 2 valves and 6 fusible plugs
    3. 1 valve and 5 fusible plugs
    4. 5 valves and 1 fusible plug
6. The IDLH for chlorine gas is _____.
    1. 5 ppm
    2. 10 ppm
    3. 20 ppm
    4. 100 ppm
7. All fatalities, serious injuries and illnesses must be reported to Cal/OSHA within _____.
    1. 8 hours
    2. 16 hours
    3. 24 hours
    4. 48 hours
8. A chronic health effect is _____.
    1. An adverse effect developing rapidly

2. An adverse effect resulting in cancer
3. An adverse effect developing over a long period of time
4. A disease with little or no symptoms

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SECTION OVERVIEW

3.1: General Safety

3.1.1: Laboratory Area

3.1.2: Personal Protective Equipment

3.1.3: Chemical Handling

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3.1.1: Laboratory Area

General Safety Practices

Lab Expectations

Food and beverages are prohibited within the lab space. Pathogens or toxic chemicals could transfer to your food or beverage, leading to illness or even death.

The environmental lab is divided into two specific areas. The classroom half is used for non-lab activities. This area accommodates backpacks, jackets, and learning equipment such as laptops and notebooks. In the classroom area, contamination risk is low but not zero. The lab half is used for experimentation, and the contamination risk is high. Students should take extra caution in the lab area. Lockers are available in the hallway for student use.

Lab Safety

Prior to beginning any experiment, students will review safety information. Safety information will include proper procedures, chemical hazards, biological hazards, and physical hazards. Students need to locate important safety equipment such as the first aid kit, emergency eyewash, emergency shower, fire extinguisher, and chemical spill kits. Students also need to locate the nearest exit in case of an emergency.

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3.1.2: Personal Protective Equipment

While the lab does minimize risk using engineering and administrative controls, personal protective equipment is required to mitigate the impact of hazards should other controls fail. Students are expected to wear the following during lab experiments where hazards are present:

- Long pants
- Closed-toed shoes
- Lab coat
- Safety glasses or goggles
- Gloves

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3.1.3: Chemical Handling

Safety data sheets are available for all chemicals used in the lab. Students, when preparing for lab, must review the safety data for any chemicals being used. Below are key points for the proper storage of laboratory chemicals:

- Chemicals must be stored in a cool, dry location out of direct sunlight
- Chemical storage in a cabinet is recommended
- Liquid chemicals should be stored below human face level to avoid splattering in case of bottle spillage or breakage
- Chemicals must be dated upon receipt, and the expiration date must be recorded
- Acids should be carefully stored, separate from other chemicals, and below eye level
- Chemicals should never be stored in unmarked containers

Other Chemical Handling Notes

- Always pour acid into water when diluting and swirl or mix to dissipate heat
- The pH of liquids poured down the drain must be between 4 and 1

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4.1.1: Glassware

Basic Glassware

Glassware	Description and Use
Volumetric flask	Bulb-shaped with a long stem. This is used to measure only one specified volume. It is best to use when making standards for calibration.
Beakers	Cylinder-shaped with a large open top. While these have volume measurements, they are not accurate enough to use for measuring. These are best used for holding liq
Erlenmeyer flask	They have wide bottoms and a narrow top. Like beakers, these are not accurate enough to use for measurement. These are best used for holding liquid that needs to b mixed.
Graduated cylinders	Tube-shaped glassware with many measurement increments. These are used for measuring liquids. Choose a size close to the volume you need to measure. Be sure bottom of the meniscus.
Burette	Similar to a graduated cylinder, but liquid drains out the bottom from a valve. High accuracy and is often used for titrations.

Pipets

Volumetric pipets are classified as "TD" (To Deliver; the new international designation is "EX") and should never be blown out. These pipets are calibrated to deliver one specific volume, and the calibration already takes into consideration the small amount of volume that may remain in the tip. Volumetric pipets may have a colored square at the top of the pipet, which is a manufacturer's mark indicating the volume of the pipet.

Serological pipets can be used to measure various volumes from a single pipet due to their volume gradations. There are two kinds of serological pipets, "blow out" and "drain out". Serological pipets from which the volume in the tip should be "blown out" typically are graduated right up to include the entire tip. These pipets are usually identified by the presence of two thin colored or etched (frosted) rings at the top of the pipet.

Serological or Mohr pipets, which should be "drained out," typically have their graduated markings stop prior to the tip. The volume should not be drained below the last marking. These pipets are usually identified by the presence of a color-coded rectangle or square (but no frosted or colored rings) at the top of the pipet.

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4.1.2: Analytical Probes

pH Probe

Water has a wide range of low pH acids and high pH bases. In most instances (drinking water, surface waters), we want water to be close to neutral (pH = 7) for both safety and taste. Water treatment processes and chemical dosing might be optimized in different pH ranges, prompting water treatment operators to both maintain and adjust pH levels based on treatment. Levels of pH are determined by the amount of hydrogen ions (H^+), causing acidity, or hydroxide ions (OH^-), causing basicity.

The pH probes are stored in a solution and must be wrapped to keep the solution from evaporating. The probe uses the internal electrolyte solution to calibrate and measure pH. Calibration of the pH probe uses three different pH buffers.

Conductivity Probe

Water conductivity is a measure of the dissolved mineral salts in water. High levels of mineral salts will give high conductivity readings. Calibration of the conductivity probe uses two different conductivity standards. Standards chosen for calibration should be one lower than your anticipated reading and one higher than your anticipated reading.

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4.1.3: Light Based Meters

Turbidimeter

Turbidity is an optical measurement of water quality. Within a turbidimeter, light will shine through the sample, particles suspended in the water will cause the light to be scattered, and a meter will measure the light able to pass through the sample. Turbidimeters are calibrated with standard solutions before measuring samples.

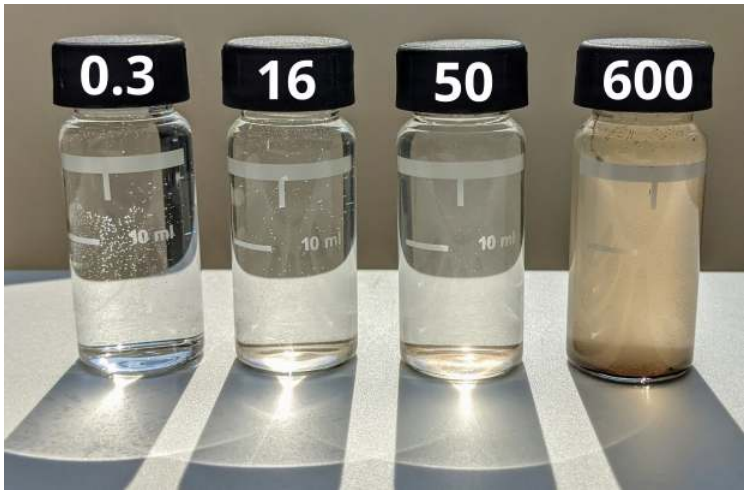


Figure **4.1.3.1**: Sample containers showing a range of turbidity.

Spectrophotometer

A spectrophotometer is a device used to measure light intensity through a liquid. When using the spectrophotometer, the following happens:

1. A light source shines through the sample
2. Some of that light gets absorbed by the sample
3. A sensor measures how much light has traveled through the sample and, therefore, how much light was absorbed by the sample
4. The machine provides a numerical output for the light absorbance.

When using a spectrophotometer in the lab, we will compare unknown samples to a clearly defined set of standard dilutions. The standard dilutions can be plotted graphically, providing a baseline that will calculate our unknown sample. Spectrophotometers are highly accurate machines and are often used for permit compliance testing or for sensitive chemical measurements, like with total phosphorus.

Colorimeter

Colorimeters are similar to spectrophotometers but are less sensitive and therefore typically more affordable. Colorimeters use internal red, green, and blue filters to measure levels of color differences in chemically altered samples. Colorimeters can be used to monitor a variety of water treatment chemicals, including fluoride, chlorine, and phosphate.

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4.2.4: Quality Assurance and Quality Control

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4.2.1: Chemistry Review

The Periodic Table of Elements

The periodic table of elements is a map of all known chemical elements organized by their atomic number, electron configuration, and chemical properties. **Groups** refer to columns in the table, and **periods** refer to the rows. Based on an element's position in the table, scientists can predict how an element will interact with other types of elements.

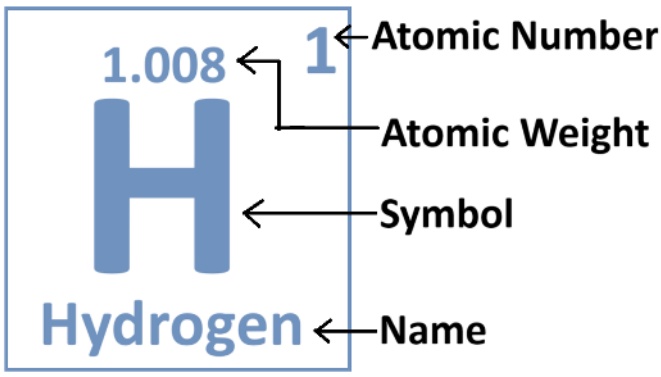


Figure **4.2.1.1**: Hydrogen's entry in the periodic table of elements.

Stoichiometry

Stoichiometry quantifies the relationships between reactants and products in a chemical reaction. Based on a balanced chemical equation, stoichiometry can determine the amounts of substances consumed and produced in a reaction. Substances can be compared by mole ratios and mass ratios.

Balancing chemical equations is a necessary first step. To achieve a balanced equation, the quantity of specific elements on the reactants side (left side) needs to equal the quantity of specific elements on the products side (right side). Begin by writing out the chemical equation, then balance the metals, non-metals, and oxygen.

Example 4.2.1.1

Write the balanced chemical equation for when magnesium metal undergoes combustion to produce magnesium oxide.

Solution

Write out the reactants and products of the equation

$$Mg + O_2 \text{ --> } MgO$$

Count the number of each atom on the reactants and products sides of the equation

Reactants		Products	
Mg	1	Mg	2
O	2	O	2

Use whole-number coefficients to balance each side

- Since there are two oxygen on the reactants, add a coefficient of 2 for the products

$$Mg + O_2 \text{ --> } 2\,MgO$$

- Now the oxygen is balanced, but the products side has two magnesium, while the reactants side has one.
- Add a coefficient of 2 before magnesium on the reactants side

$$2\ Mg\ +\ O_2\ \text{-->}\ 2\ MgO$$

- Recount the number of each atom on the reactants and products sides of the equation. They should be equal

Reactants		Products	
Mg	2	Mg	2
O	2	O	2

You have found your balanced equation

$$2\ Mg\ +\ O_2\ \text{-->}\ 2\ MgO$$

Electronegativity

Electronegativity is a measure of an atom's ability to attract and hold onto electrons within a chemical bond. It plays a crucial role in determining the nature of chemical bonds and the behavior of molecules. Here's how it relates to the periodic table:

1. **Trend Across Periods**: Electronegativity generally increases as you move from left to right across a period. This is because atoms have more protons in their nuclei, which increases their ability to attract electrons.
2. **Trend Down Groups**: Electronegativity decreases as you move down a group. This is due to the increasing distance between the nucleus and the valence electrons, which reduces the nucleus's pull on the electrons.

Electronegativity plays a role in chemical bond types. **Ionic bonds** occur when there is a large difference in electronegativity. This difference leads to the transfer of electrons from one element to another and typically happens between metals and non-metals (e.g., NaCl). **Covalent bonds** occur when there is a small difference in electronegativity. In covalent bonds, each atom contributes electrons to the bond, which exist in overlapping orbitals. Water (H_2O) is a classic example of a compound with covalent bonds. In a water molecule, each hydrogen atom shares one electron with the oxygen atom.

pH

pH is a scale measuring hydrogen ion concentrations in water. The scale ranges from 0 to 14, with low numbers indicating acidity, 7 representing neutral, and high numbers indicating basicity. The pH scale is logarithmic, so each whole-number change represents a factor of ten in hydrogen ion concentration.

Many chemical reactions are driven by the solution's pH level. The rate of reaction and the equilibrium point can change as pH increases or decreases. In water, changes in pH can modify nutrient availability. While this can negatively impact the environment, water treatment facilities use pH to their advantage when treating water. Adjusting the pH can optimize water treatment processes and decrease the overall chemical needs.

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4.2.2: Weighing

Analytical Balance

Analytical balances are most often found in a laboratory where extreme sensitivity (0.1 mg) is needed for the weighing of items. Analytical balances usually measure mass and range in capacity from 0.1 mg to 150 grams. They are typically used for the suspended solids (TSS) testing in the wastewater laboratory, where weight changes of 0.1 mg must be measured.

General Purpose or Top-Loading Balances

General-purpose or top-loading balances are also used primarily in a laboratory setting. They usually can measure objects weighing around 150-300 g. They offer less readability and accuracy than an analytical balance, but allow measurements to be made quickly, thus making it a more convenient choice when exact measurements are not needed. Top-loaders are also more economical than analytical balances and are suitable for weighing chemicals when preparing reagents.

Balance Performance

For best performance, balances need to be set up correctly. The following is a checklist for proper balance use:

- The electronic balance is turned on and allowed a warm-up time
- Balance is set on a sturdy foundation protected from vibration
- Balance is level
- Temperature and humidity are relatively constant, and samples are at room temperature
- The balance and the pan are clean, and the material is weighed in a container
- If used, sliding doors must be closed when making measurements
- Balances can be calibrated using ASTM Type 1 weights. These weights should be stored carefully and only handled with gloves

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4.2.3: Accuracy, Precision, and Error

Quality Control Standards

Quality control standards are samples prepared with a known amount of analyte. The purpose of these standards is to determine if the laboratory methods and equipment are capable of making accurate and precise measurements. These standards are important indicators of quality and provide instantaneous feedback on method and equipment performance.

Accuracy and Bias

Accuracy is the degree of closeness to the actual value. The goal of sample testing is to find the sample's true measured value for water quality parameters.

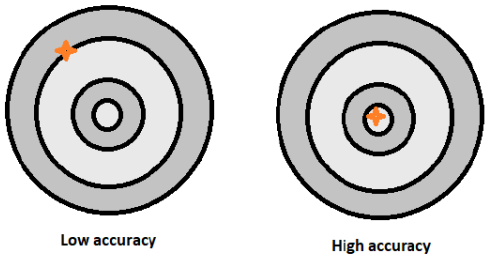


Figure **4.2.3.1**: The difference between low and high accuracy.

Bias is the systematic or persistent error in an analysis that results in the expected sample measurement being consistently different than the sample's true value. Bias results from a flaw integral to the testing system. Systematic bias will lead to systematic errors that skew high or low, as opposed to random errors, which generally cancel each other out.

> An incorrectly calibrated home thermostat may consistently read several degrees hotter or colder than the actual temperature. This is an example of bias that commonly leads to systematic errors.

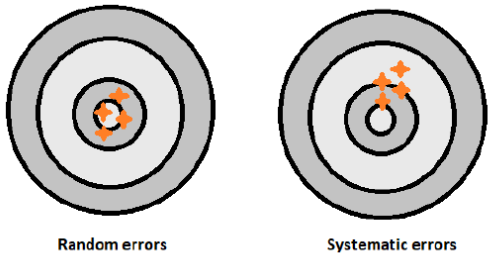


Figure **4.2.3.2**: The difference between random and systematic errors.

Precision

Precision is a measure of how closely multiple determinations performed on the same sample will agree with each other. Performing a test on a sample many times and measuring the same result each time is an example of precision. This does not mean, however, that the measured result is accurate. Systemic bias does not affect precision like it does accuracy.

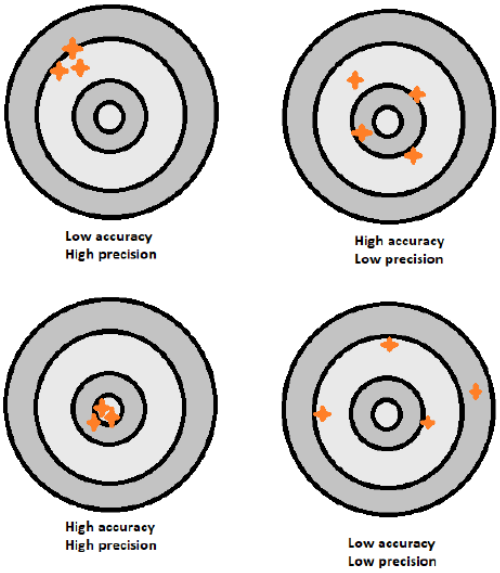


Figure 4.2.3.3: Illustration of combinations of accuracy and precision.

Error

Error is the difference between the measurement and the true value. Error is expected in many experiments, even if it is a very small amount. To account for these small errors, uncertainty values are set to indicate a range of values, based on the measurement, that the true value will be in.

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4.2.4: Quality Assurance and Quality Control

Quality Assurance

Quality assurance is an integrated system of management involving planning, implementation, documentation, assessment, reporting, and quality improvement to ensure that a process or item meets the needs of the experiment.

This includes the preparation of standard test methods, maintaining the laboratory at a constant temperature and humidity, sending equipment in for factory calibration, and maintaining chemicals within their recommended shelf life. Quality assurance should be regularly reviewed, and adjustments or corrective actions should be made as needed to achieve quality goals.

Quality Control

Quality control is the overall system of technical activities that measures the attributes and performance of a process against defined standards to verify that it meets the stated requirements. This includes operational techniques and activities used to fulfill requirements for quality.

Quality control measures can include calibrating instruments, measuring blanks or control samples, and providing training for lab technicians.

> Note
>
> Definitions referenced from the Forum on Environmental Measurements Glossary, Environmental Protection Agency
>
> Environmental Measurements and Modeling | US EPA

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SECTION OVERVIEW

4.3: Soil Properties

4.3.1: Soil Health

4.3.2: Dynamic Cone Penetrometer

4.3.3: Double Ring Infiltrometer

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4.3.1: Soil Health

Soil Health

Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Healthy soil gives us clean air and water, bountiful crops and forests, productive grazing lands, diverse wildlife, and beautiful landscapes. Soil does all this by performing five essential functions:

- **Regulating water**
  Soil helps control where rain, snowmelt, and irrigation water go. Water flows over the land or into and through the soil.
- **Sustaining plant and animal life**
  The diversity and productivity of living things depend on soil.
- **Filtering and buffering potential pollutants**
  The minerals and microbes in soil are responsible for filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposits.
- **Cycling nutrients**
  Carbon, nitrogen, phosphorus, and many other nutrients are stored, transformed, and cycled in the soil.
- **Providing physical stability and support**
  Soil structure provides a medium for plant roots. Soils also provide support for human structures and protection for archeological treasures.

Reference

- Natural Resources Conservation Service (usda.gov)

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4.3.2: Dynamic Cone Penetrometer

Dynamic Cone Penetrometer

A dynamic cone penetrometer (DCP) is a tool used for evaluating the strength of soils on-site. It also helps with monitoring the condition of granular layers and subgrade soils in pavement sections over time. It can be used to determine the right solutions for the sites, especially when soft soils are involved.

The DCP uses a 15-pound steel mass falling 20 inches to strike an anvil deeper into a hand-augured hole. Count the number of blows needed to drive the anvil down 6-inch increments.

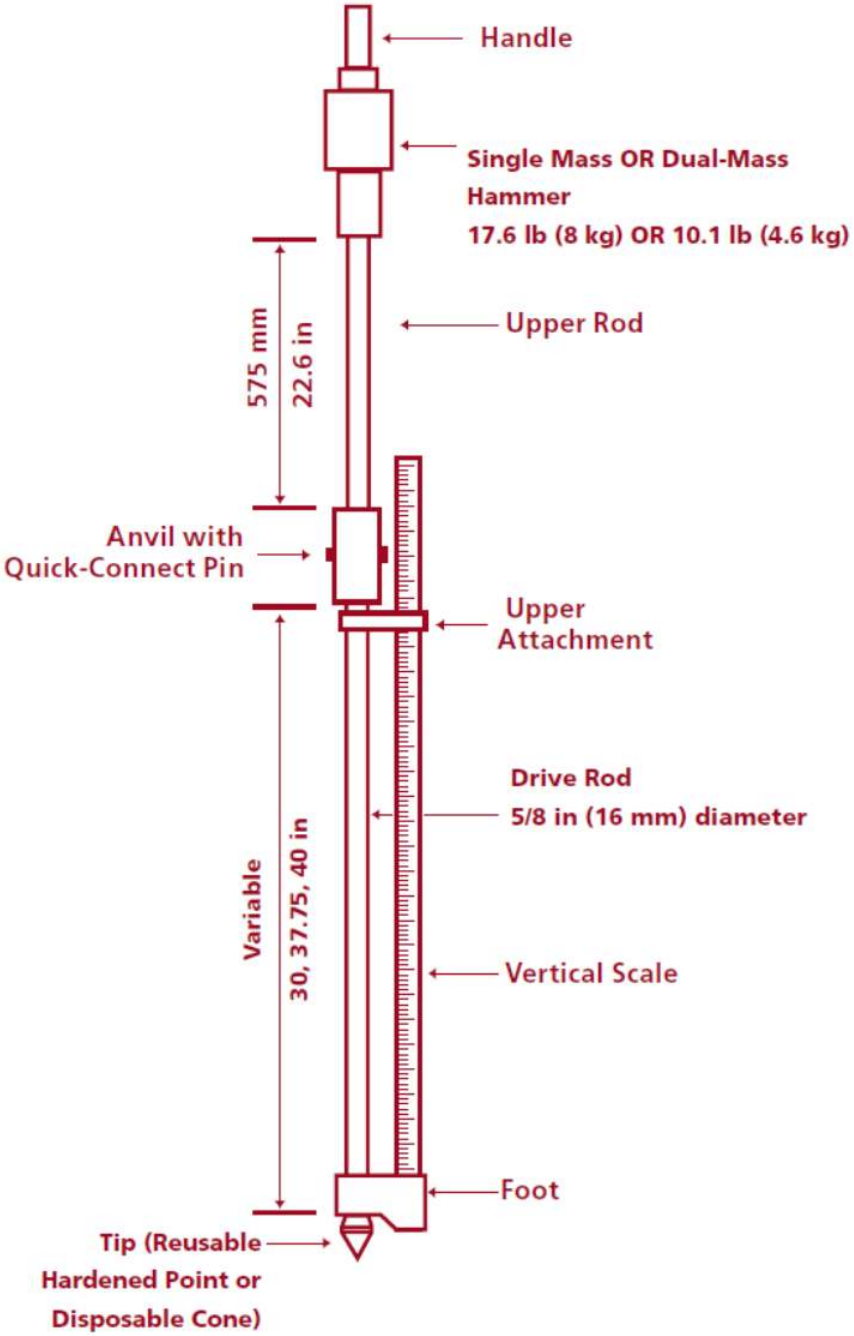


Figure **4.3.2.1**: Dynamic cone penetrometer (Tensar)

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4.3.3: Double Ring Infiltrometer

Infiltration rates impact irrigation, drainage, and how well water flows to crop roots. Infiltration measurements are used to predict erosion and determine soil health. In urban settings, stormwater systems and landfills need soil infiltration measurements to maximize or minimize water movement in the soil.

