Part 4 of 9

Radiological Control Technician Training
Fundamental Academic Training Study Guide Phase I

Coordinated and Conducted
for the
Office of Health, Safety and Security
U.S. Department of Energy

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Course Title: **Radiological Control Technician**
Module Title: **Basic Mathematics and Algebra**
Module Number: **1.01**

Objectives:

1.01.01 Add, subtract, multiply, and divide fractions.
1.01.02 Add, subtract, multiply, and divide decimals.
1.01.03 Convert fractions to decimals and decimals to fractions.
1.01.04 Convert percent to decimal and decimal to percent.
1.01.05 Add, subtract, multiply, and divide signed numbers.
1.01.06 Add, subtract, multiply, and divide numbers with exponents.
1.01.07 Find the square roots of numbers.
1.01.08 Convert between numbers expressed in standard form and in scientific notation.
1.01.09 Add, subtract, multiply, and divide numbers expressed in scientific notation.
1.01.10 Solve equations using the "Order of Mathematical Operations."
1.01.11 Perform algebraic functions.
1.01.12 Solve equations using common and/or natural logarithms.

Introduction

Radiological control operations frequently require the RCT to use arithmetic and algebra to perform various calculations. These include scientific notation, unit analysis and conversion, radioactive decay calculations, dose rate/distance calculations, shielding calculations, stay-time calculations. A good foundation in mathematics and algebra is important to ensure that the data obtained from calculations is accurate. Accurate data is crucial to the assignment of proper radiological controls.

References:

1. DOE-HDBK-1014/1-92 (June 1992) "Mathematics: Volume 1 of 2"; DOE Fundamentals Handbook Series.

SYMBOLS FOR BASIC OPERATIONS

The four basic mathematical operations are addition, subtraction, multiplication, and division. Furthermore, it is often necessary to group numbers or operations using parentheses or brackets. In writing problems in this course the following notation is used to denote the operation to be performed on the numbers. If *a* and *b* represent numbers or variables, the operations will be denoted as follows:

Table 1. Symbols for Basic Mathematical Operations

Operation	Notation			
Addition:	$a + b$			
Subtraction	$a - b$			
Multiplication	$a \times b$	$a \cdot b$	a(b)	ab
Division:	$a \div b$	a/b	$\frac{a}{b}$	$b\sqrt{a}$
Grouping:	( ) [ ]			
Equality:	=			
Inequality:	≠			
Less than:	< Less than or equal to:			
Greater than:	> Greater than or equal to:			

1.01.01 Add, subtract, multiply, and divide fractions.

FRACTIONS

Whole numbers consist of the normal counting numbers and zero, e.g.,

{0, 1, 2, 3, 4...}

A *fraction* is part of a whole number. It is simply an expression of a division of two whole numbers. A fraction is written in the format:

$\frac{a}{b}$ *or* a/b

The number above the bar *a* is called the *numerator* and the number below the bar *b* is called the denominator. A *proper fraction* is a fraction in which the number in the numerator is less than the number in the denominator. If the numerator is greater than the denominator then it is an *improper fraction.* For example, ½ and ¼ are proper fractions, while $\frac{7}{5}, \frac{25}{5}, \frac{15}{7}$, or $\frac{61}{27}$ or are improper fractions.

Any whole number can be written as a fraction by letting the whole number be the numerator and 1 be the denominator. For example:

$$5 = \frac{5}{1} \qquad 2 = \frac{2}{1} \qquad 0 = \frac{0}{1}$$

Five can be written as 10/2, 15/3, 20/4, etc. Similarly, the fraction ¼ can be written as 2/8, 3/12, 4/16, etc. These are called *equivalent fraction*s. An equivalent fraction is **built u**p, per se, by multiplying the numerator and the denominator by the same non-zero number. For example:

$$\frac{3}{4} = \frac{3 \cdot 2}{4 \cdot 2} = \frac{6}{8} \qquad \frac{3}{4} = \frac{3 \cdot 5}{4 \cdot 5} = \frac{15}{20}$$

A fraction is **reduced** by dividing the numerator and the denominator by the same nonzero number. For example:

$$\frac{12}{18} = \frac{12 \div 2}{18 \div 2} = \frac{6}{9} \qquad \frac{6}{9} = \frac{6 \div 3}{9 \div 3} = \frac{2}{3}$$

A fraction is reduced to lowest terms when 1 is the only number that divides both numerator and denominator evenly. This is done by finding the *greatest common multiple* between the numerator and denominator. In the previous example, two successive reductions were performed. For the fraction 12/18, the greatest common multiple would be 6, or (2 × 3), which results in a reduction down to a denominator of 3.

A whole number written with a fraction is called a *mixed numbe*r. Examples of mixed numbers would be 1½, 3¼, 5¾, etc. A mixed number can be simplified to a single improper fraction using the following steps:

1. Multiply the whole number by the denominator of the fraction.
2. Add the numerator of the fraction to the product in step 1.
3. Place the sum in step 2 as the numerator over the denominator.

For example:

$$5\frac{3}{4} = \frac{(5 \cdot 4) + 3}{4} = \frac{23}{4}$$

Adding and Subtracting Fractions

Fractions With the Same Denominator

To add two fractions which have the same denominator:

1. Add the numerators.
2. Place the sum of step 1 over the common denominator.
3. Reduce fraction in step 2 to lowest terms (if necessary).

For example:

$$\frac{1}{5} + \frac{3}{5} = \frac{1+3}{5} = \frac{4}{5}$$

Subtraction of two fractions with the same denominator is accomplished in the same manner as addition. For example,

$$\frac{5}{8} - \frac{3}{8} = \frac{5-3}{8} = \frac{2}{8} = \frac{2 \div 2}{8 \div 2} = \frac{1}{4}$$

Fractions With Different Denominators

To add two fractions with different denominators requires that the fractions be built up so that they have the same denominator. This is done by finding the *lowest common denominato*r. Once a common denominator is obtained, the rules given above for the same denominator apply.

For example, 1/3 + 2/5. The fraction 1/3 could be built up to 2/6, 3/9, 4/12, 5/15, 6/18, 7/21, etc. The fraction 2/5 could be built up to 4/10, 6/15, 8/20, 10/25, etc. The lowest common denominator for the two fractions would be 15. The problem would be solved as follows:

$$\frac{1}{3} + \frac{2}{5} = \frac{1 \cdot 5}{3 \cdot 5} + \frac{2 \cdot 3}{5 \cdot 3} = \frac{5}{15} + \frac{6}{15} = \frac{5+6}{15} = \frac{11}{15}$$

Subtraction of fractions with different denominators is accomplished using the same steps as for addition. For example:

$$\frac{3}{4}-\frac{2}{3}=\frac{3\cdot 3}{4\cdot 3}-\frac{2\cdot 4}{3\cdot 4}=\frac{9}{12}-\frac{8}{12}=\frac{9-8}{12}=\frac{1}{12}$$

Multiplying and Dividing Fractions

Multiplication of fractions is much easier than addition and subtraction, especially if the numbers in the numerators and denominators are small. Fractions with larger numerators and/or denominators may require additional steps. In either case, the product of the multiplication will most likely need to be reduced in order to arrive at the final answer. To multiply fractions:

1. Multiply the numerators.
2. Multiply the denominators.
3. Place product in step 1 over product in step 2.
4. Reduce fraction to lowest terms.

For example:

$$\frac{5}{6}\cdot\frac{3}{4}=\frac{5\cdot 3}{6\cdot 4}=\frac{15}{24}=\frac{15\div 3}{24\div 3}=\frac{5}{8}$$

A variation on the order of the steps to multiply fractions is to factor the numerators and denominators first, reduce and cancel, and then multiply. For example:

$$\frac{3}{8}\cdot\frac{20}{9}=\frac{3}{2\cdot 2\cdot 2}\cdot\frac{2\cdot 2\cdot 5}{3\cdot 3}=\frac{\cancel{3}\cdot\cancel{2}\cdot\cancel{2}\cdot 5}{2\cdot\cancel{2}\cdot\cancel{2}\cdot\cancel{3}\cdot 3}=\frac{5}{2\cdot 3}=\frac{5}{6}$$

Reciprocals

Two numbers whose product is 1 are called *reciprocal*s, or *multiplicative inverse*s. For example:

a. 5 and $\frac{1}{5}$ are reciprocals because $5\cdot\frac{1}{5}=1$.

b. $\frac{4}{5}$ and $\frac{5}{4}$ are reciprocals because $\frac{4}{5}\cdot\frac{5}{4}=1$

c. 1 is its own reciprocal because $1\cdot 1=1$.

d. 0 has no reciprocal because 0 times *any* number is 0 *not* 1.