In a double ring infiltrometer, the inner ring is used as the measurement of the speed of water entering the ground. The outer ring is to ensure the water in the inner ring travels only vertically.



Video Transcript

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SECTION OVERVIEW

4.4: Groundwater

4.4.1: Groundwater Well Construction

4.4.2: Groundwater Well Sampling Techniques

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4.4.1: Groundwater Well Construction

Groundwater sampling wells are bored or drilled into the ground. They consist of an outer casing to create support for the sampling pipe. The sampling pipe itself has screened openings at the bottom, below the water table, to allow water to flow in but to block any sediment. Grouting is often used between the well pipe and the outer casing to create a waterproof barrier that prevents groundwater contamination.

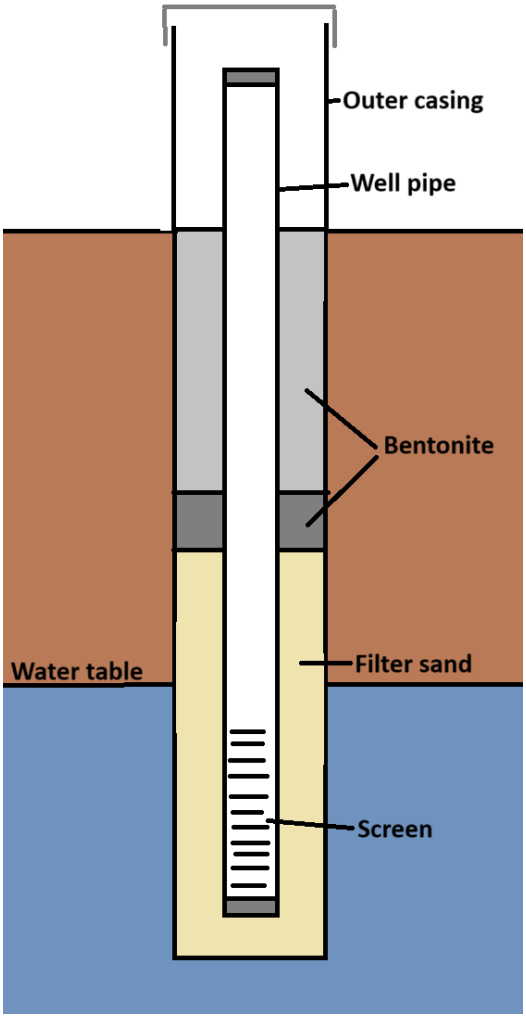


Figure 4.4.1.1: Diagram of groundwater sampling well.

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4.4.2: Groundwater Well Sampling Techniques

Purpose

Beneath our feet, an underground water world exists. This groundwater, stored in aquifers, flows and rises and falls much like our surface water sources. How can we tell what's happening underground? We will perform groundwater well sampling. We can assess the following in the field:

- The depth of the water table
- The well recharge rate
- Groundwater flow direction
- Water quality

Equipment

- PPE
- Basic tool kit
- Sample bottles and sample sheet
- Electronic water level meter
- Disposable plastic water bailers
- String or cording
- Bucket(s)
- Field testing kits

Procedures

Measuring the groundwater depth

1. Make sure the electronic water level meter/probe is turned on and functioning.
2. Identify the point on the well casing used for measuring depth.
3. Lower the probe into the well until the reel indicates you have reached water.
4. Slowly raise and lower the probe to reach an accurate reading.

Measuring the well volume

1. Use the electronic water level meter/probe to measure to the bottom of the well.
2. Subtract the water table level from the well depth level to find the depth of the water column.
3. Use a ruler to measure the inside diameter of the casing.
4. Calculate the volume.

$$V = \frac{\pi D^2}{4} \times h$$

Purging the well

Purging the well removes stagnant water and gives us a fresh, representative sample.

1. Calculate the amount of water in four well volumes:

$$V = \frac{\pi D^2}{4} \times h \times 4 \times 7.48 \frac{gal}{ft^3}$$

1. Mark the cord so you can quickly lower the bailer to the water, then slowly let the bailer fill.
2. Let the bailer fill with water, then pull it up and pour the water into a calibrated bucket. Use a windmill motion with your arms to wind the cord.
3. Purge the well of four well volumes, or purge the well dry twice.
4. Allow the well to recover before sampling.

Sampling the well

1. Have sample containers ready and labeled. Only open one container at a time to avoid contamination.
    - If samples need preserving, add them within 15 minutes of sampling.
    - If preservative is already in the sample bottle, do not rinse the bottle before filling.
2. Use the bailer to pull up a sample of water.
3. Use a bottom-emptying bailer to decant your sample into a container.

Bailing Demonstration



Video Transcript

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SECTION OVERVIEW

4.5: Total Maximum Daily Load

4.5.1: Watershed Health

4.5.2: Lower Fox River Basin

4.5.3: Volunteer Sampling Instructions

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4.5.1: Watershed Health

Background

Scientists can evaluate impaired surface waters by performing a Total Maximum Daily Load (TMDL) analysis. A TMDL is the calculated amount of pollutant a water body can receive while still meeting water quality standards. This analysis, paired with restoration plans and projects, can address surface water quality concerns.

Total Maximum Daily Load (TMDL)

TMDL = Wasteload Allocation + Load Allocation + Margin of Safety

Where:

Wasteload Allocation is the total allowable pollutant load from all point sources.

Load Allocation is the allowable pollutant load from non-point sources and natural sources.

Margin of Safety accounts for uncertainty in the analysis.

TMDLs are a tool to support the Clean Water Act's goal of restoring impaired waters to meet water quality standards. The TMDL is approved by both the State of Wisconsin and the US Environmental Protection Agency.

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4.5.2: Lower Fox River Basin

Lower Fox River Basin TMDL Program Background

The Lower Fox River Basin (LFRB) is approximately 640 square miles and extends from the outlet of Lake Winnebago to Green Bay. The TMDL program relies on citizen volunteers to collect samples from 20 unique monitoring sites. The two main goals of the project are:

1. Increase public awareness and involvement in water quality issues by engaging the public in citizen science
2. The collection of reliable surface water quality data to assess long-term water quality trends/successes

The program monitors several parameters, including:

- Total phosphorus
- Total suspended solids
- Total nitrogen
- Stream flow
- Water transparency

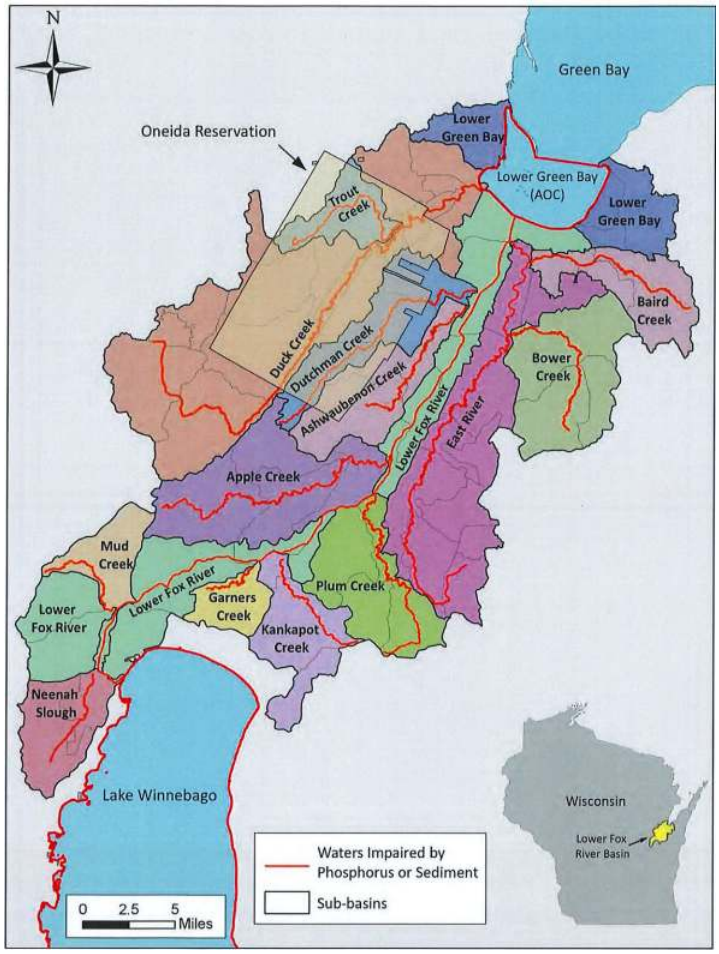


Figure 4.5.2.1: Sub-basins in the Lower Fox River Basin. (Image from Wisconsin Department of Natural Resources).

Program Progress

Volunteer monitoring began in 2015, with additional sites being added in 2018 and 2020. As the sampling program ages, trends in data become more clear. The Department of Natural Resources has formed the following key takeaways from the monitoring data analyzed from 2015 to 2023:

- Total phosphorus concentrations have decreased across many monitoring sites, with two sites achieving data below target levels.
- Dissolved reactive phosphorus concentrations remain high.
- Total phosphorus and total suspended solids concentrations correlate.
- Total suspended solids concentrations correlate with transparency tube readings.
- Rainfall contributes to the nutrient loading measured at sample sites.

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4.5.3: Volunteer Sampling Instructions

When sampling, it is important to choose a location where water is flowing. If you need to enter the stream, enter at a point downstream and then walk up to the sampling location. This ensures that sediment disturbed by your movement is not collected. If entering the stream is not possible, a sampling pole can be used to grab a sample.

Transparency Testing

Turbidity measures the amount of suspended particles and the color of the water. Sources of turbidity can include soil erosion, runoff, algae, and bottom sediments. Turbidity blocks light from traveling through the water and can have an impact on photosynthesis and temperature. Turbidity can also impact fish that hunt by sight.

Turbidity tubes use a visual test. When collecting water, you may plunge the tube into the water or use a bucket or sampling pole to transfer water from the stream to the tube. Once the tube is filled, block direct sunlight, then look straight down from the top of the tube. You are looking for a black and white disc at the bottom.

- If you **can** see the disc, record the entire tube length on the form
- If you **cannot** see the disc at the bottom, release some of the water using the valve at the bottom of the tube until you can just barely see the disc. Record the height of the water in the tube.

The following video shows the Learn Water Action Volunteers' Stream Monitoring protocols to monitor transparency in streams.



Video Transcript

This season, the DNR is collecting visual information. Photos of the overall sampling area and a photo of a water sample in a mason jar should be emailed to the coordinator.

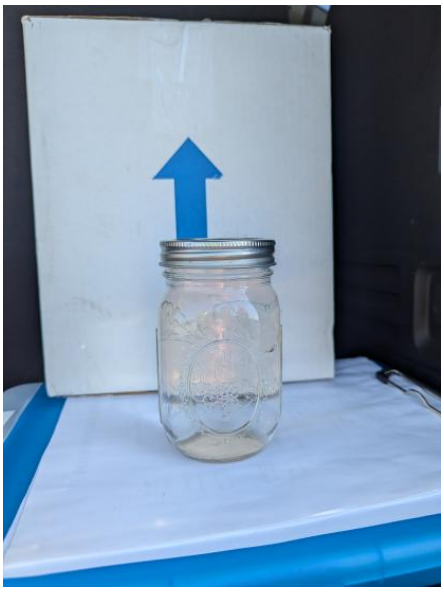


Figure 4.5.3.1: Water sample collected in a mason jar for visual information submission

Water Sampling

Sample bottles should be rinsed with sample water prior to filling. The sample should also be taken below the surface to collect a representative sample and avoid collecting contaminants.

- Open the bottle without touching the inside.
- Hold the bottle facing down, then submerge it about six inches into the water.
- Tip the bottle up to release the air and collect the water.
- Since you are rinsing the bottle three times, dump the collected water and repeat.
- Once the official sample is collected, cap the bottle.
- Some samples may require filtering or the addition of an acid preservative.



Packing and Shipping

Sample bottles are placed in a one-gallon Ziploc bag. Fill the remaining space in the cooler with ice contained in its own Ziploc bag. Double check that all fields on the lab slip have been filled out, then store the lab slip in a separate Ziploc bag and place it on

top of the cooler within the box. Samples will be shipped to the Wisconsin State Lab of Hygiene.



Video transcript

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5.1: Basic Overview/Introduction To Wastewater Treatment

Learning Outcomes

- Understand the importance of proper wastewater treatment
- Describe and construct the urban water cycle
- Analyze wastewater origins and how it is conveyed
- Differentiate between residential and industrial/commercial wastewater
- Evaluate the typical job function of a wastewater treatment operator
- Explain the certified wastewater treatment operator licensing requirements

Introduction

Proper wastewater treatment and disposal is essential for the vitality of a functioning society. Without it, a community's environment can be severely polluted and the health of the public is at great risk. To better understand the relationship between wastewater treatment and water treatment and distribution, examine the urban water cycle. Like the typical hydrologic cycle, which shows the natural movement of water in the environment, the urban water cycle shows how water is moved in an urban environment.

In some cases, wastewater that has been treated by a wastewater treatment plant will be discharged back into a natural water body. Water from that water body will then be used by downstream communities as source water for their water treatment plants. If either of these two treatment facilities are not operating to current regulations and standards, public health is at risk. In addition, if the wastewater treatment facility is not operating properly there can also be additional environmental damage to the water body.

Currently, there is a paradigm shift in water treatment and the line between water, wastewater, and stormwater is becoming thinner and thinner. For example, the use of reclaimed water from wastewater treatment plants can be used for various beneficial uses instead of being discharged into a water body. The term "One Water" is being used more frequently to encompass the idea that all of these water sources are beneficial and more innovation is needed to use these sources more efficiently. However, the focus of this textbook will be on the inner workings of a conventional wastewater treatment plant. The goal is to give you the vocabulary and knowledge needed to understand how wastewater treatment operators can take a contaminated water source and treat it to a level of quality that will not endanger the environment or public health.

The term wastewater has become the common term to describe sewage. In fact, when we talk about conventional wastewater treatment plants we are talking about facilities that take the used water from residences and businesses of a community and clean it up. Wastewater is anything and everything that goes down the drains of these households and businesses. All the water from sinks, garbage disposals, toilets, dishwashers, bathroom drains, and washing machines are considered residential wastewater. There is also commercial or industrial wastewater. Many manufacturing processes that use water, typically for washing or cooling purposes, need to properly dispose of this water. In some cases, this wastewater may be treated onsite before it is discharged into the wastewater collection system. Some municipalities will require the manufacturer to obtain an industrial waste permit that regulates what they are allowed to discharge.

Wastewater Treatment Plant Operators

A wastewater treatment plant operator's main responsibility is to ensure the wastewater treatment facility is being operated and maintained so the wastewater leaving the facility meets the limits of their National Pollutant Discharge Elimination System (NPDES) permit. We will learn the specifics of exactly what an NPDES is in later chapters. Throughout the rest of this book, we will look at the main roles and functions that wastewater treatment plant operators do every day.

Licensing Requirements

The State Water Resources Control Board (SWRCB) is the regulatory authority in California for many aspects of water laws and regulations. They are also responsible for overseeing the Operator Certification Program. In California, it is mandatory to be certified by the SWRCB if you are employed in the operation of a water distribution system, water treatment facility, or wastewater treatment plant.

To become certified there are three things that must be accomplished by the individual seeking certification. First, is to obtain the required amount of education for the level of certification. Each vocation has five levels of certification, with grade five being the highest. As the level of certification increases, more education is needed. The second requirement is experience. Just like education, higher certifications require more experience. However, these two requirements work together. The more education one has, the less amount of experience needed. Likewise, if one doesn't have a significant amount of education, they can still obtain higher certifications by gaining more work experience. The education and experience requirements for the Wastewater Treatment Operator certifications can be found here. The final thing is to pass the certification exams which are offered twice a year, in the spring and fall.

Becoming certified as a Wastewater Treatment Operator Grade 1 requires that the applicant has gained one year of work experience. This one year of work experience is one of the hardest hurdles for many people to overcome. Many employers want to hire people that already have certifications, but you can't get certified if you don't have experience. Many wastewater treatment facilities understand this predicament and offer what is called an Operator-In-Training (OIT) position. To obtain a Grade 1 OIT certificate you must have a high school diploma or GED, have six educational points by taking a college-level math or science course, and be employed by a wastewater treatment facility. These positions are becoming more competitive and often employers require additional related work experience or additional education. Successfully passing the certification examination can help set you apart from other applicants.

Type of Work

The type of work a wastewater treatment operator is involved in will be varied and depends on a lot of different factors. A common job description will include something along the lines of "to ensure the operation of the treatment facility and ancillary equipment in order to meet effluent requirements". The effluent of a wastewater treatment plant is the water that leaves the facility once it has been treated. To ensure the effluent requirements are met, an operator's typical job will include monitoring and logging critical information such as pump pressures and flow rates, tank levels, and water quality parameters such as turbidity and chlorine residual. There is also preventative maintenance that is required. Some tasks could include taking portions of the treatment system offline for cleaning and/or repairs.

Throughout the treatment system water samples will need to be taken and tested for various constituents, either for regulatory compliance or process control. Depending on the facility, the sampling may be done by operators or by laboratory technicians. However, it will almost always be the certified operators that will review the laboratory results and determine if any adjustments to the treatment process are needed.

It's important to note that wastewater treatment plants are industrial facilities and some of the work can be very dangerous. Operators can be working with heavy machinery such as forklifts, large pumps, and cranes. There is also high voltage electrical equipment that the operator will interact with on a daily basis. There can be situations where there are high-pressure lines and even the possibility to be exposed to harmful chemicals. This book will have a whole section dedicated to covering these safety topics and more.

Jobs

There are many different types of work available in the wastewater treatment industry as a whole. While this textbook will focus on the specifics of the job duties of a wastewater treatment operator (WTO), there are many other supporting jobs in both the public and private sectors. Most of the WTO positions are available through the public sector. For example, a city will be the owner and operator of a municipal wastewater treatment facility. That city will then employ as many WTOs as necessary to operate the plant. However, there will be many other jobs required to keep the facility running aside from the operators. Depending on the size of the plant, there can also be workers skilled in the maintenance of pumps and machinery, electricians, and instrumentation technicians. These jobs can also have their own trade certifications that may be required by the employer. In addition, there may be laboratory staff, administration personnel, engineers, managers, and financial experts. All of these positions will work together to keep the plant running. But it's important to remember that at the end of the day, it's the certified Wastewater Treatment Operators that can be legally responsible for the quality of water leaving the facility and compliance with the NPDES permit.

There are also many job opportunities in the private sector. There are many "package plants" that smaller private industries will operate to treat residual waste from a large scale manufacturing process. A brewery, for example, may need to treat their brewing

process wastewater before the water can be disposed of in the municipal sewer system. As of 2013, these privately run wastewater treatment plants require workers that are involved in the operation of the plant to meet the same licensing requirements as publicly operated wastewater treatment plants.

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5.2: Wastewater Quality

Learning Outcomes

- Understand the purpose of NPDES permits
- Explain how TMDLs are obtained and how they improve water quality
- Assess the difference between chemical and physical water quality contaminants
- Describe how different contaminants can affect water bodies

National Pollutant Discharge Elimination System (NPDES) Permits

Wastewater treatment plants typically discharge their treated water into a water body that is nearby. Since 1972, with the passage of the Clean Water Act, it is illegal to discharge water from a point source into waters of the United States unless an NPDES permit is obtained. Since wastewater treatment facilities have all of their discharge leaving the plant from a single discharge pipe, it is considered a point source. This differs from nonpoint sources that have large areas of discharge like runoff from agricultural fields. An NPDES permit allows discharging the treated wastewater into a water body as long as it meets the requirements of the permit. These requirements can include limits on what can be discharged, how frequently samples must be taken, and other reporting requirements. There may also be other requirements specific to the discharger to assure that the water being discharged does not harm public health or the environment.

Total Maximum Daily Loads (TMDL)

The total maximum daily load (TMDL) is a calculated value of the maximum amount of a specific pollutant that a waterbody can receive without negatively impacting that water body. For example, 10,000lbs of pollutant X naturally occurs within a stream that has a TMDL of 50,000lbs for pollutant X and contains three point source discharges. Therefore, an additional 40,000lbs of pollutant X may be discharged into the stream without exceeding the TMDL. It's the job of permit writers to use the TMDLs of a water body and the total number of point source discharges to determine the waste load allocation (WLA) for each discharge and incorporate that into the NPDES permit as a limit. To continue with the example, a permit writer could determine that with three point source discharges each one would be allowed to discharge 10,000lbs of pollutant X. This would leave a margin of safety of 10,000lbs. So in theory, the discharge of pollutant X would not negatively impact the water body because the sum of all the discharges and naturally occurring contamination is below the TMDL of the water body.

Wastewater Solids

The solids found in wastewater are comprised of many different constituents including organic and inorganic material. A variety of laboratory tests can be performed to determine the total amount of solids. The total suspended solids (TSS) test will determine the total amount of solids that are suspended and that are easily settleable. This test is done by filtering a specific volume of the wastewater through a filter pad. The water and dissolved solids will pass through the filter; and the settleable solids and suspended solids will remain on top of the filter. The difference in weight of the filter before and after filtration is used to calculate the amount of TSS.

While all the solids remaining on the filter after the TSS test are suspended, not all of the solids are settleable. Settleable solids can be determined by using an Imhoff cone. Again, a specific volume, typically 1,000 mL, is poured into the Imhoff cone and allowed to settle. The settleable solids will collect on the bottom of the Imhoff cone. After an hour, the amount of solids that settled can be determined by the graduations on the Imhoff cone as seen in the figure below.

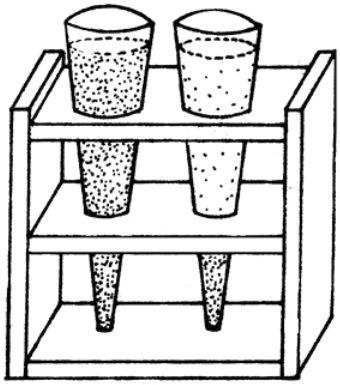


Figure **5.2.1**: Image by FAO is licensed under CC BY-NC-SA 3.0 IGO

The water that filtered through the filter pad during the TSS test still contains solids of contaminants that are dissolved into the water. Collectively this can be determined by completing a Total Dissolved Solids (TDS) test. This test takes the water left over from the TSS test and pours it into a pre-weighed dish. The water is then evaporated from the dish and weighed again. The difference in weight is then used to calculate the TDS.

Whether the solids are settleable, suspended, or dissolved, wastewater is generally made up of less than 1% solids. The other 99% is just water. The focus of the remainder of this text will be on treating the 1% of solids in wastewater. The difference in the type of solids will determine what type of treatment process is used. Settleable solids will easily settle during the primary sedimentation process. Suspended solids will require a secondary treatment process. TDS can only be removed by advanced treatment methods like membrane filtration or reverse osmosis. TDS will not be removed by conventional wastewater treatment methods.

Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) is a measure of how much organic material is in the wastewater. When wastewater with high amounts of BOD is released to a water body, the organic material will consume the dissolved oxygen in the water body. If the BOD exceeds the TMDL of the water body, then the oxygen levels can be completely depleted. Without the dissolved oxygen, fish and other aquatic life will not be able to survive.

The BOD5 test is completed in a laboratory by taking a sample of wastewater and measuring the dissolved oxygen concentration. The sample is kept in an airtight container in a refrigerator set to a temperature of 25□C. After 5 days, yes, that's why there is a subscript 5 in BOD5, the dissolved oxygen concentration is measured again. The difference in oxygen concentrations is how much oxygen was consumed by the organic material in the wastewater. The more organic material there is, the higher the BOD5 will be.

The BOD5 test is the standard test that is used to measure the organic contamination in wastewater. It is one of the main regulatory components in an NPDES. However, it has one big drawback which is that it takes five days to get results. Another test that gives similar results is the chemical oxygen demand (COD). COD will measure the amount of oxygen needed to decompose organic material as well as inorganic chemicals. The difference between COD and BOD5 is that COD will also measure other chemicals that can be oxidized besides ones that are biological. COD laboratory results can be determined in approximately 6 hours. If a wastewater treatment facility is only treating wastes from a community that is mainly residential and does not have many industrial discharges, then the COD and BOD5 can be correlated after a significant number of samples are analyzed side by side. BOD5 is routinely done to meet regulatory requirements while COD results are used for process control to make sure the treatment plant is operating efficiently.

Microbiological Contaminants and Pathogens

There are many different types of microorganisms that can be found in wastewater. Some of these microbes are pathogenic. A pathogen is a microorganism that is capable of causing disease. Some common pathogens that can be found in untreated wastewater are Cholera, Giardia, Streptococcus, E. Coli, Cryptosporidium, and Salmonella. However, not all microorganisms are pathogenic and some non-pathogenic bacteria will actually be utilized as a treatment aide to reduce the amount of BOD5 in the wastewater.

One classification of microorganisms is a protozoa. A protozoa is a single-celled organism and is essential to the biological treatment processes. Amoebae, flagellates, and ciliates are some examples of protozoa commonly found in wastewater samples. Metazoa are multi-celled organisms that can also be found in wastewater treatment facilities. Some examples of metazoa are rotifers, nematodes, tardigrade (water bears). When we discuss the various biological treatment methods later in this textbook, we will learn that a microscopic examination of wastewater samples can show the health of the treatment system by comparing the quantities of protozoa and metazoa organisms.

Viruses can also be detected in wastewater samples. Viruses must have a host organism in order to live and reproduce. Unfortunately, they can remain dormant in water until they find such a host. Hepatitis A and polio are examples of viruses that can be found in wastewater samples. Viruses can be difficult to identify in the laboratory and are not routinely tested for in wastewater samples.

Coliform bacteria is the most common laboratory test done to determine the potential of the presence of pathogenic organisms. Coliform bacteria are abundant in the natural environment and can be found in water and soils. Coliform bacteria are not pathogenic but their presence can determine if pathogenic organisms may also be present. For example, if a tested wastewater sample has large amounts of coliform bacteria, then we can say that there is a high chance that pathogenic organisms are also in that sample. If we find that there are very low amounts of coliform bacteria, then we can say that there is a very small chance that pathogenic bacteria are also present. Because of this, coliform bacteria are often called an indicator organism. The laboratory test results can be used to indicate whether the sample has the potential for containing pathogens. Since there are so many pathogenic organisms, it would be extremely cumbersome to test for each one individually. It is much more economical to complete the coliform test instead. Now if the coliform test does indicate that there are coliforms present, further testing can be done to determine if pathogenic bacteria are also there. Typically, the test to determine if *E. coli* is present.

Eutrophication Effects of Nitrogen and Phosphorus

Algae typically is not present in wastewater but wastewater can contain nutrients such as nitrogen and phosphorus which will promote algae growth in waterbodies. In pond treatment systems, algae will actually be used to aide the treatment process by supplying oxygen to beneficial bacteria that will reduce BOD5.

When treated wastewater is discharged into a waterway, the amount of nitrogen and phosphorus must be closely examined. If there is too much nitrogen and phosphorus in the waterbody, it can lead to an overabundance of algae. When there is too much algae growth, the algae will consume more oxygen from the waterbody. With large amounts of algae consuming the oxygen, there is not enough oxygen for other aquatic organisms to sustain life. This excess growth of algae resulting from the increased nutrient loading on a waterbody is called **eutrophication**.

Other Chemical Contaminants

In addition to nitrogen and phosphorus, there are other chemical contaminants that can be found in wastewater. Almost every element that can be found on the periodic table will molecularly combine with water under the right conditions. Collectively these will be determined when completing the TDS analysis. There are some elements that we are particularly concerned about and these concentrations are measured independently.

Chlorides can be introduced into wastewater from road salts, food waste, water softeners, and naturally occurring surface water contamination. Chlorides can be found in water as sodium chloride, potassium chloride, calcium chloride, and magnesium chloride. When there are excess levels of chlorides in a waterbody, it can have adverse effects on aquatic organisms. Excessive chlorides can interfere with the biological processes going on inside the bodies of freshwater aquatic organisms.

Heavy metals found in wastewater typically come from industrial discharges. Metal finishing, electroplating processing, mineral extraction operations, and textile industries can contribute to heavy metals in wastewater. Lead, copper, zinc, mercury, arsenic, nickel, and silver are some common heavy metals that can be found in wastewater samples. Although, any metal on the periodic table can find their way into the sewer system. Heavy metals are a concern due to their toxicity in aquatic systems and adverse effects on plants and animals.

The pH of wastewater is very important and can influence the treatability of wastewater. If the pH is not between 6.5 and 8.5, chemicals may need to be added to bring the pH into that range. Alkalinity is another important characteristic of wastewater.

Alkalinity is the ability of the wastewater to buffer against changes in pH. Alkalinity is measured by determining the amount of acid-neutralizing basics. It is commonly measured in mg of $CaCO_3$ equivalents per liter. Alkalinity is critical to the physical, chemical, and biological treatment processes we will discuss throughout this book. These processes do not operate well under acidic conditions. Sufficient alkalinity is needed to ensure the pH stays within the 6.5 to 8.5 range.

Other Physical Contaminants

Odor, color, turbidity, and temperature are all physical characteristics of wastewater. Unlike the biological and chemical characteristics discussed previously, physical contaminants can be observed by the human senses. We can see what the color is, we can smell if the odor is foul, and we can feel if the sample is warm or cold. Although laboratory equipment can be used to obtain more quantitative data.

As you can imagine, untreated wastewater can give off a foul odor. However, odor can give an operator great insight. If the wastewater smells like rotten eggs, this is a sign that there can be high amounts of hydrogen sulfide in the wastewater. In densely populated areas where the wastewater treatment plant is in close proximity to residents, odors may be captured and sent to an air treatment unit to reduce the objectionable odors from the facility.

Color can also provide insight into what's happening in the wastewater or where it's coming from. An unusual color in the wastewater can indicate an industrial discharge such as dye from a manufacturing process. If the wastewater is dark or black, then it has most likely undergone septic or anaerobic conditions. Fresh wastewater typically has a murky yellowish/brown color.

Turbidity can be physically seen in wastewater samples and is often described as the cloudiness in the water. In the laboratory, a nephelometer is used to obtain a quantitative result measured in **Nephelometric Turbidity Units** (NTU). A nephelometer works by shining a light through the sample of wastewater. If the water has high amounts of turbidity the light will scatter and not make it to the detector on the other side of the sample. High amounts of turbidity can impact the effectiveness of disinfection. The small particles that cause turbidity can shield microorganisms from coming in contact with the disinfectant.

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5.3: Wastewater Collection

Learning Outcomes

- Examine how wastewater is conveyed from the source to a wastewater treatment facility
- Assess the impacts and causes of odor in a collection system and explain how to mitigate the negative impacts for a community
- Analyze how gravity sewer design is used to maintain sufficient velocity
- Evaluate system conditions to determine when a sewer pump station is needed
- Differentiate between the various methods to maintain and clean sewer systems

Gravity Sewers

The main purpose of a wastewater collection system is to convey the wastewater from the source to a treatment facility. Recall from Chapter 1 that the source of wastewater contains anything and everything that goes down the drain. There are residential sources such as homes, apartments, and office buildings. And, there are industrial sources like restaurants and manufacturing processes. These sources will have laterals that are connected to a main sewer line. Laterals are usually privately owned and the maintenance on them is the responsibility of the property owner. The lateral is a direct connection from the source to the main sewer line. The main sewer line is typically owned, operated, and maintained by a public utility. The main line is several sizes larger than the laterals as it will be required to have enough capacity to accommodate all of the laterals that are being discharged into it. In larger cities, there may also be interceptors or trunk lines. These larger trunk lines collect all of the main lines through the city and send the wastewater to the wastewater treatment facility.

Whenever possible the collection system will utilize gravity to send the wastewater from a higher point to a lower point. To achieve gravity flow, the main sewer lines are designed and constructed on a slope. The amount the line is sloped is dependent on the size of the pipe and the expected quantity of wastewater. The collection system must have a minimum wastewater flow velocity of 2 ft/second (fps). At this velocity, solids will be kept in suspension. Slower velocities will allow settling in the piping collection system. If solids settle in the collection system, these depositions will accumulate over time and can cause a blockage. If the blockage becomes too severe, then wastewater will not be able to flow freely. If the blockage is large enough, it can cause the wastewater to back up and overflow onto the streets.

Pressure or Force Mains

Gravity sewer lines cannot be used in every situation. Areas that are very flat or communities that are located in a valley will require a lift or pump station. A lift station uses pumps to lift the wastewater from a lower elevation to a higher elevation. The section of pipe from the discharge to the gravity sewer connection is known as a force main. Unlike a gravity sewer, a force main is completely full and under pressure. The pressure comes from the energy of the pump which is needed to lift the wastewater to a higher elevation.

Different Types of Sewers

There are three different types of sewer systems; sanitary, stormwater, and combined. Sanitary sewer systems only convey wastewater that was derived from sanitary sources. As discussed in Chapter 1, this is wastewater from household toilets, showers, and dishwashers, as well as industrial sources of wastewater from manufacturing processes. Sanitary sewers differ from stormwater sewers in that they contain fecal matter from human waste. It’s paramount that these wastes are conveyed to a wastewater treatment facility so they can be removed and stabilized to protect public health and the environment.

Stormwater sewers are a network of pipes that collect only stormwater runoff and directs the flow to a nearby waterbody or the ocean. While stormwater does have a direct connection to human or animal waste, it is considered less harmful and can be discharged without treatment. However, it’s important to understand that stormwater is by no means “fresh water”. Stormwater can have large amounts of trash, plant material, silt gravel, oil & grease. There are even fairly high amounts of harmful bacteria from animal wastes. The theory is that during storm events there is a significant amount of water flowing through these systems that these contaminants become diluted and are not as concentrated. This theory is constantly being challenged and stormwater is now being seen as another water source that can be treated and even beneficially reused.

A combined sewer is a network of pipes that conveys both sanitary wastes as well as stormwater. This can be beneficial during dry weather flows where there is minimal stormwater. The stormwater that does exist is sent to a wastewater treatment facility where harmful contaminants are removed prior to discharge to a waterbody. However, combined sewer systems can be overwhelmed during storm events. Systems that have older infrastructure which has not been upgraded to deal with larger populations and storm events are especially vulnerable. When this happens, instead of only diluted stormwater being sent to a waterbody, sewage containing high amounts of fecal matter from the sanitary sewer is also discharged. This can cause increased pollution to the waterbody.

Infiltration and Inflow

Collectively referred to as I & I, infiltration and inflow is wastewater that has entered into the collection system unregulated. An inflow is when water other than sanitary wastewater enters the collection system through an illicit connection such as rain gutters, basement drains, or foundation drains. Infiltration is water such as groundwater and stormwater that finds its way into the sewer piping from manhole covers and cracks in the piping.

Odor Control

Sewage can have an extremely foul odor. As the organic material starts to break down in the sewer system, it will generate foul odors. Often, this breakdown of organic material and the biological reduction of sulfates in the wastewater will create hydrogen sulfide (H2S). H2S has a very distinctive rotten egg smell and can cause several problems in a wastewater collection system. H2S is extremely toxic and workers working near or inside a wastewater collection system must continuously monitor the atmospheric conditions and properly ventilate the workspace to ensure that the environment is free of H2S and other hazardous atmospheric conditions. H2S will also breakdown in the collection system forming sulfuric acid which can corrode pipes, manholes, and other parts of the system. Although H2S is heavier than air, it is still able to escape the collection system and cause nuisance odor conditions to the surrounding community.

These sewer gases can be mitigated in several different ways. One way is to add chemicals to the collection system that will prohibit the formation of H2S. For example, iron salts such as ferric chloride will react with the sulfides in the wastewater and do not allow the molecules to form H2S. Another way to remove H2S is to let it form in the sewer system and then have a fan that will pull the foul sewer gases from the sewer and convey the odors to a treatment site. Typically, the air treatment is achieved by carbon adsorption or bio-filtration. Carbon in this filter form is extremely porous when examined under a microscope. When the foul sewer gases are forced through a media of carbon particles, the gasses will adhere to these microscopic pores and be removed from the airflow. In a bio-filtration setup, the sewer gases are conveyed to a large tank where bacteria will metabolize the H2S and thus remove it from the airflow.

Collection System Maintenance

Collection systems, while underground and out of sight from the general public, still require a significant amount of maintenance to ensure that the wastewater flowing through the system stays underground. If the wastewater cannot flow through the network of pipes, it will begin to back up and overflow out of the manhole covers in the streets. When this happens, it is called either a **Sanitary Sewer Overflow** (SSO) or a **Combined Sewer Overflow** (CSO) depending on which type of wastewater collection system is used within the community. To prevent this from happening, wastewater professionals have several tools available to them.

Bucketing, rodding, flushing, jetting, and closed-circuit television are the primary means used to maintain a wastewater collection system. **Flushing** is a hydraulic process that is great for light cleaning of wastewater lines. Flushing moves a high volume of water with low pressure through the wastewater line that needs to be cleaned. Adding this extra water increases the velocity in the line. At high velocities, the flushing water scours the sediments and debris in the line and pushes everything downstream.

Rodding and **bucketing** are both mechanical mechanisms that use machinery to physically remove any obstructions and debris from the wastewater pipeline. This is typically used when flushing is insufficient to remove the debris. Rodding occurs when a cable with a special attachment at the end of it is sent down the wastewater pipe that needs to be cleaned. The rod is then rotated and the tool can break through the obstruction in the line.

Jetting combines both hydraulic and mechanical tools. Jetting is similar to rodding except a heavy-duty hose that can handle high pressures is used instead of a rod. At the end of the hose, there is a nozzle specifically designed to send concentrated streams of water at high pressures against the interior wall of the pipe to remove any debris or obstructions.

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5.4: Preliminary Treatment

Learning Outcomes

- Understand why preliminary treatment is necessary
- Compare and contrast the different types of preliminary treatment methods
- Evaluate the benefits of different treatment methods

Nuisance Substances

Preliminary treatment is the first step in treating raw wastewater. When the wastewater first enters the wastewater treatment facility there are a lot of **nuisance materials** that have found their way into the collection system. Items such as large rags, bottles, tree branches, and numerous other nuisance items can be found in the influent to the treatment facility. These large items can cause damage to downstream pumps, take up valuable space in settling tanks, and can be hazardous to other mechanical equipment needed in the treatment process. So the first, or preliminary step is to remove these large items.

Screening

One method to remove large debris items is by using a **bar screen**. Bar screens are capable of removing items that are larger than the spacing between the bars. For example, a ¾" bar screen will hold back any debris that is larger than ¾" and anything smaller will pass through it. Common items that are removed in this preliminary treatment step are rags, roots, large rocks and aggregate, bottles, cans, and numerous other large objects that can make their way into the wastewater collection system.

Over time, the debris collected behind the bar screen will need to be removed. This is done either manually or automatically. Manual bar screens typically have large spacing, 2" to 4" is common, between the bars. To manually clean a bar screen an operator will use a rake and pull out all of the debris stuck behind the bar screen. This can be extremely laborious and dangerous as the operator is lifting heavy objects over an open trench. Ideally, a wastewater treatment plant will have two or more channels with bar screens. This way one channel can be isolated and the debris can be removed without having wastewater flowing through it. Although this is safer, it is still laborious.

Newer bar screens are raked automatically. On more sophisticated systems, the channel where the bar screen is installed will have an upstream and downstream level sensor. When the debris is blocked by the bar screen it will also inhibit the flow of wastewater through the screen. This will cause the upstream water level to rise. When the difference between the upstream and downstream levels reaches a predetermined setpoint, the motorized rake will swing down and automatically pull the debris out of the channel and into a hopper. Other systems will automatically initiate the raking sequence based on a timer or will just run continuously.

Most automatic bar screens will have a washer/compactor that receives the removed debris. The washer/compactor will wash the debris removing any of the organic matter and then compact it. Washing is important because in this preliminary step we are only trying to remove the large inorganic items. We want to keep the organic material in the wastewater stream as it will be utilized in subsequent treatment processes. Compacting the debris is critical as it removes most of the water and makes it easier to transport for disposal.

Since automatic bar screens can run autonomously, the bar spacing can be smaller. Most models are around ⅝" to ¾" but newer models can be ½" or less. While automatic bar screens are capable of removing more debris with less manual labor, there is still a skill set required to properly operate this machinery. Operators will check the equipment multiple times during a day. Checks can include monitoring the rake arm and motor for proper function, removing compacted debris to a larger disposal truck, checking motor amps are within range, and calibrating level sensors.