The symbol for the reciprocal, or multiplicative inverse, of a non-zero real number a is $\frac{1}{a}$. Every real number except 0 has a reciprocal. Therefore, for every *non-zero* real number a, there is a unique real number $\frac{1}{a}$ such that:

$$a \cdot \frac{1}{a} = 1$$

Now, look at the following product:

$$(ab)\left(\frac{1}{a} \cdot \frac{1}{b}\right) = \left(a \cdot \frac{1}{a}\right)\left(b \cdot \frac{1}{a}\right)\left(b \cdot \frac{1}{b}\right) = 1 \cdot 1 = 1$$

Relationship of multiplication to division

The operation of division is really just inverted multiplication (reciprocals). Notice from the above examples that the reciprocal of a fraction is merely "switching" the numerator and denominator. The number 5 is really $\frac{5}{1}$, and the reciprocal of 5 is $\frac{1}{5}$.

Likewise, the reciprocal of $\frac{2}{3}$ is $\frac{3}{2}$.

Fractions are a division by definition. **Division** of fractions is accomplished in two steps:

1. Invert the second fraction, i.e., change it to its reciprocal, and change the division to multiplication.
2. Multiply the two fractions using the steps stated above.

For example:

$$\frac{4}{7} \div \frac{2}{3} = \frac{4}{7} \cdot \frac{3}{2} = \frac{12}{14} = \frac{12 \div 2}{14 \div 2} = \frac{6}{7}$$

$$\frac{1}{2/3} = 1 \div \frac{2}{3} = 1 \cdot \frac{2}{3} = \frac{3}{2}$$

Practice Problems

Solve the following problems involving fractions. Answers should be reduced to lowest terms.

1. 1/3 + 2/3
2. 5/7 - 3/7
3. 5/9 + 2/3
4. 6/7 - 1/2
5. 2 - 1/3
6. 3/8 + 15/16
7. 25/32 - 3/4
8. 15/21 - 4/7
9. 13/20 - 2/5
10. 7/18 + 5/9
11. 2/3 × 1/5
12. 4/7 × 3/4
13. 1/2 × 2
14. 3/5 × 4
15. 4/9 ÷ 2/3
16. 8/13 × 2/3
17. 12/15 × 3/5
18. 20/25 ÷ 4/5
19. 7/8 × 2/5
20. 14/21 ÷ 2/7

1.01.02 Add, subtract, multiply and divide decimals.

DECIMALS

A *decimal* is another way of expressing a fraction or mixed number. It is simply the numerical result of divison (and fractions are division). Recall that our number system is based on 10 ("deci" in "decimal" means ten) and is a **place-value syste**m; that is, each *digit* {i.e., 0, 1, 2, 3, 4, 5, 6, 7, 8, 9} in a numeral has a particular value determined by its location or place in the number. For a number in decimal notation, the numerals to the left of the *decimal point* comprise the whole number, and the numerals to the right are the decimal fraction, (with the denominator being a power of ten).

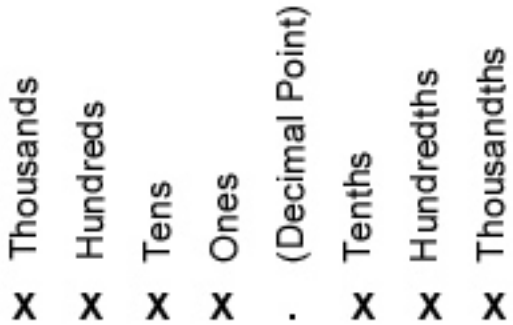

Figure 1. Decimal Place Value System

For example, the numeral 125.378 (decimal notation) represents the expanded numeral

$$100 + 20 + 5 + \frac{3}{10} + \frac{7}{100} + \frac{8}{1000}$$

If this numeral were written as a mixed number, we would write it as:

$$125\frac{378}{1000}$$

Addition and Subtraction of Decimals

In order to add or subtract decimals use the following steps:

1. Arrange the numbers in a column so that the decimal points are aligned.
2. Add or subtract in columns from right to left. Additional zeros may need to be added to the right of the subtrahend (a number that is to be subtracted from a minuend).
3. Place the decimal point in the answer in line with the other decimal points.

For example:

$$\begin{array}{r} 21.3 \\ \underline{+\ 4.2} \\ 25.5 \end{array} \qquad \begin{array}{r} 654.200 \\ \underline{-\ 26.888} \\ 627.312 \end{array}$$

Multiplying Decimals

To multiply decimal numbers, do the following:

1. Multiply the numbers as if there were no decimal points.
2. Count the number of decimal places in each number and add them together.
3. Place the decimal point in the product so that it has the same number of decimal places as the sum in step 2.

For example:

$$\begin{array}{r} 5.28 \\ \underline{\times\ \ 3.7} \\ 3696 \\ \underline{1584\ \ } \\ 19.536 \end{array} \qquad \begin{array}{r} 0.04 \\ \underline{\times\ \ 0.957} \\ 028 \\ 020\ \ \\ 036\ \ \ \ \\ \underline{000\ \ \ \ \ \ } \\ 0.03828 \end{array}$$

Division of Decimals

The steps for division of decimals are as follows:

1. Move the decimal point of the divisor (the number by which a dividend is divided) to the right until it becomes a whole number.
2. Move the decimal point of the dividend to the right the same number of places moved in step 1.
3. Divide the numbers as if they were whole numbers.

For example: $7 \div 0.25$

$$\begin{array}{r} 28 \\ 0.25\overline{)7.00} \\ \underline{50} \\ 200 \\ \underline{200} \\ 0 \end{array}$$

Decimal Forms

As we have learned, decimals are the result of division (or a fraction). When the remainder of the division is zero, the resulting decimal is called a *terminating* or *finite decima*l. For example, fractions like 2/5, 3/8, and 5/6 will all result in finite decimals. These fractions and the resulting decimals are known as *rational number*s.

On the other hand, fractions like 1/3, 2/7, 5/11, and 7/13 result in a *non-terminating* or *infinite decima*l. For example, 2/7 results in the decimal 0.285714286 . . . , the dots meaning that the decimal continues without end. These numbers are known as *irrational number*s. Note that even though irrational numbers are non-terminating, (e.g., 1/3 and 5/11) are *repeating* or *periodic* decimals because the same digit or block of digits repeats unendingly. For example:

$$\frac{1}{3} = 0.3333... \qquad \frac{5}{11} = 0.454545...$$

A bar is often used to indicate the block of digits that repeat, as shown below:

$$\frac{1}{3} = 0.\overline{3} \qquad \frac{5}{11} = 0.\overline{45}$$

Practice Problems

Solve the following problems involving decimals.

1. 0.23 + 3.4
2. 5.75 - 2.05
3. 6.1 - 1.6
4. 0.018 + 0.045
5. 468.75 - 192.5
6. 2.3 × 3.2
7. 0.007 × 2.18
8. 5.2 ÷ 1.4
9. 12.26 ÷ 0.04
10. 4.0 × 0.25

1.01.03 Convert fractions to decimals and decimals to fractions.

FRACTION TO DECIMAL CONVERSION

To convert a fraction to a decimal we simply perform the operation of division that the fraction represents. For example, the fraction 3/4 represents "3 divided by 4," and would be converted as follows:

```
      0 . 75
4 ) 3 . 00
      2 . 8
      20
      20
      0
```

Practice Problems

Convert the following fractions to decimals.

1. 1/2
2. 2/5
3. 5/8
4. 12/25
5. 13/39
6. 7/16

Convert the following decimals to fractions. Reduce answers to lowest terms.

7. 0.125
8. 0.6666
9. 4.25
10. 0.2

1.01.04 Convert percent to decimal and decimal to percent.

PERCENT

Percentage is a familiar and widely used concept for expressing common and decimal fractions. Most people know the meaning of terms such as 100 percent and 50 percent. The word *percent* actually means "out of a hundred." (Consider that there are 100 "cents" in a dollar, and that a "century" is 100 years.) A percent is simply a fraction whose denominator is 100. Thus, 50 percent means 50/100, or 0.50, while 25 percent means 25/100, or 0.25.

Percent is abbreviated by the symbol %. So, 75 percent is written 75%.

<u>Converting Decimal to Percent</u>

A decimal fraction is changed to a percent by moving the decimal point two places to the right and adding a percent sign. For example, 1/8 equals 0.125. Therefore:

$$\frac{1}{8} = 0.\underline{1}\underline{2}5 = 12.5\%$$

A percent is changed to a common fraction by omitting the percent sign, placing the number over 100, and reducing the resulting fraction if possible. For example, 32% equals 32/100 which reduces to 8/25. When the percent consists of a mixed decimal number with a percent sign, the resulting fraction will contain a mixed decimal numerator. This can be changed to a whole number by multiplying the numerator and the denominator by 10, 100, 1,000, etc. For example:

$$40.25\% = \frac{40.25}{100} = \frac{40.25 \times 100}{100 \times 100} = \frac{4025}{10{,}000} = \frac{805}{2000}$$

Percentage is most frequently used to indicate a fractional part. Thus 20% of the total power output for 75% of the employees refer to fractional parts of some total number.
To perform arithmetic operations with a percent, it is normally changed to a common or decimal fraction. Usually, a decimal fraction is more convenient.

Converting Percent to Decimal

A percent is changed to a decimal fraction by omitting the percent sign and moving the decimal point two places to the left. For example:

$$48\% = 0.\underleftarrow{48}$$

Thus, 92% equals 0.92, 8% equals 0.08, and so on.

Practice Problems

Convert the following decimals to percent.

1. 0.5
2. 0.782
3. 1.1
4. 0.06
5. 0.049
6. 0.0055

Convert the following percentages to decimals.

7. 65%
8. 0.25%
9. 300%
10. 0.09%

1.01.05 Add, subtract, multiply and divide signed numbers.

SIGNED NUMBERS

The numbers that are used to quantify the number of objects in a group, the "counting numbers", are always *positive* numbers; that is, they are always greater than zero. However, there are many occasions when *negative* numbers (numbers less than zero) must be used. These numbers arise when we try to describe measurement in a direction opposite to the positive numbers. For example, if we assign a value of +3 to a point which is 3 feet above the ground, what number should be assigned to a point which is 3 feet below the ground? Perhaps the most familiar example of the use of negative numbers is the measurement of temperature, where temperatures below an arbitrary reference level are assigned negative values.

Every number has a *sign* associated with it. The plus (+) sign indicates a positive number, whereas the minus (-) sign indicates a negative number. When no sign is given, a plus (+) sign is implied. The fact that the plus and minus signs are also used for the arithmetic operations of addition and subtraction should not be a cause for confusion, for we shall see that they have equivalent meanings.

Every number has an *absolute value*, regardless of its sign. The absolute value indicates the distance from zero, without regard to direction. The number 5 is 5 units from zero, in the positive direction. The number -5 is also 5 units from zero, but in the negative direction. The absolute value of each of these numbers is 5. The absolute value of a number is indicated by a pair of vertical lines enclosing the number: |5|.

Operations with Signed Numbers

The arithmetic operations of addition, subtraction, multiplication, and division of signed numbers can be more easily visualized if the numbers are placed on a *number line (see Figure 2*). The positive numbers are greater than zero, and they lie to the right of zero on the number line. The negative numbers are less than zero, and lie to the left of zero on the number line.

FIGURE 2. Number Line

The number line extends an infinite distance in each direction and therefore includes all numbers. The process of addition can be considered as counting in one direction or the other from a starting point on the number line. For example, let us add 1 + 2. We locate +1 on the number line and then count 2 units to the right, since we are adding +2. The result will be +3. To illustrate further, let us add +2 and -4. We first locate +2 on the number line and then count 4 units to the left. We end up at -2.

The number line is useful for illustrating the principles of addition, but it clearly would be inconvenient to use in the case of large numbers. Consequently, the following rules were developed to govern the addition process:

Adding and Subtracting Signed Numbers.

To **add** two numbers with the **same sign**s, add their absolute values and attach the common sign. For example:

$$(-3) + (-2) = -5$$

To **add** two numbers with **opposite sign**s, find the difference of their absolute values, then attach the sign of the original number which had the greater absolute value. For example:

$$(-2) + 3 = 1$$

Notice that -3 and +3 are the same distance but in *opposite* directions from 0 on the number line. What happens when you add two numbers like 3 and -3?

$3 + (-3) = 0$

$-7 + 7 = 0$

If the sum of two signed numbers is 0, the numbers are called *additive inverses* or *opposite*s. For example:

$7 - 3 = 4$	is the same as:	$7 + (-3) = 4$
$8 - 2 = 6$	is the same as:	$8 + (-2) = 6$

It can be seen that subtracting a number is equivalent to adding its additive inverse or opposite.

To **subtract** a signed number, **add** its **opposite** or additive inverse. In other words, change the subtraction symbol to addition and change the sign of the second signed number. For example:

$5 - (-8) = 5 + (+8)$ $\Leftarrow$ add +8 (Answer = 13)

$6 - 11 = 6 + (-11)$ $\Leftarrow$ add -11 (Answer = -5)

$-4 - (-7) = -4 + (+7)$ $\Leftarrow$ add +7 (Answer = 3)

<u>Multiplying and Dividing Signed Number</u><u>s.</u>

The **product** of two numbers with **like signs** is a **positive** number. The product of two numbers with **unlike signs** is a **negative** number. In symbols:

$(+) \times (+) = (+)$	$(+) \times (-) = (-)$
$(-) \times (-) = (+)$	$(-) \times (+) = (-)$

For example:

$(-4) \times (-3) = (+12)$
$(-4) \times (+3) = (-12)$

The **division** of numbers with **like signs** gives a **positive** quotient. The division of numbers with **unlike signs** gives a **negative** quotient. In symbols:

$(+)/(+) = (+)$	$(+)/(-) = (-)$
$(-)/(-) = (+)$	$(-)/(+) = (-)$

For example:

(-24)/(-6) = (+4)
(-24)/(+6) = (-4)

Remember that multiplication is really a short form of addition. When we say +4 × (- 3), we are adding the number - 3 four times, that is, (- 3) + (- 3) + (- 3) + (- 3) = - 12. Also, since division is a short form of subtraction, when we say - 24 ÷ (- 6), we subtract the number - 6 from the number - 24 four times in order to reach 0, i.e., - 24 - (- 6) - (- 6) - (- 6) - (- 6) = 0. Although we could repeat the process for the multiplication and division of any signed numbers, usage of the two rules will produce equivalent results.

Practice Problems

Solve the following problems involving signed numbers.

1. (- 28) + (- 51)
2. (- 2) + (- 5)
3. 40 + (- 21)
4. (- 87) + 50
5. 48 + (- 27)
6. 56 - (- 5)
7. 81 - 4
8. - 48 - (- 2)
9. (- 4)(5)
10. 6/(- 3)
11. 4 (- 5)
12. (- 6)/(- 3)
13. (- 6)/3
14. (- 8)(- 5)
15. (- 7)(6)

1.01.06 Add, subtract, multiply, and divide numbers with exponents.

EXPONENTS

An *exponent* is a small number placed to the right and a little above another number, called the *base*; to show how many times the base is to be multiplied by itself. Thus, 3^4 (read "three to the fourth *power*") means 3 used as a factor four times or 3 × 3 × 3 × 3. In this case, 4 is the exponent, and 3 is the base.

In general, if *b* is any real number and *n* is any positive integer, the **nth power of *b*** is written b^n (where *b* is the base and *n* is the exponent) is read as "b to the nth power." This tells you that *b* is used as a factor *n* times.

Thus, 5^2 is called "5 raised to the second power" (or 5 *"squared"*), and 2^3 is called "2 raised to the third power" (or 2 *"cubed"*). When no exponent is shown for a number or no power is indicated, the exponent or power is understood to be 1. Thus, 7 is the same as 7^1. Any number raised to the power of zero equals one; e.g., $7^0 = 1$. Normally, exponents of zero and one are not left as the final value, but are changed to the simpler form of the base.

Exponents can be expressed as integers, as in the examples above, or as fractions or decimals such as $9^{1/2}$ or $10^{3.2}$. They may also be positive or negative.

Exponents and powers are particularly useful in mathematics not only because they shorten the writing of mathematical expressions, but also because they simplify many mathematical operations. However, there are several special rules which govern mathematical operations involving numbers with exponents.

Addition and Subtraction

The addition or subtraction of numbers with exponents can be performed only if both the bases and the exponents of the numbers are the same. When the bases of the exponents are different, the multiplication indicated by the exponent must be performed and the numbers then added or subtracted. Thus, 2^5 and 2^4 cannot be added directly because their exponents are different. They can be added only by carrying out the indicated multiplication first. Thus, 2^5 equals $2 \times 2 \times 2 \times 2 \times 2$ which equals 32, and 2^4 equals $2 \times 2 \times 2 \times 2$ which equals 16. Therefore, $2^5 + 2^4$ equals 32 + 16, which equals 48.