Comminution and Barminution

An alternative to screen these large debris items is to shred or grind them. A **comminutor** is a device that sits inside the channel where wastewater is flowing into the treatment facility. The comminutor will grind the large debris items, turning them into smaller items. Communitors are designed to produce a solid size of a certain diameter. By breaking up the debris into smaller diameters, the downstream pumps and equipment will not be as impacted. It's important to note that comminutors do not remove the debris from

the flow of wastewater. The debris is just broken down into more manageable sizes. The debris will still need to be removed in the subsequent treatment process.

Barminutors combine a bar screen with a comminutor. There is a bar screen set inside of a channel where the wastewater flows. The debris is trapped behind the bars and then a device travels up and down the bars which breaks up the large solids into smaller pieces. The ground-up solids stay within the flow of wastewater and move onto the treatment process.

Grit Removal

Once the large items are managed, the next step in the treatment process is to remove the smaller inorganic solids, such as coffee grounds, eggshells, sand, silt, and gravel. These small diameter solids are collectively called **grit**. Grit must be removed because it will cause excessive wear on plant equipment such as the impeller of a pump. Also, this inorganic material can settle in the subsequent treatment process and take up valuable space in tanks which decreases plant efficiency and can inhibit further treatment. While most gritty materials are inorganic, large organic solids such as corn kernels and other food waste may also be removed.

There are several methods that can be used to remove grit but all of the methods rely on the fact the gritty material is relatively heavy. Compared to the organic solids, grit is much heavier and will settle faster. Grit can be removed by controlling the velocity of wastewater through a tank, adding air to the tank to aide in settling, or by using centrifugal force.

The basic concept of removing grit is to reduce the velocity of the wastewater flowing through a tank to less than 2 fps. Recall that in the collection system we want to achieve a velocity of 2 fps. The higher velocity in the collection system will keep all of the solids in suspension so they make their way to the treatment plant. But now that we are trying to remove these solids, we want to get the velocity between 0.7 and 1.4 fps. At this lower velocity, the heavy inorganic solids will settle to the bottom of the tank.

Detention time is a critical factor in designing the tank dimension for grit removal. The detention time needs to be long enough to allow the gritty material to settle to the bottom. The typical detention time of grit chambers is around 2 to 5 minutes. However, if the detention time is too great, then smaller organic solids will also settle out. These items are better dealt with in the next step of primary treatment.

Aerated grit chambers are set up in a similar manner except there will be air piped to diffusers at the bottom of the tank. The addition of air in the tank creates a rolling action of solids which helps keep the lighter organic solids in suspension while the heavier grit material is directed to the bottom of the tank. In aerated grit chambers, the amount of air sent to the chamber is a critical operating parameter. If too much air is supplied, then the grit material will stay in suspension and not be removed. If not enough air is supplied, then the lighter organic material can settle out.

Cyclone separators are another method of removing grit. These separators use centrifugal force to push the gritty solids to the edge of a circular chamber where they are then directed to the bottom of the tank. To create the centrifugal force, cyclone separators will require a higher velocity of wastewater moving through the unit. Typically a velocity of 2 fps to 3 fps will be sufficient.

Any of the grit removal methods described will result in an accumulation of material at the bottom of the unit. If these solids are not removed periodically, they will accumulate to the point where the unit will be ineffective. The tanks are designed to direct the gritty material toward the bottom of the tank which is sloped towards one end. This allows the settled grit to be removed from the tank for further treatment. The mixture of grit and wastewater is pumped and sent to a grit washer. Grit washers will wash out the organic material and send it back into the flow of wastewater as it moves onto the next treatment process. This allows only the inorganic abrasive solids to be collected for ultimate disposal. Once the gritty material is washed and collected it is sent to a landfill.

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5.5: Primary Treatment

Learning Outcomes

- Describe different methods to measure wastewater flow
- Examine the purpose of primary treatment
- Compare and contrast conventional primary treatment with chemically enhanced primary treatment
- Assess how specific gravity and density relates to the removal of solids able to settle

Flow measurement

After preliminary treatment, and all of the large debris and inorganic solids are removed, it's vital to measure the amount of wastewater flowing into the treatment facility. This flow rate will be an important number for process control. Many wastewater treatment plants have a typical diurnal flow pattern as flow into the wastewater treatment plant is not constant. Over a 24 hour period, the flow can fluctuate significantly. There are usually two peaks during the day, typically in the late morning and evening. In the morning, the population that the treatment facility serves is waking up, taking showers, making coffee, cooking breakfast, and using the restroom. The flow tends to lessen in the late afternoon and then increases again in the evening. In the evening, a majority of the population is cooking dinner, washing dishes, doing laundry, and taking showers. In the middle of the night, most people are sleeping and not sending water down the drain.

There are several ways that flow can be measured. A simple way to measure flow is by using a weir. Weirs can either be square or V-notched, but the principle behind them is the same. As the flow of wastewater travels through a channel, the weir is placed in its path. The wastewater is then forced to move over the crest of the weir. Based on the dimension of the square or v-notched section in the weir, the flow can be determined by the height of the wastewater over the weir crest. If there is a significant amount of flow, then the height of wastewater will also be large. When the flow decreases, the height of wastewater over the weir will be lessened.

A Parshall Flume is another way to determine the flow rate entering or leaving the treatment facility. It works similarly to a weir in that the water is forced through a restriction in the channel and the height of water before and after the restriction is used to calculate a flow rate. All Parshall Flumes have a similar shape. There is a converging section, a throat section, and a diverging section. The converging section is where the flow is channeled and forced through a narrow section. The throat section is where the wastewater flow is restricted by traveling through a slimmer channel. This restriction will increase the velocity of the wastewater as it passes through the throat section and cause the level to rise in the converging section. Just like in a weir, higher flow rates will cause the wastewater level to increase and lower flow rates will show a decrease in the wastewater level. Many treatment plants have markings in the converging section to indicate the wastewater level. Modern treatment plants will have ultrasonic level transmitters that will record the level precisely. This data can be automatically transferred to a computer system where the flow rate is instantly calculated and recorded. A benefit of using the Parshall Flume instead of a weir is that the restriction in the channel will not cause any solids to settle out. In a weir, as water builds up behind it, the velocity is reduced and solids can settle out. Those solids will have to be removed periodically or odors can become problematic.

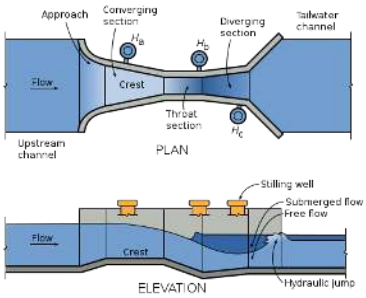


Figure **5.5.1**: Diagram of a Parshall Flume by Inductiveload is in the public domain

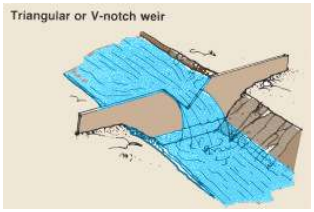


Figure **5.5.2**: Image of a v-notch weir by the FAO is licensed under CC BY-NC-SA 3.0 IGO

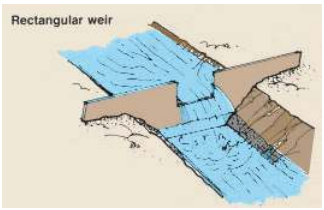


Figure **5.5.3**: Image of a rectangular weir by the FAO is licensed under CC BY-NC-SA 3.0 IGO

The most modern method of monitoring flow throughout a treatment facility is a magnetic flow meter, or “mag meter” for short. Mag meters work by having the wastewater flow through a pipe. The mag meter is connected to the pipe either by strapping the device to the outside of the pipe or more permanently, by bolting it between two sections of pipe. The device creates a magnetic field inside the pipe and as the water moves through, it creates a disturbance that is measured by the meter. Higher flow rates cause more of a disturbance. The meter can very accurately measure the flow of wastewater moving through the pipe. The benefit to mag meters is that there are no moving parts inside the pipe. So influent wastewater with lots of solids and organics will not interfere with the flow measurement. Mag meters are also very reliable and require little maintenance.



Figure **5.5.4**: Magnetic Flow Meter by Mtaylor848 is licensed under CC BY-SA 3.0

Some treatment facilities may have flow equalization. Recall that the incoming wastewater has an inconsistent flow rate that fluctuates drastically throughout a 24-hour period. This change in flow will also result in changing detention times which many of the treatment processes are dependent on. A treatment plant that utilizes flow equalization will attempt to even out the flow so it is consistent throughout the treatment plant all the time. By looking at historical data the plant operators will have a good idea of what the average flow rate for the plant is. This average flow rate is the target of the flow equalization. When the incoming wastewater is greater than the average flow, the excess amount will be directed towards a holding basin. When the flow is less than the average, typically in the middle of the night, the wastewater is pumped from the holding tank into the treatment facility. This can also reduce energy cost as day time pumping will be reduced. Energy costs are usually higher during peak periods. Some treatment facilities have flow equalization at the end of the treatment process. They may have restrictions in their discharge permit which may limit the flow rate leaving the facility. Other treatment plants don't have any flow equalization.

Sedimentation

After the incoming flow rate is measured the next step in the treatment process is primary sedimentation. The primary goal of sedimentation is to remove the settleable solids. A well-operated primary sedimentation tank can remove around 90% - 95% of settleable solids. There will also be a reduction in total suspended solids and a slight reduction in BOD5. Recall that settleable solids are the large solids in the wastewater and are measured by an Imhoff cone in the laboratory. The sedimentation process works because these solids are heavier, relative to the wastewater, and will, therefore, settle to the bottom of the tank. These tanks

are referred to as Primary Clarifiers or Primary Sedimentation Basins. A clarifier is a tank or basin where the sedimentation process will occur. The rate at which the solids will settle is determined by Stokes Law, which takes into account the size of the solid particle, the specific gravity of the particle, and the specific gravity of the liquid. Specific gravity is a unitless number and is a measure of density relative to a reference liquid. For this book when talking about specific gravity, we will assume water is the reference liquid and it has a specific gravity of 1. When determining how quickly solids will settle in the sedimentation tank, the specific gravity of the solids will be a significant factor. If the solids have a specific gravity less than 1, they will not settle at all, in fact, they will float on the water. If the specific gravity is only slightly greater than one, the solids will settle but at a much slower rate than another particle with a larger specific gravity. This is fairly intuitive. Clearly the heavier the solids the quicker they will settle.

Another phenomenon that occurs in the sedimentation process is that as the solids collect at the bottom of the tank, the weight of the solids begin to compact and compress. This causes the solids to be thickened and have slightly less water content. Detention time, or how long the wastewater takes to travel through the tank, is a critical design parameter of primary sedimentation tanks. There needs to be enough time to allow the solids to settle but not so much time that the solids start to decompose. Decomposition will cause gas bubbles to form which can hinder solids settling and create foul odors.

Primary sedimentation tanks can either be circular or rectangular. Regardless of the configuration, the tanks will have similar components. At the inlet structure where the wastewater enters the tank, the velocity is typically high in order to prevent solids settling in the piping network as the wastewater comes from the preliminary unit process to the primary tank. Once in the primary tank, the velocity must be slowed. To accomplish this there will be some type of diffuser at the inlet end that will redirect flow and prevent short-circuiting. The dimensions of the primary sedimentation tank must be able to accommodate the flow of wastewater but must also reduce the velocity.

Flotation

As discussed earlier, the specific gravity of the material in the wastewater will determine how it interacts with the wastewater in the sedimentation tank. In addition to settling solids, primary tanks will also remove floatables. Typically, these floatables are classified as fats, oils, and grease (FOG). The specific gravity of these materials is less than 1 so they will rise to the top of the sedimentation tank and be removed. A rectangular primary tank will have flights that span the width of the tank. They are connected by a chain that is motor driven to slowly move with the flow of wastewater. The flights provide several functions. They prevent short-circuiting of material on the surface, they convey the FOG on the surface to a collection trough at the end of the tank, and they convey the settled solids to a hopper at the beginning of the tank. Circular tanks have a similar mechanism called a swing arm that provides the same functions.

Sludge Removal

Once the solids have settled to the bottom of the tank, they are conveyed to a hopper in the tank. Circular tanks are typically coned at the bottom so the solids build up in the center. Rectangular tanks have a hopper at the front of the tank and the flights convey the solids there. The solids must be removed from the tank periodically so they do not cause adverse conditions. There is organic matter in the solids and if it starts to decompose, it will create foul odors and gas bubbles that will hinder other solids from settling. Typically incoming wastewater is around 1% solids. Due to the sedimentation process, the percent solids concentration increases to around 4% to 8%. Due to the high amounts of solids, a standard pump cannot be used. Instead, special pumps including a progressive cavity type pump or a stator/rotor pump are commonly used.

The stator/rotor pump has a stationary part, the stator, and a rotating element, the rotor. Both have a corkscrew type shape and the rotor moves within the stator. As it rotates, it is passing the mixture of solids and water progressively through the pump. These pumps are designed to be able to handle the abrasive nature of the solids and not clog up. The solids are sent to an anaerobic digester where they are further treated and stabilized. Eventually, they will be dewatered and sent to a landfill for disposal.

Chemical Addition

To further enhance the sedimentation process, chemicals can be added. These chemicals will adhere to the solids and increase their specific gravity. With a higher specific gravity, the solids will settle more quickly. This can either be done to increase the amounts of solids and BOD5 or can be used to achieve average results in a smaller footprint. This process is referred to as chemically

enhanced primary treatment (CEPT). Typically, ferrous or ferric chloride is used as the chemical aide. Other chemicals such as polymers may also be used. Polymers make the solids clump together which subsequently results in quicker settling in the sedimentation tank.

This process is not used as often anymore due to increasing regulatory requirements. Early in the wastewater industry, a treatment plant could have removed enough solids and BOD5 using the CEPT process. But as regulations became more stringent, many utilities upgraded to secondary treatment systems. This secondary biological treatment process is dependent on the BOD5. If too much is removed in the primary process, it will adversely affect treatment.

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5.6: Biological Treatment Overview

Learning Outcomes

- Describe different methods to biologically treat wastewater
- Examine what target contaminants are being removed by the different biological processes
- Compare and contrast different biological processes and the type of bacteria and environmental conditions needed

Aerobic, Anaerobic, and Facultative Organisms

Aerobic bacteria require an environment that has free dissolved oxygen. The bacteria use that oxygen for respiration to live. They feed on the organic matter and other nutrients in the wastewater. As the bacteria consume these materials, they are removed from the wastewater, making it less contaminated. The byproduct of the aerobic decomposition of organic matter is carbon dioxide (CO_2).

Anaerobic bacteria require an environment that has no free or combined oxygen. Free oxygen is when there is excess oxygen dissolved in the water and is available as O2. Combined oxygen is when the oxygen molecule is bound to another element. Common examples of combined oxygen in wastewater is nitrate (NO3). In anaerobic conditions, there is absolutely no oxygen available to the bacteria for respiration. Anaerobic bacteria have more sophisticated means of respiration by using other chemical reactions instead of using oxygen directly. However, similar to aerobic bacteria, when anaerobic bacteria breakdown the chemicals in wastewater for respiration and feed off other organics, they subsequently remove the contaminants from the wastewater. The byproduct of anaerobic decomposition is methane gas.

Facultative bacteria have the ability to thrive in either aerobic or anaerobic conditions. While they prefer aerobic conditions, they have the ability to adapt when no oxygen is available and survive in anaerobic conditions.

Stabilization Ponds

Stabilization ponds are a simple way to reduce the amount of organic material in wastewater and require low maintenance. However, they require a lot of land and are mainly used for smaller rural communities. The concept of ponds is pretty simple. You have a large pond filled with wastewater. The size of the pond allows for a very long detention time. The pond creates an ecosystem for bacteria to thrive and those bacteria breakdown the organic matter. Since the detention time is very long, typically 45 days or longer, solids will also settle to the bottom and be removed from the effluent. Eventually, the solids will have to be removed but a well-operated pond can go a few decades before that is needed to be done.

As discussed earlier there are several different types of ponds depending on what type of bacteria are expected to be prevalent. Aerobic ponds utilize aerobic bacteria and require oxygen. These ponds are typically more shallow, around 2ft to 5ft, since the oxygen is provided by the atmosphere and algae that is produced on the surface of the pond. Ponds have a complex relationship between how much dissolved oxygen is available to the bacteria. This is driven by sunlight over a 24-hour period and photosynthesis. Photosynthesis is where plants such as algae use sunlight and carbon dioxide (CO2) to thrive. During the day when there is plenty of sunlight, the algae will utilize the CO2 in the water and produce oxygen. This will cause the pH in the pond to decrease and the dissolved oxygen concentration to increase. This is a good thing because, in an aerobic pond, the bacteria need oxygen to live and breakdown the organic waste. During the night when the sun goes down, the reverse happens. Without sunlight, photosynthesis is reduced and the algae will utilize the oxygen and produce CO2. This causes the pH to increase and the dissolved oxygen will decrease. Because sunlight is an important factor in pond performance, there will also be seasonal variations in addition to daily fluctuations. During the winter when the sun isn't as prevalent, the amount of oxygen produced via algae and photosynthesis will be reduced. If more oxygen is required than what can be produced naturally, it can be provided by mechanical means. Surface aerators and a mixing system can be installed. However, the mechanical systems in these aerated ponds will require more maintenance. They will also require more electricity to run the aeration equipment.

Anaerobic ponds utilize anaerobic bacteria which require no oxygen. To create this environment in a pond system, the depth is increased. Typically depths can range from 6 ft to 16 ft. At these increased depths, oxygen from the atmosphere is unable to penetrate the water, and a no oxygen environment, ideal for the anaerobic bacteria to thrive, is created. In these types of ponds, the bacteria are breaking down the more complex solids and organics that are found in the wastewater. It can provide sufficient

removal of nitrogen, phosphorus, and BOD5. The solids are further stabilized, broken down, and collected as sludge at the bottom of the pond. Like the aerobic ponds, these solids will eventually need to be removed.

Facultative ponds are a mix of aerobic and anaerobic ponds. Their depth is on the order of 3ft to 8ft. Recall, that facultative bacteria can switch from living in anaerobic conditions to aerobic conditions. This can be useful during seasonal variations where little oxygen is available. The facultative bacteria can then focus on breaking down organics by anaerobic decomposition. When sufficient oxygen is available they will switch mechanisms and break down the organic matter by aerobic decomposition.

Pond Performance

To improve pond performance, it is very common to have multiple types of ponds in series. Anaerobic ponds can handle higher influent BOD5 loading, so they would be the first pond. Then a facultative pond would follow, where further BOD5 reduction is achieved. Lastly would be an aerobic pond that would reduce organic wastes and remove pathogenic organisms.

Pond performance is going to be dependent on the loading of organic wastes and detention time. Typically a max of 30lbs of BOD5/day/acre is the desired loading rate. However, ponds are able to handle fluctuations if loading rates are exceeded for short periods of time. The wastewater must remain in the pond long enough so the bacteria can come in contact with the organic matter and consume it. Anaerobic ponds will maintain a detention time of 1 to 7 days. Facultative ponds have a detention time of 5 to 30 days and aerobic ponds are usually 30 days or greater.

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5.7: Biological Treatment Methods

Learning Outcomes

- Describe different methods to biologically treat wastewater
- Compare and contrast fixed film treatment methods with other biological treatment methods
- Understand the operation of a trickling filter and how to control it

Fixed Film Processes

A fixed film treatment process is still a biological treatment method and utilizes the same type of bacteria as discussed in Chapter 6. The difference is that instead of the bacteria floating near the bottom of a pond, they are fixed to some type of medium. The media can either be natural stone, synthetic plastics, or large rotating disks.

Rotating Biological Contactors

Rotating biological contactors (RBCs) utilize aerobic bacteria to decompose the incoming BOD5. They are composed of a series of closely spaced circular disks. The disks are connected to a shaft that is coupled to a motor. The set of disks lay horizontally in a tank and rotate at a slow speed. The incoming wastewater enters the tank and submerges approximately 40% of the disks. The water moves through the tank and comes in contact with the aerobic bacteria that are growing on the disks. When the disks are submerged in the wastewater, the bacteria have access to the BOD5 and will consume it. As the disks rotate out of the liquid in the tank, they are exposed to the atmosphere where the bacteria can utilize oxygen for the aerobic decomposition of the BOD5.

The disks are typically 12 feet in diameter and multiple disks are combined together to make a long cylinder. Common lengths are 25 feet. The motor spins the disks at approximately 1.5 rpm. It's not uncommon to see multiple RBCs being used in both parallel and series configurations. As the bacteria thrive in this environment, eventually they will build up on the disks and start to slough off. The effluent of the RBC is sent to a finishing pond or clarifier to further treat these solids.

Each of the RBCs is covered for several reasons. Disks are commonly made out of plastic so covers will protect the disks from becoming brittle due to sun damage. Foul odors from the wastewater and H2S gasses will be present in the RBCs. Covering them will reduce these odors and prevent nuisance complaints from the community. Lastly, covers will protect the bacteria from being washed off the disks during rain events. Fiberglass covers are commonly used and are more cost-effective than building the RBCs in a building. The humidity and wastewater gases can be corrosive to cement, metals, and other building materials.

Trickling Filters

Trickling filters are another form of fixed film biological treatment. They are comprised of circular tanks filled with stone, lava rock, ceramic, or synthetic material all of which are referred to as media. Standard media is approximately 1 inch to 4 inches in diameter. The bacteria will become fixed to this media and aerobic decomposition will occur as the incoming wastewater comes in contact with the bacteria. While trickling filters can be relatively deep, around 3 to 8 feet, there is ample airflow in the voids of the media to allow for aerobic bacteria to thrive. Trickling filters often have ventilation ports near the bottom to ensure there is sufficient airflow to the bacteria. The wastewater enters the trickling filter at the top of the filter. Then gravity takes over and the wastewater trickles down through the media to the bottom of the tank where it is captured in an underdrain system.

The wastewater is conveyed from the primary sedimentation tanks to the trickling filters. This is either done by gravity or by using a pump. Either way, a trickling filter uses this pressure in the water to evenly distribute the wastewater to the trickling filter. There is a distributor arm that expands the diameter of the circular tank. The wastewater is forced out through small outlets on the distributor arm that will cause the arm to rotate.

The wastewater trickles through the media and comes in contact with the bacteria fixed to media. The bacteria are now in a sufficient environment where aerobic decomposition will occur and reduce the BOD5 of the wastewater. Over time the bacteria will build up on the media and eventually will fall or slough off. These solids will be captured in the underdrain system and sent to the secondary clarifier. In the clarifier, sedimentation will occur and the solids will settle to the bottom of the clarifier and be removed.

Recirculation

Recirculation of the clarified effluent is a key operational component of a trickling filter. Water from the secondary clarifiers has already gone through the biological treatment process of the trickling filter and has a lower amount of BOD5. By recirculating this treated water with the incoming wastewater, it will dilute the incoming BOD5. Recirculation will also be able to control the dissolved oxygen level in the trickling filters. Increasing the recirculation rate will cause the dissolved oxygen to increase and lowering the recirculation rate will cause it to decrease. An optimal concentration of dissolved oxygen in the trickling filter is 1.5 mg/L to 2.0 mg/L.

Organic Loading

Trickling filters can be further classified by how much BOD5 is being sent to the treatment unit. Low rate trickling filters receive up to 25 lbs of BOD5/1000 cubic feet/day. At this lower organic load, an operator can expect to achieve 80% - 90% BOD5 removal. Intermediate filters can handle up to 40 lbs of BOD5/1000 cubic feet/day but will see lower removal efficiencies of BOD5. High rate and roughing filters will have BOD5 loading in excess of 50 lbs of BOD5/1000 cubic feet/day. At these higher loadings, BOD5 removal significantly drops and will not meet current regulatory requirements. High rate and roughing filters are often used as a preliminary step and are combined with other forms of treatment to ensure regulatory compliance is achieved.

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5.8: Activated Sludge

Learning Outcomes

- Compare and contrast the difference between fixed film and suspended growth biological treatment systems
- Describe how the activated sludge process can more efficiently reduce organic wastes
- Understand how different process control strategies work in an activated sludge system
- Examine how a secondary clarifier is utilized in an activated sludge system

Suspended Growth Processes

Unlike the fixed film biological systems discussed in Chapter 7, activated sludge uses a suspended growth process. This means that there is no media for the bacteria to become fixed to. The microorganisms are suspended in the tanks either by a mixer or air diffusers and are then mixed in with the incoming wastewater. This mixture of wastewater and microorganisms is referred to as the Mixed Liquor Suspended Solids (MLSS). A sample can be taken from the activated sludge system and analyzed in a laboratory to determine how many mg/L there are of MLSS in the system. This laboratory result will be a critical design and operational parameter that will need to be continually monitored to ensure effective treatment.

Activated Sludge Treatment

The activated sludge process was developed by two scientists, Edward Arden and William Lockett, in England in 1914. Their experiments showed that by taking the microorganisms that were already established from aerobic decomposition and introducing them to fresh wastewater, it would speed up the decomposition of the new organic wastes. Instead of relying on the 30 to 45 days that it would normally take to breakdown these organic wastes, the activated sludge process can achieve the same level of treatment in less than one day. This means that an activated sludge wastewater treatment system will be able to handle higher flow rates and higher organic loading than pond treatment or fixed film systems.

To achieve this on a large scale, conventional activated sludge systems are comprised of an aeration tank followed by a secondary clarifier. In the secondary clarifier, the microorganisms will separate from the now treated wastewater. A majority of those microorganisms will be returned back to the reactor and are now activated to treat more of the incoming wastewater. In the aeration tanks, the bacteria are in an environment with dissolved oxygen readily available and organic matter to consume. Like the other biological processes, this is how the reduction of BOD5 occurs, through aerobic decomposition. What makes activated sludge unique is that in the secondary clarifier, the bacteria become stressed because their food source has been drastically decreased and there is no more dissolved oxygen. They begin to go through endogenous respiration. The bacteria basically become so starved that they begin to breakdown their own cellular structure. Before the bacteria completely cannibalize themselves, they are sent back to the aeration tank where they are re-introduced to readily available dissolved oxygen and organic matter. The starved bacteria are then able to rapidly re-start aerobic decomposition and quickly reduce the BOD5 in the wastewater.

Food to Microorganism Ratio

A key parameter to determine the effectiveness of activated sludge systems is the food to microorganism ratio, or F/M. The food is determined by the amount of BOD5 in the incoming wastewater and the amount of microorganisms available to consume that food is determined by the amount of MLSS in the aeration tanks. Since it's a ratio, the units of these two laboratory results must be the same. The mg/L concentration of the laboratory results is converted into a mass with the units of lbs. While each treatment plant will determine which level of F/M has historically given effective treatment, a common range is around 0.2 to 0.5.

Return Activated Sludge

The return activated sludge, or RAS, are the bacteria that have settled in the secondary clarifier and are being sent back to the aeration tank. The rate of speed at which the microorganisms are returned is something that the operator can control.

Waste Activated Sludge (WAS)

Like the other biological process discussed, the bacteria, overtime will grow and their population will increase. To control the amount of bacteria in the system, a portion of the RAS will not be returned to the aeration tank but instead is directed to a separate

solids handling treatment unit. Typically, these solids are combined with the settled solids from the primary sedimentation tanks and sent to an anaerobic digester. After anaerobic digestions, the solids will be dewatered and ultimately sent to a landfill for disposal.

How much bacteria remains in the system and how much is wasted can be determined by the mean cell residence time or MCRT. The MCRT is a theoretical calculation of the average time a single bacteria will stay within the activated sludge system before being wasted. To calculate the MCRT an operator would determine how many pounds of MLSS there is in the system and divide that by how many pounds were removed from the system.

Process Control

The F/M ratio, MCRT, RAS, WAS, and dissolved oxygen concentrations can all be manipulated by the operators of a wastewater treatment facility to optimize the effectiveness of treatment. In fact, those parameters are the only things that can be easily controlled. The amount of incoming wastewater is going to be what it is and it will fluctuate throughout a 24 hour period as well as vary by season. The incoming BOD5 loading is what it's going to be and the operators can't control it.

If the F/M is too low, it means that there are more bacteria than what is needed to consume the available food. This is inefficient because supplying oxygen to the bacteria requires a significant amount of energy. If there is too much bacteria in the system and not enough food, the bacteria will still be consuming oxygen but the BOD5 won't be further reduced. To increase the F/M ratio operators can only control the "M" portion of the equation. By increasing the wasting rate, the MLSS will be reduced causing the F/M ratio to increase.

If the F/M ratio is high, then there is not enough bacteria to consume the large amounts of incoming BOD5. This will lead to poor treatment and the effluent will have a high BOD5 concentration. Operators cannot decrease the amount of BOD5 coming into the plant so they will have to increase the amount of MLSS in the system. They can do this by decreasing or stopping the wasting rate. Decreasing the wasting rate will cause the MLSS to increase and the F/M ratio will be reduced.

The MCRT is another process control tool that is used to determine the wasting rate by manipulating the equation to calculate the MCRT. Often the desired MCRT rate is determined by the design of the treatment facility or from historical data. By taking the pounds of MLSS in the system and dividing it by the desired MCRT, you will determine what the wasting rate needs to be to achieve that MCRT. However, the MCRT and F/M methods for determining the wasting rate can often conflict with each other. Operators need to look at the changes in MCRT and F/M over time and make minor adjustments to the process so the bacteria aren't "shocked".

Alternative Process Configurations

There are many different types of process configurations of activated sludge systems that differ by how the wastewater enters the aeration tanks. A plug flow reactor has all of the wastewater and RAS entering at the beginning of the tank. This will have a large organic loading at the beginning of the tank and as the wastewater moves through the tank, the load will lessen. Often, tapered aeration will be used in plug flow reactors. Tapered aeration will have lots of air diffusers at the beginning of the tank so more oxygen is available to the bacteria to handle the increased organic loading. As the wastewater flows through and the BOD5 is reduced, the air diffusers are also reduced.

An alternative is a step feed reactor where the incoming wastewater is split and sent to different portions of the tank. For example, 25% of the flow is sent to the first ¼ of the tank, another 25% to the second ¼ of the tank, and so on. This allows for a more even distribution of the organic loading as well as a more uniform demand for the air diffusers. Typically, a steep feed system will use less air overall than a plug flow reactor.

Secondary Clarification

A secondary clarifier is a key component of the activated sludge system. Not only does it separate out the microorganisms from the now treated wastewater, but it will also concentrate them through the sedimentation process. A secondary clarifier works exactly as discussed previously in primary sedimentation. The only difference is that in a primary sedimentation tank the main goal is to remove unwanted solids. In a secondary sedimentation (or clarifier) tank, the goal is to concentrate the MLSS so it can be returned to the aeration tanks.

How the biomass is settling in the clarifier can be difficult to see in real-time as the tanks are typically below-grade and made of concrete. A “sludge judge” is used to determine how many feet of MLSS are settled on the bottom and how much clear water there is on top. The tool is simply a clear PVC pipe with a ball check valve at the bottom. As the pipe is inserted into the water, the ball check valve opens, letting liquid in. When the stick hits the bottom, the operator will pull the PVC pipe out of the water forcing the ball check to close producing a cross-sectional sample of MLSS on the bottom and clear water on top. There are markings on the PVC pipe for every foot. So as the operator pulls it out of the clarifier, they can see where the clear water stops and where the MLSS is settling. Typically a sludge blanket of 1 to 3 feet on the bottom of the clarifier is optimal.

The settleability of the MLSS can also be seen in the laboratory by taking a sample of the MLSS and putting it into a 1000 mL beaker. After 30-minutes have gone by, the graduations of where the MLSS has settled will be recorded. Dividing the settled sludge volume in mLl/L, dividing by the MLSS in mg/L, and multiplying by 1,000 mg/g will yield the Sludge Volume Index (SVI) in mL/g. The SVI is utilized to gauge how well the MLSS will settle in the clarifier and will also shed light on how the activated sludge plant is operating.

Typical SVI is around 100 to 200 mL/g. Less than 100 mL/g will often show rapid settling of the sludge in the clarifier. When the MLSS settles too quickly, smaller “pin floc” particles will remain suspended in the middle of the clarifier. This will also be seen in the sludge judge test where there is clear water on top of the sludge judge, murky water in the middle, and darker solids on the bottom. This is usually caused by having a higher MCRT. An SVI greater than 200 mL/g will have sludge settling very slowly in the clarifier. This can be caused by having a low MCRT.

The water leaving the secondary clarifier has now gone through all of the previous treatment steps from preliminary screening, to primary sedimentation, and activated sludge treatment. In some areas with less stringent regulations, this water is clean enough to be discharged to the ocean or a nearby waterbody. However, some additional treatment like filtration and disinfection may be needed to meet regulatory compliance. Also, the solids that were removed from the primary and secondary process will still need to be treated and disposed of.

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CHAPTER OVERVIEW

6: Water Customers

6.1: Water Rates
6.2: Public Relations

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6.1: Water Rates

Student Learning Outcomes

After reading this chapter, you should be able to:

- Evaluate different rate structures
- Understand why water rates are needed
- Analyze water rights and utility ownership

Why Are There Water Rates?

Water must be sold in order for a utility to be able to treat, distribute, and deliver water. There are chemical, electrical, infrastructure, labor, and a variety of expenses a water utility must cover. In order to pay for all these expenses, they must receive revenue to cover all the costs associated with operating and maintaining a water utility. This required revenue is referred to as revenue requirements.

Revenue requirements can be explained, as the total revenue required to ensure proper operations and maintenance, development, and perpetuation of a distribution system, and preservation of the utilities' financial integrity. Most of the revenue received by a water utility comes from the sale of water. However, some utilities receive supplemental revenue from renting property, merchandising, services related to other utilities, taxes, capacity, and impact fees.

Utilities must properly budget based on projections of water sales and all associated expenses for proper water rates are assigned in order to generate enough revenue. Sometimes budgets and associated projections extend out multiple years. Regardless of budgetary projections, they should be reviewed annually and adjusted accordingly.

Water rates studies and analysis usually accompanying any rate changes. Budget projections aid this process of rate-making. Additional studies can also include financial and budgetary planning, support for issuance of debt, and evaluation of past and future adequacy of contractual, litigation, rate proceeding or other requirements.

When a utility is calculating the adequacy of revenue in order to recover costs. Budgeting may require projections into the future. Projections beyond ten (10) years tend to be quite speculative, while five (5) projections are usually considered adequate. Historical water usage and other data is used to help determine appropriate water rates. However, the data must be normalized or adjusted to reflect conditions that may not continue in the future. For example, if there will be no future growth of additional customers, the need for additional sources of supply and storage may not be needed.

Below is a list of some factors affecting revenues:

- Number of customers served
- Customer water use
- Rate changes
- Non-recurring sales
- Weather
- Conservation
- Use restrictions
- Price elasticity

Below is a list of factors affecting revenue requirements:

- Number of customers served
- Customer water use
- Non-recurring sales
- Weather
- Conservation
- Use restrictions
- Inflation

- Interest rates on debt
- Capital financing needs
- Changes to tax laws
- Other changes in operating
- Economic conditions

There are two general approaches for projecting revenue requirements. They are cash-needs approach and utility approach.

Cash-Needs Approach

The cash-needs approach ensures revenues are sufficient to recover all the utility cash needs for a given projected time period. This approach simply means the total amount of revenue needed to meet cash expenditures. The cash-needs approach usually relies on debt financing. Debt indentures usually specify sufficient cash to meet cash expenditures, deposits are made to reserve account(s), and debt-service coverage requirements are met.

The accounting term “cash” refers to revenues being recognized as earned when cash is received and expenses charge when cash is disbursed. The term “accrual” refers to revenues being recorded when earned and expenditures are recorded when the become liabilities for benefits received and are not dependent on what period of time they are received.

The cash-needs approach is usually followed by public (government-owned) water utilities. Elected officials of public water utilities are tasked with approving water rates.

Utility Approach

The utility approach of projecting revenue requirements is mandated for all investor-owned (private) water utilities. This approach is also referred to as “utility basis” approach. This approach is similar to the cash-needs approach. However, the governing regulatory body assigns a “rate payer advocate”. In California, this rate payer advocate group is referred to as the Division of Rate Payer Advocate (DRA) and the governing body is the California Public Utility Commission (PUC).

This approach involves measuring revenue requirements with or without concern for allocating revenue requirements among classes of customers served. This means assigning or not assigning specific revenue requirements to specific classes of customers.

Revenue Requirement Components

In order to determine the revenue requirements, a utility must determine all the operating expenses. In other words, what does it cost the utility to provide service. On the surface, this might seem like an easy and straightforward task. However, there are a lot of aspects to operating a water utility and it is important to capture all these expenses. The following list is not exhaustive, but it is fairly comprehensive.

- Administrative costs
- Salaries
- Benefits
- Energy costs
- Chemicals
- Supplies
- Fuel
- Equipment costs
- Equipment replacements
- Principal and interest payments on debt
- Miscellaneous

The paragraphs below will provide additional detail for some of these operating costs.

Operations and Maintenance

These expenses are usually based on actual expenditures and adjusted to reflect anticipated changes. Operations and maintenance (O & M) costs include employee salaries, wage, benefits, purchased power to operate pumps and equipment, purchased water from

other utilities, chemicals for treatment, supplies, tools, equipment, vehicles, fuel, outside services, and general overhead. Some outside services can include, billing services, construction contractors, engineering and other consultants, other utility services. This list is not exhaustive but should provide a good general understanding of the various O & M expenses.

Some utility expenses are considered fixed costs while others are referred to as variable costs. Fixed costs are the costs the utility most cover to keep the utility in operation and are independent on the amount of water the utility sells. For example, if the water utility does not experience the anticipated water demand (this could be due to water use restrictions during a drought) the amount of revenue recovered would be lower than expected. However, the utility would still need to out salaries, benefits, and administrative costs. The staffing requirements are not directly proportional to the amount of water sold. Water meters would still need to be read, infrastructure, equipment, and vehicles would also need to be maintained. These costs would be considered fixed costs. Whereas, the amount of chemicals needed to treat the water might be less if the utility is producing less water. Therefore, the cost for chemicals would be less and this would be considered a variable cost. Regardless of the type of cost, the utility would still need to recover these revenue requirements.

Debt Service

Sometimes utilities require large amounts of funds in order to pay for large capital improvement projects. Some of these projects consist of new sources of supply such as groundwater wells, large storage facilities, and other major infrastructure improvements. If a utility had to spend several millions of dollars in a given year and tried to collect these expenditures in the same year, water rates would be unusually high. Therefore, a utility acquires debt in order to spread out these costs over multiple years. Debt service is the annual cost to pay the debt back. It includes both principal and interest.

Reserves

Water utilities commonly maintain reserve accounts. Reserve accounts are savings accounts. They are usually set aside for emergencies or unexpected needs. For example, if a utility has earthquake insurance, a specific reserve account can be set aside to cover the deductible costs and start making payments to begin the immediate process for repairs to the system. Another example might be a reserve account to replace a large expensive facility if there is an unexpected failure.

Capital Expenditures

Water utilities will typically have normal routine replacement of existing facilities. All equipment and infrastructure have reasonably expected operating lives. For example, groundwater might last fifty (50) years. The utility would have to plan for the replacement of these facilities. Another example is the piping infrastructure. A utility might have two hundred (200) miles of underground pipelines. Let's assume the average lifespan of this pipe is seventy-five (75) years. This would mean the utility would need to replace on average 2.7 miles or 14,256 feet a pipe per year to keep up on the replacement schedule. Capital improvement projects (CIP) would also include annual extensions and other improvements. Often times, large CIP is financed through debt, reserves, or some combination. Very rarely are large projects paid for with cash. Issuing debt or using reserve funds prevents the customers from paying 100% of the initial cost of facilities.

Coverage Ratio

A common measurement to help determine the financial health of a utility is the coverage ratio. This is the measure of the ability of the utility to pay the principal and interest on all loans and bonds. It is calculated by subtracting the non-debt expenses from the total revenue divided by debt service expenses. A good financial coverage ration would be above 1.0.

Revenue

Where does a water utility get the money to fulfill revenue requirements? There are typically three (3) classes of revenue; Operating revenues, non-operating revenues, and contributions to capital.

Operating revenues include both metered and unmetered water sales. Most of the time, the sale of water is metered. This means a customer pays for the water, which flows through their meter. Sometimes, utilities sell water at a flat rate or unmetered. If a water utility sells water to another water utility they would be considered a wholesale water provider. The revenue earned from these sales are also considered operating revenue. Any fee for or charge for water service is also considered operating revenue. For example, some utilities have a monthly fee for something referred to as a "readiness to serve" charge. This means if a customer has

a meter service, but does not use any water for a period of time (i.e., month) the utility would still bill the customer for the ability or readiness to serve the customer. Often times this monthly service charge is based on the size of the meter. The larger the meter the higher the monthly charge. If a water utility rents property (i.e., cellular leases) or charges for the use of the utilities operating property, these would also be considered operating revenues.

Non-operating revenues is a smaller amount of revenue most utilities earn, but they still need to be taken into account. Examples of non-operating revenues include merchandising interest, dividends, sale of property, tax revenues, and various other revenues not associated with operating the utility. The last classes of revenue include funds contributed by developers and grant funds. These are considered contributions to capital.

Customer Classes

There are generally four (4) main classes of customers. These are identified as residential, commercial, industrial, public authority, and dedicated landscape. Residential customers consist of single and multi-family dwellings. This would include attached and detached homes, apartment buildings, condominiums, and townhomes. Commercial customers would include businesses such as restaurants, small and large businesses. Industrial customers would include manufacturing and processing establishments. Public authority would be public establishments such as schools, city, and county buildings. Dedicated landscape service connections are commonly separated from other service classes.

There are also some special classes of customers. These would include wholesale service, fire-protection, and service for air conditioning and refrigeration.

Wholesale service is usually defined as a situation in which water is sold to a customer at one or more major points or delivery for resale to individual retail customers within the wholesale customer's service area. This water is typically treated before being sold and is sold to a separate municipality or water district.

Fire protection service is primarily a standby service. There is a readiness to deliver relatively large quantities of water for short periods of time at any of a large number of points within a distribution system. The total quantity of water used is typically small and service costs are based on one of the following two criteria:

1. Cost of service is determined on the basis of the potential demand for water for fire fighting purposes in relationship to the total of all potential demands for water.
2. Cost of service is allocated as an incremental cost to the costs of general water service. It is based on the premise that the prime function of a water utility is to supply general water service.