When the bases and the exponents are the same, the numbers can be added or subtracted directly. For example:

$$3^5 + 3^5 = 2(3^5) = 2(243) = 486$$

Multiplication

The multiplication of numbers with exponents of the same base is performed by adding the exponents. The general form is as follows:

$$(a^m)(a^n) = a^{(m+n)}$$

It is important to remember that the **bases of the numbers must be the same** before they can be multiplied by adding their exponents. The base of the product is the same as the base of the two factors. Thus,

$$3^2 \times 3^3 = 3^5 = 243$$

Division

The division of numbers with exponents of the same base is performed by subtracting the exponent of the divisor (denominator) from the exponent of the dividend (numerator). The general form is:

$$\frac{a^m}{a^n} = a^{(m-n)}$$

Again, it is important to remember that the bases of the numbers must be the same before they can be divided by subtracting their exponents. The base of the quotient is the same as the base of the number divided. Thus,

$$\frac{2^5}{2^2} = 2^{(5-2)} = 2^3 = 8$$

Division of numbers with exponents can be used to show why any number raised to the power of zero equals one. We know that any fraction in which the numerator equals the denominator can be reduced to 1; e.g., 2/2 = 1. Similarly:

$$\frac{2^3}{2^3} = 2^{(3-3)} = 2^0 = 1$$

Exponent Raised to a Power

Raising a number with an exponent to a power is performed by multiplying the exponent by the power. The general form is:

$$(a^m)^n = a^{mn}$$

The base of the answer is the same as the base of the number raised to the power. Thus:

$$(5^2)^3 = 5^{(2\times 3)} = 5^6 = 15{,}625$$

Product Raised to a Power

Raising a product of several numbers to a power is performed by raising each number to the power. The general form is as follows:

$$(ab)^n = a^n b^n$$

For example:

$$[(2)(3)(4)]^2 = (2^2)(3^2)(4^2) = (4)(9)(16) = 576$$

This same result can also be obtained like this:

$$[(2)(3)(4)]^2 = 24^2 = 576$$

Mixed Product and Exponents Raised to a Power

The same rule can be used to raise a product of several numbers with exponents to a power. The general form looks like this:

$$(A^a B^b C^c)^n = A^{(a \times n)} B^{(b \times n)} C^{(c \times n)}$$

For example:

$$[(2)^4 (3)^3 (4)^2]^2 = (2^{4\times2}) (3^{3\times2}) (4^{2\times2}) = (2^8) (3^6) (4^4) = (256) (729) (256)$$

Fraction Raised to a Power

Raising a fraction to a power is performed by raising both numerator and denominator to the power. It should be remembered that with a proper fraction (i.e., numerator is less than the denominator) the resulting number must be less than one. Also, the resulting number will be less than the value of the original fraction. Thus, $(2/3)^3$ equals $2^3/3^3$, which equals 8/27, which is less than one and less than the original fraction, 2/3.

Negative Exponents and Powers

A negative exponent or power has a special meaning. Any number, except 0, with a negative exponent equals the *reciprocal* of the same number with the same positive exponent. For example:

$$6^{-2} = \frac{1}{6^2} = \frac{1}{36}$$

The same rules for addition, subtraction, multiplication, division, and raising to a power apply to negative exponents that apply to positive exponents. However, in adding, subtracting, or multiplying the exponents, the rules for signed numbers must also be observed.

Fractional Exponents

Fractional exponents are used to represent roots (see next section). The general form of a fractional exponent is $a^{\frac{m}{n}}$, which reads "the nth root of a^m." For example, $a^{1/2}$, means *a* the square root of a^1, or a. In other words, $a^{1/2} = \sqrt{a}$

Calculator Method

To raise a number to a power using a scientific calculator, use the following steps:

1) Enter the number. (Fractions must first be converted to decimal form.)
2) Press the key. $\boxed{y^x}$
3) Enter the power. (Fractions must first be converted to decimal form.)
4) Press the $\boxed{=}$ key. The number displayed will be the number entered in step 1 raised to the power entered in step 3.

Practice Problems

1. $(3^2)(3^3)$
2. $7^5/7^3$
3. $(10^5)(10^6)$
4. $(10^6)(10^{-4})$
5. $6^{-4}/6^{-3}$
6. $6^{-8}/6^3$

1.01.07 Find the square roots of numbers.

SQUARE ROOTS

To *square* a number means to multiply the number by itself, i.e., raise it to the second power. (Consider that a square is two-dimensional.) For example, 2 squared is 4, since $2 \times 2 = 4$. The square of 3 is 9, 4 squared is 16, and so on.

Just as subtraction "undoes" addition and division "undoes" multiplication, squaring a number can be "undone" by finding the *square root*. The general definition is as follows:

If $a^2 = b$, then a is a **square root** of b.

Be careful not to confuse the terms *square* and *square root*. For example, if $5^2 = 25$, this indicates that 25 is the **square** of 5, and 5 is the **square root** of 25. To be explicit, we say that it is a *perfect square* because 5 times itself is 25.

All perfect squares other than 0 have two square roots, one positive and one negative. For example, because $7^2 = 49$ and $(-7)^2 = 49$, both 7 and -7 are square roots of 49. The symbol $\sqrt{\ }$, referred to as the *radical*, is used to write the *principal*, or positive, square root of a positive number.

$\sqrt{49} = 7$ is read "The *positive* square root of 49 equals 7."

A negative square root is designated by the symbol $-\sqrt{\ }$.

$-\sqrt{49}$ = -7 is read "The *negative* square root of 49 equals -7."

It is often convenient to use *plus-or-minus* notation:

$\pm\sqrt{49}$ means the positive **or** negative square root of 49.

Therefore, the rule is that every positive real number *a* has two square roots: $\sqrt{a}$ and - $\sqrt{a}$.
It follows from the definition of square root that $\left(\sqrt{a}\right)^2 = a$, and that $\sqrt{a^2} = a$. Because the square of every real number is either positive or zero, negative numbers do not have square roots in the set of real numbers.

Notice that $\sqrt{4\cdot 25} = \sqrt{100} = 10$, and $\sqrt{4}\cdot\sqrt{25} = 2\cdot 5 = 10$. Therefore, $\sqrt{4\cdot 25} = \sqrt{4}\cdot\sqrt{25}$
Therefore, in general, we can say:

For any nonnegative real numbers *a* and b: $\sqrt{a\cdot b} = \sqrt{a}\cdot\sqrt{b}$

It also follows that $\sqrt{\frac{a}{b}} = \frac{\sqrt{a}}{\sqrt{b}}$

Calculator Method

To calculate the square root of any number using a scientific calculator, follow these steps:

1) Enter the number. (Fractions must first be converted to decimal form.)
2) Press the $\boxed{\sqrt{x}}$ key. The number displayed will be the square root of the number entered in step 1. An alternate method is to press the $\boxed{y^x}$ key and then type 0.5. This raises the number in step 1 to the power of 0.5, or ½.

Other roots

For informational purposes only, we mention the fact that other roots may be found for a number. One of these is the cube root. To *cube* a number means to multiply the number by itself three times, i.e., raise it to the third power. (Consider that a cube is three-dimensional.) For example, 2 cubed is 8, since 2 × 2 × 2 = 8. The *cube root* (or third root) of a number, then, is the number that, when raised to the third power (cubed), equals the first number. The notation for a cube root is $\sqrt[3]{a}$.

Note that any root may be taken from a number to "undo" an exponent, such as the fourth or fifth root. The general definition for a root is:

If a^n = b, then *a* is the nth root of b.

The notation for the nth root is $\sqrt[n]{a}$. These roots follow the same general rules as the square root.

Practice Exercises

Find the indicated square roots.

1. $\sqrt{16}$
2. $\sqrt{144}$
3. $(\sqrt{6})^2$
4. $\sqrt{\frac{1}{64}}$
5. $\sqrt{\frac{81}{36}}$
6. $-\sqrt{81}$
7. $\sqrt{15^2}$
8. $-\sqrt{400}$
9. $\sqrt{9 \cdot 49}$
10. $-\sqrt{625}$

1.01.08 Convert between numbers expressed in standard form and in scientific notation.

SCIENTIFIC NOTATION

The difficulty in writing very large or very small numbers in the usual manner is that a large number of zeros are required to write these numbers. This difficulty is overcome by using *scientific notatio*n, in which integral powers of ten are used instead of a large number of zeros to indicate the position of the decimal point. In addition to simplifying the writing of very large or very small numbers, scientific notation clearly identifies the number of significant digits in a number and simplifies arithmetic calculations involving multiplication, division, or raising to a power. For these reasons, it is good practice to write numbers in scientific notation when these operations are involved.

The following demonstrates how the number 1 million can be represented by various factors of 10:

$$
\begin{aligned}
0.00001 &\times 10^{11} \\
0.0001 &\times 10^{10} \\
0.001 &\times 10^{9} \\
0.01 &\times 10^{8} \\
0.1 &\times 10^{7} \\
1{,}000{,}000 = 1 &\times 10^{6} \\
10 &\times 10^{5} \\
100 &\times 10^{4} \\
1000 &\times 10^{3} \\
10{,}000 &\times 10^{2} \\
100{,}000 &\times 10^{1} \\
1{,}000{,}000 &\times 10^{0} \\
10{,}000{,}000 &\times 10^{-1} \\
100{,}000{,}000 &\times 10^{-2}
\end{aligned}
$$

Converting From Standard Form To Scientific Notation

There are two steps involved in writing a number in scientific notation.