Air conditioning and refrigeration is water sold for use in water-cooled air conditioning and refrigeration systems. Most units now use water referred to as "make-up" water. This is water recycled within the business.

Water Rates

It is common practice for a water utility to provide water service to all general service customers within a given jurisdiction through a single rate schedule, comprised of a two-part rate. There are three (3) common general classes of customers and these are:

- Residential—This customer class generally comprises of one and two family dwellings, usually physically separate.
- Commercial—This customer class is commonly comprised of multifamily apartment buildings and nonresidential, nonindustrial business enterprises.
- Industrial—This customer class represents manufacturing and processing establishments

Sometimes a utility will subdivide the general classes of customers into more specific groups. Water use characteristics, service requirements, and other various reasons may set certain customer classes apart from one another. Sometimes utilities will create special classes of customers, which can include wholesale, fire-protection, irrigation, and air conditioning/refrigeration services.

The jurisdictional area referred to above is the service area boundary. A governing body of each water utility determines service area boundaries. In the case of investor-owned private utilities in California, the governing body is the California Public Utilities Commission (CPUC). Within the County of Los Angeles, the governing body is the Local Agency Formation Commission (LAFCO). Commonly, a two-part water rate includes an initial charge, which generally recovers customer related and possibly

some volume related costs of the utility, together with a volumetric charge to recover the remaining costs. Some utilities recover their fixed costs with a monthly charge not associated with the amount of water sold. The variable revenue requirements would then be covered by the volumetric charge for water. The volumetric charge is based on the amount (or volume) of water sold.

Why would a utility have a two-part rate versus just charging water based on the actual usage of each customer? This is a common question people sometimes ask. The simple answer is because of the variability in how much water people use. What would happen if every customer only used a small quantity of water? Earlier in this text, we discussed revenue requirements. A utility must sell enough water or more importantly collect enough revenue from the sale of water, to cover all their related "requirements" to operate. If customers use too little water, then the utility would not be able to collect enough revenue, unless they charged an exorbitant amount for each unit of water. An example of this will be presented in the last chapter of this text (Waterworks Mathematics). Therefore, oftentimes, a utility will have a "fixed" charge. This fixed charge is sometimes referred to as a readiness to serve charge. This allows the utility to collect sufficient revenue to keep the utility running regardless of the amount of water sold. It commonly covers meter reading, billing, and day-to-day operational costs. Therefore, a two-part rate, one part fixed and the other part variable is commonly used.

Flat Rates

A fixed charge is different than a flat rate. A flat rate is something utilities sometimes use when the water supply is plentiful. It is the same charge across all customer classes and users. It is an amount, which must cover the revenue requirements of the utility, but is blind to the amount of water each customer uses. This type of rate is becoming less common, especially in California where drought often affects certain parts of the state. It is also not an even or equitable means of charging for water service. It also does not encourage water savings or conservation.

Variable Rates

As previously mentioned, a variable rate is based on the amount of water customers use. Therefore, the more water a customer uses the more revenue the utility collects. Conversely, if a customer uses zero units of water over the billing cycle, then the utility would collect no revenue from this particular customer. Also, as previously mentioned, fixed charges can and are oftentimes included with a variable water rate.

Tiered Rates

Much like variable rates, a fixed charge is usually included with tiered rates. Tiered rates are another type of variable rate structure. However, in a tiered rate the variable price increases with usage. For example, each unit of water would be sold at a specific amount up to a certain unit usage set point. Then after the designated amount, the charged amount is increased until another specific usage amount, and so on. See a simple example below.

- 0 – 9 Units of Water Used = $1.00
- 10 – 19 Units of Water Used = $2.00
- 20 – 29 Units of Water Used = $3.00
- 30 or More Units of Water Used = $4.00

Tiered rates are designed to encourage water conservation. The belief is as water becomes more expensive as usage goes up, usage would be curbed. While tiered rates have been shown to contribute to conservation efforts. However, there are other issues associated with charging more for water based on customer usage. The utility must explain the reason they are charging more for quantities above specific usage amounts. There have been several lawsuits associated with the legality of tiered water rates. One such lawsuit was in 2015 between a group of San Juan Capistrano taxpayers and their local water utility. It is extremely important a utility properly explains and notifies their customers before implanting water rates, especially tiered water rates.

Budget Based Rates

A budget based rate structure is similar to a tiered rate structure. The difference between the two is instead of charging water purely based on the quality of water used. In a water budget based rate structure, water charges are assigned based on customer usage both indoors and outdoors. While most utilities do not measure these (indoor/outdoor) uses separately, under a budget based water rate, a certain volume is often assigned for indoor water use. In addition, a specific amount is assigned for outdoor water use (irrigation).

These assigned amounts are considered a customer's budget. The rate assigned to the budget is a standard volumetric water rate. If customer's stay within their budget, do not use more than the allocated amount, then the rate does not change. However, if a customer uses more water than their allocation, the cost of water increases similar to a tiered structure.

Another difference to a water budget rate structure compared to a standard tiered rate structure is budgets are commonly personalized for each customer. In a tiered system, all customers follow the same tiered rate, whereas budgets can be based on the specific water needs of each customer.

Regardless of the rate structure, the utility must be able to adequately recover its revenue requirements with the chosen rate structure. Rates are designed for specific periods of time known as the rate schedules. Projections of expenses are compared against projections of water use and then a rate can be calculated. During a water rate study, utilities will commonly use something referred to as a test year. A test year is an annualized period for which costs are analyzed and rates are established.

Utility costs for ongoing operations and maintenance of the system as well as past large capital improvements must be incorporated into the water rate. In addition, utilities need to properly account for future replacements and growth of the utility. While existing customers typically cover a large portion of these costs, some of the future expansion of a system should be and often times is paid for through fees to construction developers. These fees are referred to as facility capacity and connection fees. These fees are associated with expanding a system in order to supply water to additional customers.

The concept of recovering costs and expenditures through the sale of water is a fairly simplistic concept. However, determining necessary costs and expenditures and calculating the water rate associated with recovering this money is a difficult and complex process in order to keep the customer of water reasonable to the customer, but also ensuring the utility has enough cash flow to keep operations flowing.

Sample Questions

1. Budget projections beyond 10 years tend to be _____.
    1. Accurate
    2. Speculative
    3. Adequate
    4. Both 1 and 3
2. The "Cash-Needs" approach is typically used by _____.
    1. Private utilities
    2. Public utilities
    3. Agencies with multiple commodities
    4. All of the above
3. Which of the following is not included in O&M expenses?
    1. Salaries
    2. Purchased water
    3. Chemicals
    4. None of the above
4. Investor-owned utilities are governed by _____.
    1. An elected board of directors
    2. A City Council
    3. The California Public Utilities Commission
    4. A Mayor
5. A periodic stated charge for utility service not based on the metered quantity of service defines _____.
    1. Firm service
    2. Flat rate
    3. Rate blocks
    4. Standard rates
6. The annualized period for which costs are to be analyzed and rates established defines _____.

1. Test year
2. Yearly projections
3. Annual analysis
4. None of the above

7. Connection fees are charged to _____.
    1. Create revenue for O&M expenses
    2. New customers for the costs of new facilities needed to apply water
    3. Help establish service area boundaries
    4. All of the above

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6.2: Public Relations

Student Learning Outcomes

After reading this chapter, you should be able to:

- Explain the importance of public relations as it pertains to public perception
- Identify the key areas where communicating to the public is important
- List four (4) main areas the public experiences a water utility and their workers

Many times, public relations are looked at as a marketing strategy for businesses selling a product, or, perhaps a government agency disseminating information to a certain constituency or group of voters. Public relations (PR) is nothing more than the spread of information between an individual or an organization to the public. Therefore, PR is just as important for a water utility.

Even though customers do not have a choice who they receive their drinking water from, it is important for a water utility to be open, transparent, and helpful to their customers. Therefore, providing good public relations is important.

A water utility is in the public eye in a variety of ways. Utility vehicles are driving throughout a town performing work. Meter readers often visit customer homes to read a water meter. Every time someone turns on their faucet and the water coming out is unacceptable or when someone receives a high water bill, the water utility is often the one a customer will blame.

Some areas water utility workers are exposed to the general public include, but are not limited to meter reading, operations and maintenance workers, vehicle operation, public meetings, and customer calls and complaints. These are not the only instances where customers can and interact with water utility workers.

Meter Readers

Meter readers have the potential of interacting with customers on a routine basis. Meters are generally located near the property boundary of customers and in some parts of the United States; they can be installed inside customer buildings. Therefore, a customer might approach an employee reading meters. Customers can be in search of specific information about the service they are receiving or perhaps they might have questions about something they heard about in the news. Regardless of what a customer might be asking, it is important for meter readers to be respectful and polite.

Meter readers should maintain a neat appearance. Many utilities provide their employees with uniforms, which clearly display the utility's name. If a meter reader is speaking with a customer they should provide some form of identification letting the customer know who they are and whom they work for. If a customer's meter is inside a customer's residence, a customer may be reluctant to allow them into their home without proper identification or someone who is wearing worn-out clothes, dirty, or unshaven. Meter readers should be properly trained and have a good general understanding of utility operations. However, at no time should any employee, including meters, feel responsible to answer any questions they are unfamiliar with. Sometimes meter readers will carry around brochures with frequently asked questions and they should always provide the customer with a phone number to call, in order to receive additional information. While reading meters, a meter reader should also be aware of any abnormalities with the customer's service. If a leak is detected on the customer's side of the service, they should attempt to contact the customer. If a customer is not home, often times a water service notice tag is left on the customer's door. Whenever dealing with the public a meter reader should stay pleasant and polite.

Operations and Maintenance Workers

This group of workers does not typically have direct contact with customers. Therefore, while they should maintain a neat appearance, it is not as important as with meter readers. Sometimes when workers are working in the public right of way (i.e., streets, sidewalks, etc) a local resident may inquire about the work they are doing. While it may seem obvious to the worker, they need to remember most of the time the public is just curious. Therefore, it is important for the worker to be polite and to refrain from "smart aleck" responses. It is oftentimes best for a worker to refer the inquisitive public to the supervisor in charge of the work instead of trying to answer all the questions they might be asked. It is important for the utility to give the public proper notice whenever service is planned to be disrupted or when streets might be closed. This can be accomplished through mailers, calls, or

signs placed in the work area. During planned shutdowns for repairs or new installs, door hangers are commonly used to provide the local residents notice.

All work zones should be properly marked and kept safe. Safety cones, tape, and other means can be used to block public access in order to protect public safety. Work zones should also be kept as clean as possible and workers should avoid sitting or walking on private property. Customers generally do not like workers taking their breaks on their lawns. Equipment and vehicles should look clean and professional and tools should not be scattered around the worksite. After the work is complete, the workers need to leave the area in the condition (or better) as they found it.

Vehicle Operation

Water utility workers generally drive a significant amount throughout their day. This increases the potential for accidents and citations. Therefore, it is critical that all utility drivers need to be careful, follow all driving rules, and be extremely cautious of their surroundings. Careless driving also makes people angry. If a utility worker is driving too fast or appears to be driving carelessly, residents often take note and many times will call the utility to complain. This generally leads to a situation where it is the worker's word versus the resident's word. Courteous driving leaves a better impression on the public and leads to less potential issues. Utility workers should also use good judgment on where they park their vehicles. It might make a bad impression if someone sees a utility truck parked in front of the local tavern, even if the worker is actually working around the corner.

Water Quality

Water quality throughout the United States is highly regulated and safe to drink. However, that doesn't mean customers like the taste, smell, and look of their water. Even if the water is considered safe to drink, if it is discolored, has an odor, and tastes odd, customers will complain. A good PR strategy for handling water quality complaints is very important in order for customers to be confident in the water they are being served. Typically, there are water quality professionals employed by a water utility to answer questions related to water quality complaints. They are trained to explain the potential causes of these unpleasant aesthetic qualities, offer suggestions to improve the quality, and offer to sample the water if necessary.

Many times, the aesthetic quality of the water is a result of internal home plumbing problems, such as old galvanized plumbing. However, sometimes water can be discolored in the distribution system from flushing or other flow changes in pipes. Other times a utility might change the disinfection practices for various reasons. This can result in taste and odor issues. If the utility is aware of potential changes in water quality from distribution activities, it is advised the utility notify customers ahead of time in order to prevent a large number of complaints.

In accordance with federal and state drinking water quality regulations, annual reports must be provided to customers stating the quality of water they are being served. These reports are referred to as annual water quality reports or consumer confidence reports. These reports typically list the sources of supply, results from water quality samples collected, and health effects data related to constituents found in the water supply. These reports while regulatory requirements are also public relations materials and it provides utilities another avenue for communicating with their customers.

Customer Service

The staff in customer service departments is the first exposure a customer has with a utility. Customers often call with questions or complaints about their service. Some customers pay their water bills in person. Customer service representatives can experience angry and hostile customers who are unhappy with the service provided by the utility. They may receive calls and complaints about high water bills, poor water quality, low or high water pressure, leaks, and a host of other issues customers might experience. These customer service representatives should be trained to be able to appropriately handle customer complaints and when to escalate complaints to their supervisors.

Customer service representatives should remain calm and polite, even if a customer raises their voice and/or gets angry. This is easier said than done. However, it is important to try and diffuse conflict with customers. If a customer is aggressive with an employee of a utility getting angry will only escalate the problem. Instead, it is recommended to listen, listen, and listen. People taking the time to call a utility and complain, want to be heard. Once you have listened to the customer's issue, offer to help. Even if there is not much you can do, the simple offer of wanting to help will go a long way.

Customer service representatives need to be provided with the proper tools to be able to adequately address customer concerns. Access to customer account information is important as well as a list of staff that the representative can refer or transfer customers to. For example, if a customer is complaining or has questions about the quality of their water, there should be staff within the organization that are able to answer questions and provide answers to customers. Therefore, properly trained staff is an important aspect of public relations and good customer service.

Media

The general rule most water utility workers should follow when it comes to talking with anyone from the media is, *don't do it*. There are too many opportunities for being misquoted and it can be embarrassing to see incorrect information in print, on the radio or television. Water utilities should have a designated media spokesperson to handle all questions and interviews from reporters. However, oftentimes, the front line workers are the first people on the scene and might be approached by reporters. If this happens, workers should give very brief and factual information about what they are doing and that is all. For example, if crews are responding to a water main break that is all the information the workers should offer. They can explain what they are doing and why they are at the location. However, they should avoid speculating as to the cause of the problem or how long they will be at the work location. They should let reporters know they are not qualified to go into more detail and that a supervisor or media representative will arrive on site soon.

Larger organizations can have designated public relations departments and spokespeople, commonly public information officers. In smaller utilities, middle or upper management staff is typically the designated spokesperson. Regardless of the spokesperson they should speak in facts only and never speculate.

Communication

It is important for a utility to properly communicate with its customers and the community as a whole. General communication about the service provided by the utility is important to convey to customers. Informing customers about changes in their water rates, conservation information, how to pay or where to pay water bills, or things such as business hours are all important items to communicate. In addition, it is important to properly notify customers and the general public whenever there's going to be work performed or water outages.

Strategic communication planning is also important. It is important to properly plan and relay information about changes in regulations, which can affect customers, changes in water quality or service reliability, and meet the public's expectations. There are four steps to successful communication planning. These include understanding the message, identifying the audience who will receive the communication, deciding on the type of communication, and the strategic planning of the dissemination of the communication.

It is important to establish a good working relationship with the local media. Working directly with reporters and writers for local newspapers and news media who typically write and report on environmental and utility-related issues is suggested. Working with the local media provides a means to open and honest dialog and the ability to help frame the stories they cover.

Public relations representatives should be accessible for comments regardless if the story is positive or negative. Access to subject matter experts should also be provided. Many times a story is about a topic involving issues of a complex nature. The subject matter experts should be available for interviews. However, they should also be able to explain complex subject matter in non-technical and understandable terms.

Public Media Events

Often times a utility will host a variety of public events. These events should be designed to provide valuable information and educate the participants about the event. These events can be joint events with other local agencies and organizations. They are typically intended to create public involvement and participation.

It is important to properly advertise the events and host in a location with ample space. All public events should be held in locations convenient to the public, have plenty of parking, and access to restrooms. A public event is designed to create a positive and informative perception of the local community.

While it is not necessary, utilities often have free items to hand out to the visiting public. If the event is a water conservation event, the utility may offer free low flow showerheads or other water-saving devices. If the event is about drinking water quality, free sample water testing kits are sometimes offered. Regardless of the event, free “trinkets” with the utilities logo or name are good ways to publicize the agency.

Emergency Information

No one looks forward to a crisis or emergency. However, all water utilities should be prepared to properly respond to and notify their customers in the case of one of these events. An emergency can be associated with a large water main break where traffic is disrupted and water service is lost to several customers to a major catastrophe where water service is lost to thousands of customers. Regardless of the extent of the emergency, the utility needs to be properly prepared.

In addition to operational planning of how a utility will respond to water quality and operational issues, a utility needs to have proper public relations planning and preparation. Some media notifications are required by regulations. For example, if a utility has a Tier 1 water quality violation, they must notify all of their customer within twenty-four (24) hours. In these situations, it is important not to waste any time. Therefore, it is important for the public relations team to prepare ahead of time. In these situations, if the utility has developed a good working relationship with the media, disseminating information is easier. It is important to know all the media outlets in the utilities service area, including but not limited to newspapers, radio stations, and television stations.

Interviews

When possible, interviews should be conducted with public relations personnel or by knowledgeable staff. There are things you definitely don’t want to say during an interview and there are strategies for giving a successful interview.

One common mistake by interviewees is not listening to the interviewer’s question. You should always take your time before answering a question and listen carefully to what is being asked. If the interview is live radio or television, be sure to speak clearly and try to avoid using acronyms and too technical details. An interviewee should always assume they are providing information to an uninformed audience. Keeping things to basic grade level responses can be effective. Always look at the person (reporter) interviewing you and try and not look at the camera.

Whether in print, audio, or visual media, the interviewee should try and disseminate information that is factual and stands on its own merit. Sometimes interviewers paraphrase information and you want to avoid any misinterpretation. In any print media, in-depth detailed information is generally acceptable. The reader has the opportunity to reread statements if they do not understand something. However, it is still important to provide facts and not opinions.

Sample Questions

1. Which one of the following is not an example where utility workers are exposed to the public?
    1. Meter reading
    2. Public Meetings
    3. Accounting
    4. Vehicle Operation
2. What would be a common mistake in a public relations interview?
    1. Not listening to the interviewer's question
    2. Answering a question specifically
    3. Looking at the person conducting the interview
    4. Disseminate factual information
3. In larger organizations, it is common to have _____ act as the organization's public spokesperson.
    1. Middle Manager
    2. Public Information Officer
    3. Customer Service Representative
    4. Consultants
4. Operations and Maintenance workers typically have frequent contact with the public.

1. True
2. False

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7.1: Conventional Treatment Review

Learning Outcomes

- Describe the difference between wastewater, stormwater, and combined collection systems
- Understand the general treatment process of wastewater
- Compare and contrast the different stages of wastewater treatment

Wastewater Collection

The wastewater collection system is the network of pipes that convey the wastewater from households and business to a wastewater treatment facility. Each customer will have a lateral connected to the main sewer lines. In order to keep sediment from settling out in the collection system and causing a blockage, the pipe is sloped to ensure a velocity of 2 ft/sec. A majority of the system will utilize the slope of the pipe and gravity so the water travels downhill. However, that is not always feasible and when needed a lift station will be installed. The lift station is comprised of a wet well where the wastewater is collected and pumps the water to a higher elevation where it can then resume to flow by gravity. The portion of the pressure pipe that is connected to the lift station is called a force main. The force main is always under pressure and the wastewater completely fills the pipe. Where a gravity sewer has minimal pressure and under normal conditions only about ⅓ of the pipe is filled with wastewater.

There are three different types of sewer systems; sanitary, stormwater, and combined. Sanitary sewer systems only convey wastewater that was derived from sanitary sources. This includes wastewater from household toilets, showers, and dishwashers, as well as industrial sources of wastewater from manufacturing processes. Sanitary sewers differ from stormwater sewers in that they contain fecal matter from human waste. It's paramount that these wastes are conveyed to a wastewater treatment facility so they can be removed and stabilized to protect public health and the environment.

Stormwater sewers are a network of pipes that collect only stormwater runoff and direct the flow to a nearby waterbody or the ocean. While stormwater does have a direct connection to human or animal waste, it is considered less harmful and can be discharged without treatment. However, it's important to understand that stormwater is by no means "fresh water". Stormwater can have large amounts of trash, plant material, silt gravel, oil & grease. There are even fairly high amounts of harmful bacteria from animal wastes. The theory is that during storm events there is a significant amount of water flowing through these systems that these contaminants become diluted and are not as concentrated. This theory is constantly being challenged and stormwater is now being seen as another water source that can be treated and even beneficially reused.

A combined sewer is a network of pipes that conveys both sanitary wastes as well as stormwater. This can be beneficial during dry weather flows where there is minimal stormwater. The stormwater that does exist is sent to a wastewater treatment facility where harmful contaminants are removed prior to discharge to a waterbody. However, combined sewer systems can be overwhelmed during storm events. Systems that have older infrastructure which has not been upgraded to deal with larger populations and storm events are especially vulnerable. When this happens, instead of only diluted stormwater being sent to a waterbody, sewage containing high amounts of fecal matter from the sanitary sewer is also discharged. This can cause increased pollution to the waterbody.

Preliminary Treatment

Preliminary treatment is the first step in treating raw wastewater. When the wastewater first enters the wastewater treatment facility there are a lot of nuisance materials that have found their way into the collection system. Items such as large rags, bottles, tree branches, and numerous other nuisance items can be found in the influent to the treatment facility. These large items can cause damage to downstream pumps, take up valuable space in settling tanks, and can be hazardous to other mechanical equipment needed in the treatment process. So the first, or preliminary step is to remove these large items.

Methods used in preliminary treatment include screening, communition, and grit removal. A wastewater treatment facility may use one or all of these methods to handle the large items that may enter the treatment facility. Bar screens are capable of removing items that are larger than the spacing between the bars. For example, a ¾" bar screen will hold back any debris that is larger than ¾" and anything smaller will pass through it. Common items that are removed in this preliminary treatment step are rags, roots,

large rocks and aggregate, bottles, cans, and numerous other large objects that can make their way into the wastewater collection system.

An alternative to screen these large debris items is to shred or grind them. A comminutor is a device that sits inside the channel where wastewater is flowing into the treatment facility. The comminutor will grind the large debris items, turning them into smaller items. Communitors are designed to produce a solid size of a certain diameter. By breaking up the debris into smaller diameters, the downstream pumps and equipment will not be as impacted.

Smaller inorganic solids, such as coffee grounds, eggshells, sand, silt, and gravel are collectively called grit. Grit must be removed because it will cause excessive wear on plant equipment such as the impeller of a pump. Also, this inorganic material can settle in the subsequent treatment process and take up valuable space in tanks which decreases plant efficiency and can inhibit further treatment. While most gritty materials are inorganic, large organic solids such as corn kernels and other food waste may also be removed. There are several methods in removing grit. One common method is an aerated grit chamber. Aerated grit chambers will have air piped to diffusers at the bottom of the tank. The addition of air in the tank creates a rolling action of solids which helps keep the lighter organic solids in suspension while the heavier grit material is directed to the bottom of the tank. In aerated grit chambers, the amount of air sent to the chamber is a critical operating parameter. If too much air is supplied, then the grit material will stay in suspension and not be removed. If not enough air is supplied, then the lighter organic material can settle out.

Primary Treatment

The primary goal of sedimentation is to remove the settleable solids. A well-operated primary sedimentation tank can remove around 90% - 95% of settleable solids. There will also be a reduction in total suspended solids and a slight reduction in BOD_5. The sedimentation process works because these solids are heavier, relative to the wastewater, and will, therefore, settle to the bottom of the tank. Another phenomenon that occurs in the sedimentation process is that as the solids collect at the bottom of the tank, the weight of the solids begin to compact and compress. This causes the solids to be thickened and have slightly less water content. Detention time, or how long the wastewater takes to travel through the tank, is a critical design parameter of primary sedimentation tanks. There needs to be enough time to allow the solids to settle but not so much time that the solids start to decompose. Decomposition will cause gas bubbles to form which can hinder solids settling and create foul odors.

Primary sedimentation tanks can either be circular or rectangular. Regardless of the configuration, the tanks will have similar components. At the inlet structure where the wastewater enters the tank, the velocity is typically high in order to prevent solids settling in the piping network as the wastewater comes from the preliminary unit process to the primary tank. Once in the primary tank, the velocity must be slowed. To accomplish this there will be some type of diffuser at the inlet end that will redirect flow and prevent short-circuiting. The dimensions of the primary sedimentation tank must be able to accommodate the flow of wastewater but must also reduce the velocity.

In addition to settling solids, primary tanks will also remove floatables. Typically, these floatables are classified as fats, oils, and grease (FOG). A rectangular primary tank will have flights that span the width of the tank. They are connected by a chain that is motor driven to slowly move with the flow of wastewater. The flights provide several functions. They prevent short-circuiting of material on the surface, they convey the FOG on the surface to a collection trough at the end of the tank, and they convey the settled solids to a hopper at the beginning of the tank. Circular tanks have a similar mechanism called a swing arm that provides the same functions.

Once the solids have settled to the bottom of the tank, they are conveyed to a hopper in the tank. Circular tanks are typically coned at the bottom so the solids build up in the center. Rectangular tanks have a hopper at the front of the tank and the flights convey the solids there. The solids must be removed from the tank periodically so they do not cause adverse conditions. There is organic matter in the solids and if it starts to decompose, it will create foul odors and gas bubbles that will hinder other solids from settling. Typically incoming wastewater is around 1% solids. Due to the sedimentation process, the percent solids concentration in the sedimentation tanks increases to around 4% to 8%. Due to the high amounts of solids, a standard pump cannot be used. Instead, special pumps including a progressive cavity type pump or a stator/rotor pump are commonly used.

Secondary Treatment

Secondary treatment methods typically involved some form of biological treatment to further reduce the amount of BOD_5. Trickling filters and activated sludge treatment plants will utilize a secondary clarifier to separate the treated wastewater from the

microorganisms of the biological treatment step.

A key component of a trickling filter is the recirculation of the clarified effluent back to the trickling filter. Water from the secondary clarifiers has already gone through the biological treatment process of the trickling filter and has a lower amount of BOD_5. By recirculating this treated water with the incoming wastewater, it will dilute the incoming BOD_5. Recirculation will also be able to control the dissolved oxygen level in the trickling filters.

A secondary clarifier is also a key component of the activated sludge system. Not only does it separate out the microorganisms from the now treated wastewater, but it will also concentrate them through the sedimentation process. A secondary clarifier works exactly as discussed previously in primary sedimentation. The only difference is that in a primary sedimentation tank the main goal is to remove unwanted solids. In a secondary sedimentation tank, the goal is to concentrate the Mixed Liquor Suspended Solids(MLSS) so it can be returned to the aeration tanks.

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7.2: Biological Treatment Overview

Learning Outcomes

- Understand which environments the different types of bacteria thrive
- Explain how activated sludge treatment process is more efficient than other methods
- Describe the nitrogen cycle and how it's used to remove nitrogen from wastewater

Aerobic, Facultative, and Anaerobic Organisms

Aerobic bacteria require an environment that has free dissolved oxygen. The bacteria use that oxygen for respiration to live. They feed on the organic matter and other nutrients in the wastewater. As the bacteria consume these materials, they are removed from the wastewater, making it less contaminated. The byproduct of the aerobic decomposition of organic matter is carbon dioxide (CO_2).

Anaerobic bacteria require an environment that has no free or combined oxygen. Free oxygen is when there is excess oxygen dissolved in the water and is available as O_2. Combined oxygen is when the oxygen molecule is bound to another element. A common example of combined oxygen in wastewater is nitrate (NO_3). In anaerobic conditions, there is absolutely no oxygen available to the bacteria for respiration. The byproduct of anaerobic decomposition is methane gas.

Facultative bacteria have the ability to thrive in either aerobic or anaerobic conditions. While they prefer aerobic conditions, they have the ability to adapt when no oxygen is available and survive in anaerobic conditions.

Activated Sludge Treatment

The activated sludge process was developed by two scientists, Edward Arden and William Lockett, in England in 1914. Their experiments showed that by taking the microorganisms that were already established from aerobic decomposition and introducing them to fresh wastewater, it would speed up the decomposition of the new organic wastes. Instead of relying on the 30 to 45 days it would normally take to breakdown these organic wastes, the activated sludge process can achieve the same level of treatment in less than one day. This means that an activated sludge wastewater treatment system will be able to handle higher flow rates and higher organic loading than pond treatment or fixed film systems.

Activated sludge treatment systems consist of an aeration tank followed by a secondary clarifier. These two tanks each provide a unique function but also work together to reduce the BOD_5 in the wastewater. In the aeration tanks, oxygen is diffused into the water so the bacteria can survive in aerobic conditions. The air diffusers also keep the bacteria in suspension so it can continually be in contact with the incoming wastewater. In the secondary clarifiers, the bacteria will be separated from the treated wastewater. The treated wastewater will continue on to the tertiary treatment step. A majority of the settled bacteria will be sent back to the beginning of the aeration tanks. In the clarifier, the bacteria were stressed due to a lack of food and oxygen. They begin to undergo endogenous respiration and are so starved they begin to breakdown their own cells to survive. When the stressed bacteria are reintroduced into the aeration tanks they are now in an environment with plenty of oxygen and food. These bacteria will now quickly begin to breakdown the organic wastes in the wastewater much faster than before.

Return Activated Sludge

The return activated sludge, or RAS, are the bacteria that have settled in the secondary clarifier and are being sent back to the aeration tank. The rate of speed at which the microorganisms are returned is something that the operator can control.

Waste Activated Sludge

Like the other biological process discussed, the bacteria, overtime will grow and their population will increase. To control the amount of bacteria in the system, a portion of the RAS will not be returned to the aeration tank but instead is directed to a separate solids handling treatment unit. Typically, these solids are combined with the settled solids from the primary sedimentation tanks and sent to an anaerobic digester.

Food to Microorganism Ratio

A key parameter to determine the effectiveness of activated sludge systems is the food to microorganism ratio, or F/M. The food is determined by the amount of BOD_5 in the incoming wastewater and the amount of microorganisms available to consume that food is determined by the amount of MLSS in the aeration tanks. Since it's a ratio, the units of these two laboratory results must be the same. The mg/L concentration of the laboratory results is converted into a mass with the units of lbs. While each treatment plant will determine which level of F/M has historically given effective treatment, a common range is around 0.2 to 0.5.

Mean Cell Residence Time

How much bacteria remains in the system and how much is wasted can be determined by the mean cell residence time or MCRT. The MCRT is a theoretical calculation of the average time a single bacteria will stay within the activated sludge system before being wasted. To calculate the MCRT an operator would determine how many pounds of MLSS there is in the system and divide that by how many pounds were removed from the system; typically over a 24 hour period.

Review of Basic Principles of Operation

The F/M ratio, MCRT, RAS, WAS, and dissolved oxygen concentrations can all be manipulated by the operators of a wastewater treatment facility to optimize the effectiveness of treatment. In fact, those parameters are the only things that can be easily controlled. The amount of incoming wastewater is going to be what it is and it will fluctuate throughout a 24 hour period as well as vary by season. The incoming BOD_5 loading is what it's going to be and the operators can't control it.

If the F/M is too low, it means that there are more bacteria than what is needed to consume the available food. This is inefficient because supplying oxygen to the bacteria requires a significant amount of energy. If there is too much bacteria in the system and not enough food, the bacteria will still be consuming oxygen but the BOD_5 won't be further reduced. To increase the F/M ratio operators can only control the "M" portion of the equation. By increasing the wasting rate, the MLSS will be reduced causing the F/M ratio to increase.

If the F/M ratio is high, then there is not enough bacteria to consume the large amounts of incoming BOD_5. This will lead to poor treatment and the effluent will have a high BOD_5 concentration. Operators cannot decrease the amount of BOD_5 coming into the plant so they will have to increase the amount of MLSS in the system. They can do this by decreasing or stopping the wasting rate. Decreasing the wasting rate will cause the MLSS to increase and the F/M ratio will be reduced.

The MCRT is another process control tool that is used to determine the wasting rate by manipulating the equation to calculate the MCRT. Often the desired MCRT rate is determined by the design of the treatment facility or from historical data. By taking the pounds of MLSS in the system and dividing it by the desired MCRT, you will determine what the wasting rate needs to be to achieve that MCRT. However, the MCRT and F/M methods for determining the wasting rate can often conflict with each other. Operators need to look at the changes in MCRT and F/M over time and make minor adjustments to the process so the bacteria aren't "shocked".

Toxic Substances

Toxic substances can be detrimental to the efficacy of activated sludge systems. Activated sludge treatment relies on living bacteria to feed off the organic wastes, thus removing it from the wastewater. If toxic substances are introduced to the activated sludge system, the bacteria can die off. Without a significant population of bacteria, the organic wastes will not be consumed and the effluent of the treatment plant will have high amounts of BOD_5.

Toxic substances can include heavy metals, pesticides, high concentrations of salts, cyanide, PCBs, and other chemicals. These toxic substances, if introduced in the wastewater collection system, will be sent to the wastewater treatment facility and can destroy the population of bacteria that treats organic wastes. To prevent toxic substances from entering the collection system, municipalities will have pre-treatment programs. These programs will have a public outreach component to inform the community of its wastewater infrastructure and the harm it can cause if chemicals and other toxic materials are dumped down the drain. In addition to household waste, pre-treatment programs will also work closely with manufacturing and processing facilities to ensure they are not discharging toxic materials into the wastewater collection system.

Pure Oxygen Treatment

Many treatment plants utilize air blowers or surface aerators to provide oxygen to the bacteria in the aeration tanks. These systems provide oxygen that's in the atmosphere and diffuses it into the wastewater in the tank. One drawback of these methods is that our atmosphere is only around 21% oxygen. A majority of the atmosphere is nitrogen. Having a pure oxygen system is more efficient because the oxygen concentrations can be as high as 99% pure oxygen. However, there are many drawbacks to pure oxygen plants. First off, extra equipment will be needed to create pure oxygen. This equipment will have electrical, maintenance, and operational costs associated with it. Secondly, pure oxygen can be extremely hazardous to deal with. At higher purities oxygen can be explosive. Extra caution must be taken to ensure no sparks, oil, or other contaminants are near the pure oxygen generators.

Enhanced Biological Treatment

If the treated wastewater leaving a treatment facility is being discharged into an impaired waterbody, the NPDES permit will most likely have limits on ammonia, nitrogen, and phosphorus. These nutrients at high concentrations can cause eutrophication in a waterbody. Eutrophication occurs when there is an excess of nutrients in a waterbody that spurs algae growth. The algae population will become out of control and consume dissolved oxygen in the waterbody to the point where fish and other aquatic life can not survive. Nitrogen and phosphorus can be removed from the treatment plant by utilizing biological nutrient removal (BNR) processes.

Nitrogen Removal

Nitrogen can be removed from the wastewater by making slight modifications to the activated sludge treatment process. Nitrogen enters the treatment plant as ammonia (NH_3). In the aeration tank, aerobic bacteria will nitrify this ammonia to create nitrite (NO_2) and nitrate (NO_3). In a well-operated plant, a majority of the nitrogen formed is nitrate. The wastewater is then conveyed to an anoxic tank. Anoxic means that the environment where the bacteria are living contains no free dissolved oxygen but there is combined oxygen. The combined oxygen is due to the NO_3 sent to the tank from the aeration tanks. In this anoxic condition facultative bacteria break apart the NO_3 bond and use the oxygen for respiration. The nitrogen molecules combine to form nitrogen gas (N_2) which is vented back to the atmosphere. Recall that 78% of the Earth's atmosphere is N_2 gas.

The anoxic tanks in a BNR system can be placed in a number of different configurations. Since the nitrification process is required first to create the NO_3 one would expect to have the anoxic tanks following the aeration tanks. While there are treatment plants that operate in this manner, it may require additional chemicals as the denitrification process requires a certain amount of carbon for the bacteria to feed off of. The amount of carbon available in the wastewater can be measured by the $CBOD_5$ or carbonaceous biochemical oxygen demand. At the end of the aeration tank, the aerobic bacteria have significantly reduced the amount of $CBOD_5$ in the wastewater. A process alternative is having the anoxic tank prior to the aeration tank. The wastewater at the end of the aeration tank that has been nitrified is then recycled back to the anoxic tank. Here, fresh wastewater with high amounts of $CBOD_5$ is mixed with the NO_3 and the conditions will be just right for denitrification to occur. This will also lessen the aeration demands since some of the $CBOD_5$ will be reduced in the anoxic tanks before it enters the aeration tank. One drawback is that not all of the nitrate will be captured and sent back to the anoxic tank. Therefore, another process set up is to have alternating zones of anoxic, aerobic, anoxic, aerobic.

Phosphorus

Phosphorus can also be reduced in a well-operated wastewater treatment facility. The amount of phosphorus coming into the facility will determine the level of treatment required. Much of the phosphorus can be removed during the primary and secondary sedimentation processes. If more phosphorus removal is required then treatment plants can utilize enhanced biological phosphorus removal (EBPR). EBPR uses polyphosphate accumulating bacteria (PAO) that, under anaerobic conditions, will accumulate phosphorus in their cells and remove it from the wastewater. A typical configuration of an EBPR process is the RAS and influent wastewater will be mixed in an anaerobic tank where phosphorus reduction occurs. Then the wastewater enters the anoxic tank where the RAS, influent wastewater, and nitrified effluent from the aeration tanks create the ideal environment for denitrification. Then everything is conveyed to the aeration tanks where free dissolved air is added. The incoming ammonia is nitrified to NO_3 and the remaining BOD_5 is reduced.

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7.3: Tertiary Treatment

Learning Outcomes

- Explain which water quality characteristics tertiary treatment is targeted to remove
- Describe the breakpoint chlorination curve
- Understand how the mixture of ammonia and chlorine creates chloramines
- Compare different methods of wastewater disinfection

Filtration

After the wastewater leaves the secondary clarifiers, filtration is commonly used to remove fine particles that were carried over in the clarifier. Conventional filtration methods use sand and anthracite coal to filter the treated wastewater. The sand and anthracite coal are referred to as media. The filtration process works by gravity. If needed, the water will be pumped to a higher elevation, then the gravity will force the water through the media. The media creates small voids between the grains of sand and coal. These voids are small enough that water molecules will pass through but the solids will be trapped. Underneath the media, there is an underdrain system that will collect the treated water and convey it to the next treatment process. Eventually, the media will be clogged with solids and needed to be backwashed. During a backwash cycle, the filter is isolated so water is entering the filter. Air is then piped into the filter that agitates the media and separates the solids from the media. The air is then turned off and water is pumped from the bottom of the tank and is directed towards a backwash drain. The media is typically heavier than the solids being removed so the media will settle back to the bottom of the filter while the solids are carried with the water into the backwash drain. When the backwash cycle is complete the filter is put back online.

More advanced filtration methods include membrane filtration such as microfiltration and reverse osmosis. These filtration methods work in a similar manner as sand filters but are able to filter smaller sizes. The membranes are manufactured and can have very small pores. Membrane filtration is able to remove contaminants such as arsenic, asbestos, atrazine, fluoride, lead, mercury, nitrate, radium, benzene, and other unwanted chemicals. With the very small micro-holes in the membrane, gravity does not provide enough pressure to force the water through the membrane. Therefore, the water is pumped through the membrane filtration system which increases the pressure.

Disinfection

Disinfection is a critical treatment step to ensure that the wastewater treatment facility is protecting public health and the environment. Pathogenic organisms, such as *E. coli*, *Vibrio cholerae*, and *Salmonella*, can spread disease to aquatic life and humans. There are other bacteria, microorganisms, and viruses that can be present in wastewater. The disinfection process will limit the presence of pathogens. It's important to note that the disinfection process is not the same as sterilization. Sterilization will remove all of the bacteria but comes at an extremely high cost that is uneconomical considering the volume of wastewater that must be treated. However, disinfection is still highly effective at limiting pathogens to a level that is acceptable to protect public health and the environment.

Chlorination and Chloramination

Chlorine is the most common form of disinfectant in the United States and has been in use for over one hundred years in the water and wastewater industry. Chlorine is commercially available as gaseous chlorine or in the liquid form as sodium hypochlorite. Gaseous chlorine is purer, so less gas is needed for disinfection. However, because of the high purity, gaseous chlorine can be very dangerous to work around. Treatment facilities that use gaseous chlorine have to comply with rigorous safety training and purchasing regulations. Sodium hypochlorite is commonly sold with a chlorine concentration of 12.5%. Safety precautions must still be used when handling sodium hypochlorite but is a lot safer and easier to work with than gaseous chlorine.

Chlorination works due to the fact that chlorine is highly reactive. When chlorine is added to the wastewater it begins to react with all of the chemicals and organic matter in the wastewater. This is known as demand. Once the chlorine demand is met the extra chlorine added will begin to react with the water creating hypochlorous and hydrochloric acid. Both of these chemicals will be created and the amount of each will depend on the pH of the water.

Hypochlorous acid is more efficient at disinfection and is more prominent at lower pH values. Typical wastewater has a pH of around 6.5 - 7.5 and hypochlorous is the predominant acid. If the pH is above 7.5, treatment facilities may look into adding chemicals to reduce the pH to increase the efficacy of disinfection. When operating chlorination in this manner it's called free chlorine. Enough chlorine has been added to satisfy the demand and the residual is measured as free chlorine. Free chlorine is highly reactive and is a strong disinfectant. Because it's highly reactive, the residual does not persist for a long time.