1) Move the decimal point just to the right of the first significant digit. The first significant digit is the first non-zero digit counting from the left.
2) Indicate multiplication of the resulting number by a power of ten that makes its value equal to the original value. The power of ten is found by counting the number of places the decimal point was moved from its original position. If counted to the left, the power is positive; if counted to the right, it is negative. For example:

Suppose you want to express a number such as 700 in scientific notation.

$$700 = 7 \times 10^2$$

Suppose you want to express 0.0014 in scientific notation.

$$0.0014 = 1.4 \times 10^{-3}$$

Converting from Scientific Notation to Standard Form

To transform from scientific notation to standard form, follow the opposite procedure.

$1.96 \times 10^5 = 196000$

$2.27 \times 10^{-2} = 0.0227$

There are two parts of a number written in scientific notation, the *significant digits* and the power of ten. Thus, in the number 3.21×10^6, 3, 2, and *1* are the significant digits and 10^6 is the power of ten.

The ability to clearly see the number of significant digits can be helpful in performing arithmetic calculations. For example, the number of significant digits which should be reported in the product of two numbers can be readily determined if the two numbers are first written in scientific notation.

When numbers are expressed in scientific notation, calculations can be more easily visualized. This is because they involve only numbers between 1 and 10 and positive and negative integral powers of ten which can be treated separately in the calculations using the rules for numbers with exponents.

1.01.09 Add, subtract, multiply, and divide numbers expressed in scientific notation.

Addition and Subtraction Using Scientific Notation

Addition and subtraction cannot normally be performed directly using scientific notation because they require adding or subtracting digits of equal place value. Thus, when numbers expressed in scientific notation are to be added or subtracted, they must first be converted to forms having equal place value. This is commonly done by expressing them as numbers which are multiplied by the same integral power of ten. The sum or difference of these significant digits, multiplied by their common power of ten, is the sum or difference of the original numbers. For example:

$(3.54 \times 10^5) + (2.51 \times 10^4)$

3.54×10^5 is first changed to 35.4×10^4

$$\begin{array}{r} 35.4 \times 10^4 \\ \underline{+\ 2.41 \times 10^4} \\ 37.91 \times 10^4 \end{array} = 3.79 \times 10^5$$

Multiplication and Division Using Scientific Notation

Multiplication or division of numbers using scientific notation is performed by multiplying or dividing the significant digits and the powers of ten separately. The significant digits are multiplied or divided in the same manner as other mixed decimals. The powers of ten are multiplied or divided by adding or subtracting their exponents using the rules for multiplication and division of numbers with exponents. For example:

$(2.7 \times 10^2)(3.1 \times 10^{-3}) = (2.7)(3.1) \times (10^2)(10^{-3}) = 8.37 \times 10^{-1}$

which should be rounded off to 8.4×10^{-1}

One of the most useful applications of scientific notation is in arithmetic calculations which involve a series of multiplications and divisions. The use of scientific notation permits accurate location of the decimal point in the final answer. For example:

Perform the following calculation using scientific notation:

$$\frac{(219)(0.00204)}{(21.2)(0.0312)}$$

1) Write each term in scientific notation:

$$\frac{(2.19 \times 10^{2})(2.04 \times 10^{-3})}{(2.12 \times 10^{1})(3.12 \times 10^{-2})}$$

2) Multiply and divide the significant digits:

$$\frac{(2.19)(2.04)}{(2.12)(3.12)} = \frac{-4.46}{6.61} = 0.675$$

3) Multiply and divide the powers of ten by adding and subtracting exponents:

$$\frac{(10^{2})(10^{-3})}{(10^{1})(10^{-2})} = \frac{10^{-1}}{10^{-1}} = 10^{-1+1} = 10^{0}$$

4) Combine the results:

$$0.675 \times 10^{0} = 0.675 = 6.75 \times 10^{-1}$$

"E" Notation

An alternate method for annotating scientific notation is often used by pocket calculators, computers, and some references. The method uses an E in place of the "× 10," and the number written after the E is the *exponent* of 10. The standard and alternate methods for scientific notation are equivalent and can be converted from one form to another without a change in value. The examples below use both methods in equivalent expressions:

$3.79 \times 10^{5} = 3.79E5$

$4.02 \times 10^{-6} = 4.02E-6$

$5.89 \times 10^{0} = 5.89E0$

Using "E" Notation with a Calculator

Numbers in scientific notation are entered into a scientific calculator as follows:

1) Enter the significant digits.
2) Press the [E] or [EXP] key. (Actual key label may vary.)
3) Enter the power of 10. If the power is negative press the [+/-] key in conjunction with entering the power.

Practice Problems

1. $(2 \times 10^{-2})(3 \times 10^{2})$
2. $(6 \times 10^{-8})/(3 \times 10^{3})$
3. $(9 \times 10^{4})(- 1 \times 10^{-2})$
4. $(3 \times 10^{-7})(9 \times 10^{2})$
5. (7E2)(6E4)
6. (5E - 3)/(5E - 2)

1.01.10 Solve equations using the "Order of Mathematical Operations.

ORDER OF MATHEMATICAL OPERATIONS

In solving any equation it is necessary to perform the operations in the equation in accordance with a certain hierarchy or *order of operation*s. Equations are solved by simplifying operations of higher order first, according to group, left to right. The order for solving equations is as follows:

1) Simplify expressions within grouping symbols, beginning with the innermost set if more than one set is used.

2) Simplify all powers.

3) Perform all multiplications and divisions in order from left to right.

4) Perform all additions and subtractions in order from left to right.

For example: $(3 + 1)^2 \times 3 - 14 \div 2$

1) Simplify parentheses: $\underbrace{(3+1)}^{2} \times 3 - 14 \div 2$

2) Simplify powers: $\underbrace{(4)^2 \times 3 - 14 \div 2}$

3) Perform multiplication and $\underbrace{16 \times 3} - \underbrace{14 \div 2}$ division left to right:

4) Perform subtraction: 48 - 7 = 41 *(final answer)*

Practice Problems

1. $5 + (- 3) - (- 2) - 6$
2. $18 - [52 \div (7 + 6)]$
3. $19 - 7 + 12 - 2 \div 8$
4. $2^3 - 20 \div 4 + 4 - 3$
5. $10 + 6(0.5)^3$
6. $3^3 + 10 \div 5$
7. $(8 + 4 - 3)^2$
8. $7(4^2 - 10) \div (12 - ¾)$
9. $7(6 - 2^2)$
10. $(57 - 2^5)^{1/2}$

1.01.11 Perform algebraic functions.

ALGEBRA

Algebra is the branch of mathematics which deals with the manipulation of words and letters, generically called *symbol*s, which represent numbers. Two factors contribute to the widespread use of algebra in scientific calculations. First, by using words and letters to represent the values of physical quantities, physical relationships can be expressed in clear, concise, and completely generalized form. Second, by using words and letters in place of numbers, combinations of physical relationships may be simplified to yield results applicable to any set of numbers.

For example, the area of a rectangle equals the product of the length of the rectangle multiplied by its width. In generalized terms, this statement can be written as:

Area = Length × Width.

This expression is a simple rule which tells the relationship between the area and the length and width of a rectangle. It does not mean that words are multiplied together but rather that numbers are inserted for the length and the width to obtain the area. For example, if the length is 4 feet and the width is 2 feet, the area is 2 feet × 4 feet or 8 square feet. This expression can be further simplified by using symbols or letters instead of words. For example, if area is designated by the letter A, length designated by the letter l, and width designated by the letter w, the following expression results:

$A = l \times w$ or $A = lw$

In algebraic expressions, when two or more letters representing numbers are written next to each other without a symbol between them, multiplication is indicated.

Variables vs. Numbers

When words or letters are used to represent numbers, they are called *variable*s. Thus, when letters like x, y, z, f, or *k* are used to represent the values of physical quantities, they are called variables because their value varies with the actual numbers they may be chosen to represent. In the area calculation above, A, l, and *w* are variables used to represent the numerical values of area, length and width, respectively.

Properties of Variables

Recall that every number has a sign and an exponent associated with it. Recall also that any number can be written as a fraction by putting that number as the numerator and 1 as the denominator, e.g., 5 = 5/1. These properties also apply to any symbols that we might use to represent numbers. Additionally, a symbol by itself stands for one of whatever the variable represents. That is to say, the symbol *a* by itself means "one of the variable represented by the letter a", or *1*a. Combining this with the other "invisible" properties mentioned, the symbol *a* is understood to represent "positive one of the variable represented by the letter *a* to the power of one, over 1," which would be expressed as:

$$\frac{+1a^1}{1} = a$$

An expression that is either a numeral, a variable or the product of a numeral and one or more variables is called a *monomial*. A combination or sum of monomials is called a *polynomial*. Examples of each are:

Monomials: 12 z br $-4x^3$

Polynomials: $3x + 9$ $6a^2 - 15$

Equations

An *equation* is a statement that indicates how two quantities or expressions are equal. The two quantities are written with an equal sign (=) between them. For example,

$1 + 1 = 2$ $10 = 6 - (-4)$
$5 \times 3 = 15$ $18 \div 2 = 9$

are all equations because in each case the quantity on the left side is equal to the quantity on the right side.