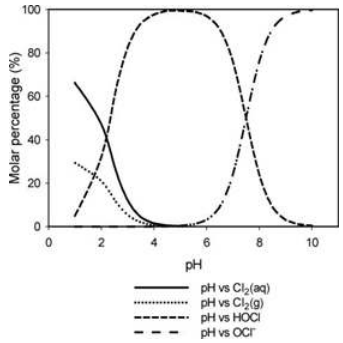


Figure **7.3.1**: Title: Chlorination Curve - Description: pH values of chlorine on graph. Image by L. Wang, Ph.D., M. Bassiri, PhD, R. Najafi, Ph.D., K. Najafi, MD, J. Yang, BS, B. Khosrovi, Ph.D., W. Hwong, BS, E. Barati, BS, B. Belisle, Ph.D., C. Cereli, MS, and M.C. Robson, MD is licensed under CC BY

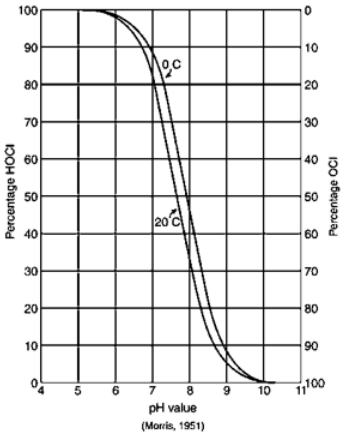


Figure **7.3.2**

An alternative to chlorination is chloramination. Chloramination is a combined chlorine compound and is created by mixing chlorine and ammonia. Depending on the ratio of chlorine to ammonia, the chloramines created are monochloramine, dichloramine, and trichloramine. Monochloramine is the desired form as it provides a better disinfectant. A ratio of five parts chlorine to one part ammonia will typically yield monochloramine. Chloramination provides some benefits to chlorination. Less chlorine is used since all of the demand doesn't have to be met. Free chlorine has the potential of creating disinfection-by-products. Since chloramination is not as reactive, there is less chance of creating disinfection-by-products. One disadvantage of chloramination is that, since it's not as reactive as free chlorine, it takes a longer time to achieve the same level of disinfection as free chlorine.

The relationship between the different chloramines and free chlorine is best understood by examining the breakpoint chlorination curve.

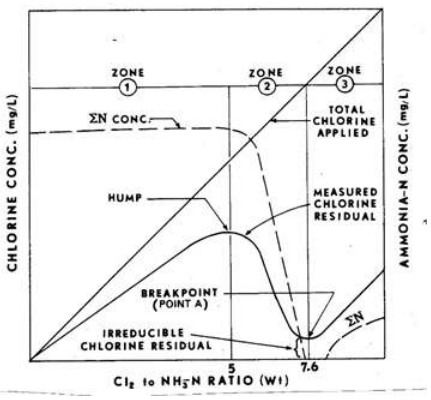


Figure 7.3.3: Title: Graph of breakpoint chlorination - Description: Breakpoint Chlorination Curve. © State of New South Wales NSW Ministry of Health. For current information go to www.health.nsw.gov.au. – Image licensed under CC BY 4.0

In the first part of the breakpoint curve, chlorine is applied but no residual is seen. This is because there is an excess demand for organic matter and other chemicals. Once that initial demand has been met, more chlorine is applied and a combined residual is formed. In this second zone, ammonia begins to react with the chlorine to create chloramines. In this early stage, monochloramine is the predominant form. If the treatment plant is utilizing chloramination, then ammonia will be added to purposefully stay in this zone. As more chlorine is applied, the ratio of chlorine to ammonia increases. In the third zone, the chlorine residual will decrease as the extra chlorine further reacts with the ammonia creating dichloramine and trichloramine. Once the chlorine has reacted with all of the ammonia, it reaches a breakpoint. After the breakpoint, only free chlorine is available.

Dechlorination

Once the wastewater has been properly disinfected the chlorine residual must be neutralized. Chlorine can be harmful to aquatic life and the environment. Since most wastewater is discharged into a waterbody it must be dechlorinated. There are two common chemicals used for dechlorination, sulfur dioxide, and sodium bisulfite. Sulfur dioxide is available in its gaseous form and has a lot of the same equipment and safety regulations requirements as gaseous chlorine. Therefore, if a treatment plant uses gaseous chlorine for disinfection, it will most likely be using sulfur dioxide for dechlorination. Sodium bisulfite is available in its liquid form is commonly used at treatment facilities that use sodium hypochlorite for disinfection.

UV disinfection

Chlorine is not the only method that can be used for disinfecting pathogens in wastewater. Ultraviolet (UV) light is becoming a popular alternative. UV disinfection is a physical process rather than a chemical process, like chlorination and chloramination. Because no chemicals are used, there is no residual effect that could be harmful to public health and the environment. UV disinfection works by the intensity of the UV light that disrupts the cell walls of the pathogens. Because the light needs to come in contact with the bacteria, it is critical that the turbidity of the water being disinfected is low. If there is too much turbidity in the wastewater, the pathogens will be shielded by the material causing the high turbidity.

Ozonation

Ozonation is more widely used in Europe and Asia. Ozone is three oxygen molecules bonded together, O_3. Ozone is highly reactive and must be generated onsite and directly mixed in with the wastewater being disinfected. Ozone is made by taking atmospheric oxygen, O_2, and using electricity to break apart the bond between the two oxygen molecules. The individual oxygen molecules then combine with existing O_2 molecules to create O_3. When the O_3 reacts with the wastewater it will create hydrogen peroxide (H_2O_2) and hydroxyl (OH). These compounds are highly reactive and will disinfect the pathogenic organisms in the wastewater.

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7.4: Water Recycling

Learning Outcomes

- Understand the requirements of Title 22 for recycled water
- Know what level of treatment is needed for different recycled water uses

Discharge

By now the wastewater has been completely treated. By undergoing preliminary, primary, biological, secondary, tertiary, and disinfection treatment the water should now meet the rigorous requirements of a National Pollutant Discharge Elimination System (NPDES) permit and be able to discharge in a nearby waterbody. Often, the addition of this treated water provides a riparian habitat to many aquatic species. However, a lot of time, money, and energy were put into treating this water. If advanced treatment methods like BNR and membrane filtration were utilized, then the water can be used for other beneficial reuses.

Non-Potable Reuse & Reclamation

To reuse treated wastewater for non-potable reuse, meaning it cannot be consumed, it must comply with Title 22 of the California Code of Regulations. Title 22 outlines what level of treatment is required for different types of reuse applications. There are four different types of classifications of water under Title 22, undisinfected secondary recycled water, disinfected secondary-23 recycled water, disinfected secondary-2.2 recycled water, and disinfected tertiary recycled water. Undisinfected secondary recycled water is the lowest level of treatment and therefore has limited application uses. It can be used for orchards or vineyards where the recycled water does not come into contact with the edible portion of the crop. It can also be used for ornamental nursery stock and non-food-bearing trees as longs as no water is applied to the plants for 14 days prior to harvesting, retail sale, or allowing access by the general public.

Disinfected secondary 23 and 2.2 differ in the level of disinfection. The 23 and 2.2 are referring to results from the Most Probable Number (MPN) test used to determine the effectiveness of the disinfectant. An MPN of 2.2 is the lowest level of detection for the test and therefore a lower chance of pathogenic organisms existing in the sample. As the wastewater goes through higher levels of treatment it can be used for more non-restrictive uses. Disinfected secondary-23 recycled water can be used for irrigation purposes but only in areas where there is a limited chance of the water coming in contact with the general public. For example, it can be used to water freeway landscaping, cemeteries, and golf courses with restricted access. Disinfected secondary 2.2 recycled water can be used for irrigation of food crops where the edible portion is produced above ground and not contacted by the recycled water.

Disinfected tertiary recycled water is the highest level of treatment defined by Title 22 and can be used for pretty much any type of irrigation. It can be used on food crops where the recycled water does come into contact with the edible portion of the crop. It can be used to irrigate parks, playgrounds, schoolyards, and residential landscaping. Disinfected tertiary recycled water can also be used for other purposes such as flushing toilets, industrial processes, fire fighting, decorative fountains, and car washes.

Indirect Potable Reuse

Title 22 also regulates using recycled water for indirect potable reuse. It outlines two ways to do this, either by surface application or subsurface application of groundwater replenishment. Surface application is when the recycled water is sent to a percolation basin. The water is forced by gravity through the voids in the soil which adds an extra layer of filtration as the water enters a groundwater aquifer. The water is then pumped out of the aquifer and sent to a water treatment facility where it is further treated and ultimately is used for potable water.

Subsurface application is when the water is pumped directly from the treatment plant discharge to the groundwater aquifer. Since this method does have the added treatment benefit of the water percolating through the soil, additional advanced treatment methods are needed at the wastewater treatment facility. The tertiary treated wastewater will typically go through reverse osmosis membrane filtration prior to being injected into the groundwater aquifer.

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7.5: Solids Handling Processes

Learning Outcomes

- Understand where solids from the wastewater treatment are generated
- Compare the different ways to thicken wastewater solids

Biosolids

For many years the solids leaving the wastewater treatment plant were referred to as sludge. The term sludge is still used but typically refers to the untreated raw sludge leaving the primary clarifiers or the waste activated sludge (WAS) leaving the secondary clarifiers. However, once the sludge has been treated, it can be converted to biosolids. Biosolids can be used for many beneficial purposes such as compost, fertilizer, and landfill cover. In the liquid portion of wastewater treatment, the goal was reduction of organic matter. Much of that organic matter ends up in the sludge. In biosolids, it's that organic matter that can be used for composting. There is also an ample amount of nitrogen and phosphorus which are key components in fertilizer. That organic matter has a lot of potential energy. During the digestion treatment stages, this energy can be captured and used to power other portions of the treatment process.

Primary Treatment Sludge Thickening

Gravity thickening is commonly used to thicken primary solids. The purpose of thickening is to reduce the water content. This makes a more concentrated sludge that will require smaller digesters in the next treatment stage. Gravity thickening works very similarly to primary sedimentation. However, instead of starting with raw wastewater we are starting with concentrated sludge. In the primary sedimentation tank, the raw wastewater will increase from around 1% solids to up to between 4% and 6% solids. Starting with the higher percent solids concentration and putting it through a similar treatment process can further increase the solids concentration to 10% or greater. By increasing the percent solids the sludge becomes thicker. It's getting thicker because the water is being removed.

Similar to the sedimentation process gravity thickeners rely on the heavy solids in the sludge to settle by gravity to the bottom of the thickener. As the solids settle the water will be separated out. The tank will become stratified with larger amounts of solids on the bottom of the tank and layer of water with less solids on top. The top layer is referred to as the supernatant and the bottom layer is called subnatant. To optimize the performance of a gravity thickener it's critical to have "fresh" primary sludge. Sludge that is becoming or has already gone septic will not settle as easily as newer sludge. Therefore, controlling the rate of pumping from the primary sedimentation tank to the gravity thickener must be closely watched. If the sludge is going septic in the primary tanks then the pumping rate will need to be increased. This will lower the detention time and keep the sludge from going septic. However, if it's pumped too quickly then the percent solids might be decreased which is also not optimal. Another way to deal with septic sludge is to add chlorine to reduce biological activity.

Secondary Treatment Sludge Thickening

When thickening secondary sludge or a mixture of secondary and primary sludge, a dissolved air flotation thickener (DAFT) is commonly used. A DAFT works by taking a portion of the clear subnatant leaving the DAFT and pressurizes the water with an air compressor. The water is then conveyed back into the DAFT where it is exposed to atmospheric pressure. The difference in pressure causes lots of tiny air bubbles to be released, just like opening a soda bottle. The tiny air bubbles will float to the top of the DAFT. The incoming sludge will not be able to settle to the bottom because of the rising air bubbles. Therefore, the solids remain on the top layer and the bottom layer is clearer water. The solids will be skimmed off and sent to a hopper where it will be pumped to the next stabilization treatment stage. The clearer water on the bottom will be sent back to the headworks to be further treated in the liquid portion of the treatment process.

A DAFT can typically create a solids concentration between 4% and 8%. The return water is pressurized between 40 and 70 psi. A key parameter to a well operated DAFT is the air to solids ratio. A common air to solids ratio is around 0.02 to 0.04. If not enough air is supplied to the tank, the solids will settle to the bottom. Other operational parameters are the speed of the skim arm. Operators should set the speed to slowly skim the thickened sludge into a hopper. If the skim arm speed is set too high it will thin out the solids and reduce the percent solids concentration. There should be about a 1 to 3 foot blanket of thickened sludge on the DAFT.

Polymer is often added to aid the coagulation of solids. This also causes the solids to bind together and make larger particles that will more easily float to the top of the unit.

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7.6: Biosolids Stabilization

Learning Outcomes

- Compare and contrast the various sludge stabilization methods
- Understand the different biological processes to stabilize wastewater solids
- Describe the different types of bacteria used during anaerobic digestion at different temperatures

Sludge Stabilization

Once the solids have been thickened they are ready to be stabilized. At this point, the solids have only been thickened and they are the waste products of the liquid portion of the treatment process. There is a large amount of volatile organic material that needs to be stabilized. Stabilization will also help reduce odors and destroy pathogens. There are several different methods to achieve this. Digestion is the most common but stabilization can also be achieved by adding chemical or thermal stabilization by heating the sludge.

Aerobic Digestion

Aerobic decomposition is very similar to the aeration tanks discussed earlier in the activated sludge systems. The primary and/or secondary sludge is digested aerobically, meaning that aerobic bacteria will break down the organic matter. The digesters can either be rectangular or round. The bacteria are aerobic so air must be applied to the digester.

One major difference between the aeration tank in the activated sludge tanks and the aerobic digester is that there is not a continual supply of fresh BOD_5. In the digester, there is no fresh wastewater coming in only the settled solids. In the digester, the aerobic bacteria will be able to breathe but with no food source, they will undergo endogenous respiration. In this state, the bacteria begin to breakdown their own cell mass and thus reduce the amount of volatile suspended solids. Aerobic digesters will have a longer detention time, typically on the order of 30 days or more. Common volatile solids reduction can be around 45% to 70%.

Anaerobic Digestion

Recall that anaerobic means the environment has no free or combined sources of oxygen. Bacteria must find a different source of respiration. Anaerobic digestion is a two-step biological treatment process. The first step is done by a group of bacteria that breakdown solids to form volatile acids. The second step is another group of bacteria breaking down those volatile acids to form methane, carbon dioxide, and water.

When checking the operation of a digester, pH is a critical parameter. The first step of the digestion process is to create volatile acids. Excessive acids will cause a drop in pH. A pH between 6.6 and 7.6 is considered an acceptable range. If the pH drops below this, that is a sign that there are not enough methane forming bacteria to breakdown the volatile acids. Another way to examine this is by looking at the volatile acid to alkalinity ratio. Large amounts of alkalinity in the sludge will be able to buffer drastic changes in pH. If there isn't enough alkalinity the pH could drop significantly and adversely affect the bacteria in the digester.

Mixing is also an important design and operation requirement. Good mixing will distribute the sludge evenly throughout the tank. This allows the bacteria to come in contact with the raw sludge and aid the digestion process. Proper mixing will also prevent the separation of grit and other inert solids. It will also prevent the development of a scum layer at the top of the digester.

There are three different types of anaerobic digestion based on what the operating temperature of the digester is. They are classified by the type of bacteria that is most abundant at the specified temperature ranges. The most common type is mesophilic, which operates between 85℉ and 100℉. This is the same type of anaerobic digestion that occurs in the human stomach. Psychrophilic digesters will operate between 50℉ and 68℉. The advantage of this type of digester is external heating systems are not needed to raise the temperature. However, at these colder temperatures, the bacteria are not as active. Therefore, psychrophilic digesters will require a longer detention time to achieve stabilization of the solids. Going hotter than mesophilic is thermophilic. These digesters operate between 120℉ and 135℉. At these higher temperatures, a detention time of 5 to 12 days can sufficiently stabilize the solids. However, there is an added cost to heat the sludge to these higher temperatures.

Chemical Stabilization

Chemical stabilization is achieved by adding calcium hydroxide, $Ca(OH)_2$. It is also commonly known as **slaked lime**. Adding the lime will raise the pH of sludge to the point where biological activity is drastically reduced. This is much different from digestion because the organic matter is not reduced. The lime temporarily halts the biological activity and thus stabilizes the sludge. The sludge is then disposed of to a landfill. Chemical stabilization is not as common due to the high costs, regulations, and environmental impacts of handling chemicals.

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7.7: Biosolids Treatment

Learning Outcomes

- Compare and contrast the different methods of biosolids dewatering
- Understand the limits of different biosolids dewatering methods
- Compare the energy and labor requirements of different biosolids dewatering methods

Sludge Dewatering

Sludge dewatering is exactly what it sounds like. At this point, the sludge has been stabilized by reducing the amount of volatile organic material. It's almost ready for disposal which usually means it will need to be transported somewhere. This can be very expensive because the sludge is still mostly water. Dewatering removes a lot of the water and increases the percent of solids. This will make transporting the dewatered biosolids much more cost-effective.

Drying Beds

The simplest and cheapest way to dewater sludge is by drying beds. The sludge is sent to the drying beds where the sun heats it up and evaporates the water. This process can take several weeks or even months to achieve the desired percent solids. Also, the process is dependent on the weather. In colder months it can take even longer. There are some adaptations to increase the process. Some drying beds will be slightly sloped with sand in the middle. There is an underdrain system beneath the sand. With sand beds, the water is being evaporated by the sun but is also being directed towards the sand and filtered through to the underdrain system where it is then sent back to the headworks of the treatment plant. There are also vacuum assisted drying beds. Similar to sand drying beds but instead of relying on gravity for the water to drain a vacuum is created to force the water out. Drying beds are efficient and cost-effective for smaller systems and where land is available.

Belt Presses

A belt filter press consists of two long filters. The sludge will be conveyed in between these two filters and then sent through progressively higher areas of pressure where water is squeezed through the filter and the solids are left behind. The first part of the belt filter press is the gravity zone. Here the digested sludge is mixed with polymer and begins to coagulate the solids. The solids are then conveyed and sandwiched between the other filter. There is then a low-pressure section where water is forced between the filters and removed. The pressure then gradually increases as the filters are rolled through the belt press. This gradual increase allows more and more water to be removed. At the end of the belt press, the two filters separate and the biosolids are scraped off and sent to a conveyor belt. Belt presses can achieve around 13% to 18% solids. Oftentimes belt presses are combined with drying beds to further increase the percent solids.

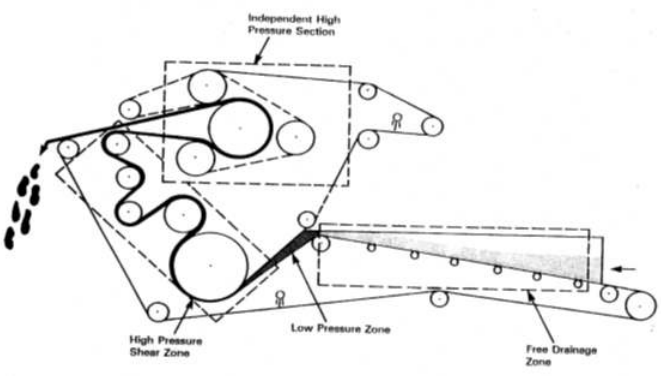


Figure 7.7.1: Filter Press - Image by the EPA is in the public domain

Filter Presses

There are a couple of different types of filter presses. The most common is the plate and frame filter press. The unit consists of a series of filter plates. The plates are forced together with a hydraulic press and sludge is conveyed in between each of the plates. As

the sludge is pumped into the filters the solids are trapped by the filter and the water passes through and is collected in a drain system. As more and more sludge is pumped into the filters the pressure will begin to increase. This extra pressure will cause even more water to be forced through the filters and out of the sludge. When the pressure reaches its maximum the operator will stop feeding sludge to the filters. The plates are then released from the hydraulic press and separated. As the plates separate, the dried biosolids will fall off the filter plates and drop below to either a conveyor belt or oftentimes to the bed of a dump truck. The biosolids will then be sent off for ultimate disposal. A well-operated plate and frame press can achieve a solids concentration of 40% to 50%.

Another type of filter press is vacuum filtration. This consists of a circular drum with a filter material on the outside. The drum is submerged into a trough filled with the digested sludge. The drum slowly rotates while a vacuum is being created inside the drum. The vacuum pulls the water out of the trough. The solids are stuck on the outside of the filter while water is able to filter through and be sent to the drain system. By the time the drum does a full circle, the percent solids has increased significantly and the biosolids are scraped off to a conveyor system where they are sent to a dump truck.

Waste Stream Recycling

The water being removed from the dewatering process needs to be sent back to the liquid portion of the treatment plant to be further treated. However, this water is often very high in ammonia and can overwhelm the bacteria in the activated sludge process. Some treatment plants will slowly pump this water back to the treatment plant so there isn't a large slug of ammonia going through the system. Others will only pump the water back during the night time hours when ammonia coming into the treatment plant is often lower. Some newer technologies will actually treat the water prior to being sent back to the headworks.

Sludge Disposal

Now that the sludge from the primary sedimentation and secondary clarifiers have been stabilized and dewatered we can call it biosolids. The biosolids need to either be disposed of or reused. Biosolids are classified into two separate types by the EPA. Class B biosolids have been treated by the processes discussed in this chapter but can contain high levels of pathogenic organisms. Therefore, Class B biosolids have greater restrictions on land application and crop harvesting. Class A biosolids typically undergo a combination of the treatment processes discussed in this chapter to achieve lower levels of pathogens. Class A biosolids that meet EPA regulations can legally be resold as fertilizers.

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