In algebra we use variables to represent numbers in equations. In this lesson we will *manipulate* and *solve* equations involving more than one variable, but we will find the *solution*, i.e., the final answer, to equations having only one variable.

Algebraic Manipulation

The basic principle, or *axiom*, used in solving any equation is: **whatever operation is performed on one side of an equation - be it addition, subtraction, multiplication, division, raising to an exponent, taking a root - must also be performed on the other side if the equation is to remain true**. This principle MUST be adhered to in solving all types of equations.

This axiom can be thought of by visualizing the balancing of a scale. If the scale is initially balanced, it will remain balanced if the same weight is added to both sides, if the same weight is removed from both sides, if the weights on both sides are increased by the same factor, or if the weights on both sides are decreased by the same factor.

Here are the general forms for algebraic manipulation of equations. For the real numbers *a, b, c* and *n*:

Table 2. Rules for Algebraic Operations

Addition:	If $a = b$, then	$a + c = b + c$
Subtraction:	If $a = b$, then	$a - c = b - c$
Multiplication:	If $a = b$, then	$a \cdot c = b \cdot c$
Division:	If $a = b$, then	$a \div c = b \div c$
Involution: *"Raising to an exponent"*	If $a = b$, then	$a^n = b^n$
Evolution: *"Taking a root"*	If $a = b$, then	$\sqrt[n]{a} = \sqrt[n]{b}$

Manipulating and Solving Linear Equations

The addition or subtraction of the same quantity from both sides of an equation may be accomplished by *transposing* a quantity from one side of the equation to the other. Transposing is a shortened way of applying the addition or subtraction axioms. Any term may be transposed or transferred from one side of an equation to the other if its sign is changed. Thus, in the equation below the +4 can be transposed to the other side of the equation by changing its sign:

$$5x + 4 = 14$$
$$(5x + 4) - 4 = (14) - 4$$
$$5x = 14 - 4$$
$$5x = 10$$

Transposing also works with multiplication and division. Remembering that any number can be expressed as a fraction we can rewrite the last line of the equation above. We can then move the 5 in the numerator of the left side to the denominator of the right side:

$$\frac{5x}{1} = \frac{10}{1}$$
$$\frac{x}{1} = \frac{10}{5}$$
$$x = \frac{10}{5}$$
$$x = 2$$

Some linear equations may contain multiple terms (monomials) involving the same variable. In order to simplify the equation like terms must be combined. Don't forget those "invisible properties of variables." Here's an example:

$3x - 5 = x + 3$	⇐ To solve for x:
$3x - 5 - x = x + 3 - x$	⇐ Subtract x from both sides.
$2x - 5 = 3$	⇐ Combine like terms and cancel.
$2x - 5 + 5 = 3 + 5$	⇐ Add 5 to both sides.
$2x = 8$	⇐ -5 and $+5$ cancel.
$\frac{2x}{2} = \frac{8}{2}$	⇐ Divide both sides by 2.
$x = 4$	⇐ 2 over 2 cancels. Reduce.

Quadratic Equations

In manipulating an equation involving multiple variables, the "variable of interest" (or the variable to be solved for) must be moved to one side of the equal sign and all other variables must be moved to the other side. In order to accomplish this, operations must be performed on both sides of the equation that will result in a variable or group of variables, to be canceled out from one side. This cancellation can only occur if the "opposite function" is performed on a function that already exists on that side of the equation. This means that a variable that is being multiplied can be canceled by dividing by the same variable. Addition can be canceled with subtraction, multiplication with division, etc.

For example:

$a + b = c$	⇐ To solve for a:
$a + b - b = c - b$	⇐ Subtract b from both sides
$a = c - b$	⇐ $+b$ and $-b$ cancel

Another example:

$ab = c$	⇐ To solve for a:
$\frac{ab}{b} = \frac{c}{b}$	⇐ Divide both sides by b
$a = \frac{c}{b}$	⇐ b over b cancels

Do not forget that the order of operations must be observed when manipulating equations. Otherwise a completely different solution may result. The key is to **do the opposite function in reverse ord**er. Here is an example which shows how this is done.

$$\frac{a + b}{c} = d$$ ⇐ To solve for a:

$$c \cdot \frac{(a + b)}{c} = d \cdot c$$ ⇐ Multiply both sides by c.

$$a + b = dc$$ ⇐ c over c cancels.

$$a + b - b = dc - b$$ ⇐ Subtract b from both sides.

$$a = dc - b$$ ⇐ $b - b$ cancels

Once the order of the arithmetic functions has been established, manipulation of the formula can begin. In the example above, if the values for a, b, and *c* were known, the first step would be to add *b* to a. The second step would be to divide by c. Therefore, in order to solve it, we do the opposite functions in reverse order. So, we first multiply by c. Then, we would subtract b. It is a good idea to rewrite the equation each time so that the operations can be reevaluated before the next step.

One final example: $ab^2 = cd^2$ ⇐ To solve for d:

$$\frac{ab^2}{c} = \frac{cd^2}{c}$$ ⇐ Divide both sides by c.

$$\frac{ab^2}{c} = d^2$$ ⇐ c over c cancels.

$$\sqrt{\frac{ab^2}{c}} = \sqrt{d^2}$$ ⇐ Take the square root of both sides.

$$\sqrt{\frac{ab^2}{c}} = d$$ ⇐ Square root of square cancels.

The above example involves the equation known as the *inverse square law* and will be seen again in Lesson 1.11.

Substitution

Linear equations are solved by combining like terms and reducing to find the solution. Quadratic equations are solved by substituting given values into the equation for all but one of the variables, thus making it a linear equation. The best approach is to first solve for the variable of interest by algebraic manipulation. Then find the solution by substituting the given values into the equation for the respective variables. The single, unknown variable, or the *variable of interes*t, will be left on one side, being set equal to the solution. For example:

Given the equation: $2x - y^2 = 3a$ - b; where $x = 5$, $y = (-4)$ and $a = 3$; solve for b:

$2x - y^2 = 3a - b$	⇐ To solve for b:
$2x - y^2 + b = 3a - b + b$	⇐ Add b to both sides, and cancel.
$2x - y^2 + b = 3a$	⇐ $-b + b$ cancels.
$b = 3a - 2x + y^2$	⇐ Transpose $2x - y^2$ to right side.
$b = 3(3) - 2(5) + (-4)^2$	⇐ Substitute known values.
$b = 9 - 10 + 16$	⇐ Perform operations.
$b = 15$	⇐ Simplify.

Practice Problems

Solve for the unknown variable:

1.	$x + 3 = 10$	**2.**	$5 + z = 8$
3.	$\frac{y}{4} = 2$	**4.**	$\frac{r}{2} = 6$
5.	$5(j + 5) = 45$	**6.**	$5d = 25$
7.	$9n^2 = 81$	**8.**	$a + 6 - 6a = -14$

Solve for a:

9.	$a^2b = c^2d$	**10.**	$\frac{b}{a} = \frac{c}{d}$

Substitute the values given and simplify the expression.

11.	$3x + 14y - xy$	where $x = 5$, $y = 2$
12.	$\frac{4s + 1}{6t + s}$	where $s = -3$, $t = 10$
13.	$\frac{16a + 5b}{1 - 4a}$	where $a = -1$, $b = 5$
14.	$3i + \frac{j}{1 + k} = 0$	where $k = 2$, $j = -12$, solve for i
15.	$7(2m - \frac{3}{4}n) + l = 10$	where $m = \frac{1}{2}$, $n = 8$, solve for l

1.01.12 Solve equations using common and/or natural logarithms.

LOGARITHMS

In many cases, arithmetic operations can be performed much more quickly if the numbers involved are numbers with exponents to the same base. For example, the multiplication or division of numbers with exponents to the same base can be performed by merely adding or subtracting the exponents. Raising to a power or taking a root can be performed by merely multiplying or dividing the exponents by the power or root. It is this feature of numbers with exponents which led to the development of *logarithm*s. If all numbers could be readily written as numbers with exponents to the same base, multiplication, division, raising to powers and taking roots could be performed much more quickly.

Any number can be expressed as a power of any other number. For example, 64 equals 2^6, 4^3, or 8^2. 64 also equals $7^{2.137}$ or $10^{1.806}$. The use of logarithms involves expressing numbers as powers of a common number, such as 10, so that arithmetic operations with these numbers can be performed more quickly.

Simply put, a logarithm is an exponent. More explicitly, the logarithm of a number *n* is the exponent *x* of a given base *b* that is required to produce that number. The symbol **log** is used to denote taking a logarithm. The base is usually indicated by a small number written to the right and slightly below the symbol log (e.g., $\log_b$). The general relationship and form are as follows:

If $n = b^x$; where $b > 0$ and $b \neq 1$, then: $\log_b n = x$.

For example:

$1000 = 10^3 - \log_{10} 1000 = 3$

This says that the base ten logarithm of 1000 is 3, which means that the base number, 10, must be raised to the power of 3 to equal 1000.

Here are some additional examples:

$2^3 = 8 \quad \Rightarrow \log_2 8 = 3$
$4^{3/2} = 8 \quad \Rightarrow \log_4 8 = 3/2$

Before the development of the scientific calculator, the use of logarithms saved considerable computation time. For example, the evaluation of the following expression by hand would take a very long time.

$$\frac{(865)^3(0.0247)^{1/2}(93{,}800)}{(0.00186)(4.53)^2}$$

However, using logarithms the above expression could be evaluated in a matter of minutes. Thus, logarithms, or *log*s, became one of the most useful tools in mathematics. In addition to simplifying arithmetic calculations and shortening computation time, logs are also important in engineering applications. The relationship between a number and its logarithm is used frequently to assist in measuring physical quantities when they vary over a wide range. For example, logarithmic scales are used to measure the neutron flux in nuclear reactors. Logarithms are also used for scales on charts and meters.

Properties of Logarithms

Since logarithms are exponents, the basic rules of exponents can be used to develop several useful properties of logarithms. Suppose that a, x, and *y* are numbers, and *a* is a suitable base for a logarithm ($a > 0$, $a \neq 1$). The product rule for exponents says:

$$a^x \cdot a^y = a^{(x+y)}$$

Let us say that: $u = a^x$ and $v = a^y$

If we write each of these in logarithmic form we would have:

$$x = \log_a u \text{ and } y = \log_a v$$

Then: $$u \cdot v = a^x \cdot a^y = a^{(x+y)}$$

If we write this in logarithmic form it would be:

$$\log_a (u \cdot v) = x + y$$

If we substitute the values for *x* and *y* from above we have:

$$\log_a (u \cdot v) = \log_a u + \log_a v$$

This results in one of the rules for logarithms, the **product rul**e. Using similar methods, we could also prove the other two rules that have been developed for logarithms.

Table 3. Rules for Logarithms

Product Rule:	$\log_a uv = \log_a u + \log_a v$
(The log of a product is the sum of the logs.)	
Quotient Rule:	$\log_a \frac{u}{v} = \log_a u - \log_a v$
(The log of a quotient is the difference of the logs.)	
Power Rule:	$\log_a u^n = n \log_a u$
(The log of a number to a power is the power times the log of the number.)	

Base Ten Logarithms

Logs with the base of 10 are the most commonly used logarithms because of their relationship to the place values in the decimal system. Because of their wide use, base ten logarithms are often referred to as *common logarithm*s. Observe the patterns in the number line and table below. Notice the relationship between the power of ten and the logarithm.

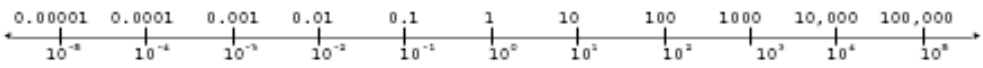

Table 4. Log to Power of 10 Relationship

Decimal	Power	Log
0.00001	10^{-5}	−5
0.0001	10^{-4}	−4
0.001	10^{-3}	−3
0.01	10^{-2}	−2
0.1	10^{-1}	−1
1	10^{0}	0
10	10^{1}	1
100	10^{2}	2
1000	10^{3}	3
10,000	10^{4}	4
100,000	10^{5}	5

Any number can be expressed as a power of ten. Thus, 10 equals 10^1, 1,000 equals 10^3, 64 equals $10^{1.806}$ and 527.3 equals $10^{2.7221}$. Once a number has been expressed as a power of ten, the base ten logarithm of the number is known-it is the exponent of 10. Thus $\log_{10}$ 10 equals 1, $\log_{10}$ 1000 equals 3, $\log_{10}$ 64 equals 1.806 and $\log_{10}$ 527.3 equals 2.722. Since base ten logarithms are so commonly used, the subscript 10 is often omitted after the symbol log. Thus, log 27.3 means the logarithm of 27.3 to the base 10.

A common logarithm is most often a mixed number consisting of a whole number part and a decimal fraction part. The whole number part is called the *characteristic* of the logarithm. The decimal fraction part is called the *mantiss*a. For example, in the logarithm of 527.3, which equals 2.7221, the characteristic is 2 and the mantissa is 0.7221. The mantissas of most logarithms are rounded off to a specified number of significant digits, typically four.

Table 5. Four-place Logarithms

											Proportional Parts								
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1.0	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
1.1	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
1.2	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
1.3	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
1.4	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
1.5	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
1.6	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
1.7	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
1.8	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
1.9	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
2.0	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
2.1	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
2.2	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
2.3	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
2.4	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
2.5	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
2.6	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
2.7	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
2.8	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
2.9	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
3.0	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
3.1	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
3.2	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
3.3	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
3.4	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
3.5	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
3.6	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
3.7	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
3.8	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
3.9	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
4.0	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
4.1	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
4.2	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
4.3	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
4.4	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
4.5	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
4.6	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
4.7	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
4.8	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	5	5	6	7	8
4.9	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	5	5	6	7	8
5.0	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
5.1	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
5.2	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
5.3	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
5.4	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

Table 5. Four-place Logarithms

											Proportional Parts								
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
5.5	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
5.6	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	1	2	3	4	5	5	6	7
5.7	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
5.8	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
5.9	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
6.0	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
6.1	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
6.2	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
6.3	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
6.4	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
6.5	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
6.6	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
6.7	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
6.8	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
6.9	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
7.0	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
7.1	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
7.2	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
7.3	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
7.4	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
7.5	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
7.6	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
7.7	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
7.8	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
7.9	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
8.0	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
8.1	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
8.2	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
8.3	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
8.4	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
8.5	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
8.6	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
8.7	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
8.8	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
8.9	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
9.0	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
9.1	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
9.2	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
9.3	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
9.4	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
9.5	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
9.6	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
9.7	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
9.8	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
9.9	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

Log-Table Method

To find the common logarithm of a number using four-place log tables, use the following steps:

1) Write the number in scientific notation with up to four significant digits.

2) Using the product rule for logarithms, write the log of the product as the sum of the logs of the factors.

3) Determine the mantissa as follows:

   a) Find the row in the table corresponding to the first two digits of the number, then move over to the column corresponding to the third digit of the number.
   b) Find the number under the proportional parts section corresponding to the fourth digit of the number, and add it to the last digit of the decimal obtained in step 3.a.

4) Determine the characteristic by using the power of 10 written in step 1 and write the logs in the form of a sum.

   NOTE: If the power of 10 is negative, the log may be left in this form.

5) Using the product rule, write the sum of the logs as the log of a product.

   NOTE: If the power of 10 is negative, the mantissa will be changed because of the subtraction of a whole number.

Example:	log 45,830
1) Write the number in scientific notation.	$\log (4.583 \times 10^4)$
2) Use the product rule to write the product as the sum of the logs.	$\log 4.583 + \log 10^4$
3) a) Find the 4.5 row of the log table. Move over to the 8 column to find the mantissa. 0.6609	$\log 4.583 + 4$
b) Find the 3 column under the proportional parts section of the log table. Add this to the last digit of the mantissa in step 3.a.	$\underline{+\ 0.0003}$ 0.6612
4) Write the mantissa and characteristic as a sum.	$0.6612 + 4$
5) Add the characteristic to the mantissa.	4.6612

Example:	log 0.004583
1) First, we write the number in scientific notation.	$\log (4.583 \times 10^{-3})$
2) Next, we use the product rule to write the product as the sum of the logs.	$\log 4.583 + \log 10^{-3}$
	$\log 4.583 + (- 3)$
3) The mantissa will be the same as in the previous example because the significant digits are the same.	0.6612
4) Now, we write the mantissa and characteristic as a sum. Since the characteristic is negative we could leave the logarithm in this form.	0.6612 + (- 3)
	0.6612 - 3
5) Add the characteristic to the mantissa. Note that the mantissa has changed. Also note that this is not the same as - 3.6612.	- 2.3388

As you may have observed, the mantissa of the base ten logarithm of a number depends only on the succession of significant digits in the number. The position of the decimal point in the number does not affect the mantissa. Of course, the characteristics are different for each of these numbers.

Table 6. Mantissa for Successive Significant Digits

Number	Scientific Notation	Log Long form	Log Short form
0.000524	5.24×10^{-4}	0.7193 – 4	–3.2807
0.00524	5.24×10^{-3}	0.7193 – 3	–2.2807
0.0524	5.24×10^{-2}	0.7193 – 2	–1.2807
0.524	5.24×10^{-1}	0.7193 – 1	–0.2807
5.24	5.24×10^{0}	0.7193 + 0	0.7193
52.4	5.24×10^{1}	0.7193 + 1	1.7193
524	5.24×10^{2}	0.7193 + 2	2.7193
5240	5.24×10^{3}	0.7193 + 3	3.7193
52,400	5.24×10^{4}	0.7193 + 4	4.7193

Note that any time the logarithm of a number is rounded off it would be considered an approximate answer since each digit is necessary to exactly duplicate the number when the base is raised to that exponent. Since each significant digit of the logarithm affects the actual value of the number, a standard of four significant digits should be maintained to ensure appropriate accuracy in the answers.

Calculator Method

Since hand-held scientific calculators are readily available today, it is impractical to use log tables. To find the logarithm of a number with a calculator:

1. Enter the number.
2. Press the $\boxed{\text{log}}$ key. The number displayed is the logarithm of the number entered in step 1.

Natural Logarithms

A logarithm can be written to any base. For most practical computations, base ten logarithms are used because of their relationship to the place values in the decimal system. However, in many scientific and engineering problems, it is convenient to use another base, symbolized by the letter e. *e* is an irrational number whose value is 2.71828 . . . The actual value of *e* is the limiting value of $(1 + 1/n)^n$ as n gets larger and larger.

Although it is an irrational number, it can still be used as the base for logarithms in the same way as 10 is used for base ten logarithms. *e* is the basis for many laws of nature, such as the laws of growth and decay of physical quantities, including the decay of radioactive substances and the growth and decay of neutron population in a nuclear reactor. Because of the relationship of *e* to natural phenomena, logarithms to the base *e* are called *natural logarithm*s.

The natural logarithm of a number is the exponent to which e must be raised in order to get that number. The symbol **ln** is used to denote a natural logarithm which is the same as saying $\log_e$. The relationship is expressed as follows:

If $e^x = n$ then $\ln n = x$

For example:

$\ln 2 = 0.693147\ldots$	which means that $e^{0.693147\ldots} = 2$.
$\ln 10 = 2.302585\ldots$	which means that $e^{2.302585\ldots} = 10$
$\ln e = 1$	which means that $e^1 = e$

Natural logarithms are not often used for computations. However, they appear frequently in decay and shielding calculations problems because of the relationship of *e* to natural phenomena. As a result, it is important to know how to determine the natural logarithms of numbers.

Tables of natural logarithms are available in several standard handbooks. However, there are several important differences between natural logarithms and base ten logarithms which must be understood to use natural logarithms. A natural logarithm is not separated into a characteristic and a mantissa. This is because the whole number part of a natural logarithm

does not relate to the position of the decimal point. Therefore, tables of natural logarithms give the entire logarithm, not just the decimal fraction part. Moreover, if a natural logarithm is negative, the entire logarithm is negative and is shown as such in a table of natural logarithms. Further, there is no part of the natural logarithm of a number which is not affected by the position of the decimal point. For all these reasons, tables of natural logarithms cannot be made concise.

To find the natural log of a number using a hand-held calculator:

1. Enter the number.
2. Press the $\boxed{ln}$ key. The number displayed is the natural logarithm of the number entered in step 1.

Antilogarithms

An *antilogarith*m, usually shortened to "antilog," is the opposite of a logarithm and is much easier to do. The antilog of a given number is the value obtained by raising the base to that number. Finding antilogs is an important part in the overall use of logarithms in computations. If numbers are converted to logarithms to perform calculations, the answer must be converted back from logarithms once the calculations have been performed. The symbol $\mathbf{log}^{-1}$ is used in calculations to indicate the antilog is going to be taken. The base of 10 is assumed unless otherwise noted. The general form is:

log -1 $x = n$ which means 10 $x = n$

For example:

$\log^{-1} 3$ which means $10^3 = 1000$

To find the antilog of a number using log tables:	$\log^{-1} 2.7832$
1) Write the number in log long form.	$\log^{-1} (0.7832 + 2)$
2) Find the mantissa in the table. Take the value at the head of the row and attach to it the value at the head of the column.	6.0 7 6.07
3) Write this value in scientific notation, putting the characteristic of the original number as the power of ten.	$6.07 \times 10\ 2$
4) Write this number in standard form.	607

On a scientific calculator the antilog of a number is obtained by raising the base (10) to that number.

1) Enter the number.
2) Press the $\boxed{\log^{-1}}$ or $\boxed{10^x}$ key. The number displayed is the antilog of the number log of entered in step 1. In other words, 10 raised to that power.

The symbol $\mathbf{ln^{-1}}$ is used to denote the inverse natural log, i.e. the antilog of base e.

$\ln^{-1} x = n$ which means $e^x = n$

For example:

$\ln^{-1} 0.693 \ldots$ which means $e^{0.693\ldots} = 2$

On a scientific calculator the inverse natural log of a number is obtained as follows:

1) Enter the number.
2) Press the $\boxed{\ln^{-1}}$ or $\boxed{e^x}$ key. The number displayed is the inverse natural log of the number of entered in step 1. In other words, *e* raised to that power.

Table 7. Summary of Common and Natural Log Definitions

Expression	Meaning	Example	Key-in
	10 is the base of the common logarithm.		
$\log n$	Asks: "10 raised to what power will equal n?	$\log 100 = 2$	$\boxed{\log}$
$\log^{-1} n$	Asks: "10 raised to the n power equals what?	$\log^{-1} 2 = 100$	$\boxed{10^x}$
	e is the base of the natural logarithm.		
$\ln n$	Asks: "*e* raised to what power will equal n?	$\ln 2 = 0.693\ldots$	$\boxed{\ln}$
$\ln^{-1} n$	Asks: "*e* raised to the n power equals what?	$\ln^{-1} 0.693\ldots = 2$	$\boxed{e^x}$

Solving for Variables as Exponents

One of the useful applications for logarithms is to solve algebraic equations with unknown exponents. In the following example, for instance, if the exponent is not known, it would be difficult to determine the correct value of *x* in order to make the statement (or equation) true.

$2356 = 3^x$

With the use of logarithms, however, this type of problem can be easily solved. The steps for solving an equation of this type are:

1) Make sure the base raised to the unknown exponent is isolated on one side of the equation (this may involve some manipulation of the formula in more complicated equations).

2) Take the log of both sides of the equation:

   $\log 2356 = \log 3^x$

3) The right side of the equation can be rewritten using the power rule:

   $\log 2356 = x (\log 3)$

4) Divide both sides by log 3 which moves it to the right side of the equation:

$$\frac{\log 2356}{\log 3} = \frac{x(\log 3)}{\log 3}$$

5) Cancel terms and rewrite the equation:

$$\frac{\log 2356}{\log 3} = x$$

6) Perform the operations and solve:

7) This answer can now be checked by substituting it back into the original equation to see if it makes the statement true:

$$2356 = 3^{7.068}$$

Some problems may involve the base of the natural logarithm *e* raised to an unknown power. This exponent can be determined by isolating *e* on one side of the equation and then taking the natural log of both sides. This is done because the natural log of *e* is 1. For example:

$$125 = 1000e^n$$

$$\frac{125}{1000} = e^n$$

$$\ln \frac{125}{1000} = \ln e^n$$

$$\ln 0.125 = (\ln e)(n)$$

$$\ln 0.125 = (1)(n)$$

$$-2.0794 = n$$

Practice Problems

Perform the following operations:

1. log 6.40
2. log 0.5
3. $\log^{-1} 16$
4. $\log^{-1} 3.7846$
5. ln 86
6. ln 0.5
7. $\ln^{-1} 0.695$
8. $\ln^{-1} 1$

Use logarithms to solve for the unknown variable:

9. $5 = 4^x$
10. $23 = 6^t$
11. $9 = 22(3)^y$
12. $50 = 2000(½)^n$

SUMMARY

A good foundation in mathematics is essential for the RCT. Calculations of various types are performed routinely in radiological control operations. The skills learned in this lesson will be applied in many of the lessons that follow as well as in the workplace.

ANSWERS TO PRACTICE PROBLEMS:

Fractions

1. 1/3 + 2/3 = 3/3 = 1
2. 5/7 _ 3/7 = 2/7
3. 5/9 + 2/3 = 5/9 + 6/9 = 11/9 = 1 2/9
4. 6/7 _ 1/2 = 12/14 _ 7/14 = 5/14
5. 2 _ 1/3 = 6/3 _ 1/3 = 5/3 = 1 2/3
6. 3/8 + 15/16 = 6/16 + 15/16 = 21/16 = 1 5/16
7. 25/32 _ 3/4 = 25/32 _ 24/32 = 1/32
8. 15/21 _ 4/7 = 5/7 _ 4/7 = 1/7
9. 13/20 _ 2/5 = 13/20 _ 8/20 = 5/20 = 1/4
10. 7/18 + 5/9 = 7/18 + 10/18 = 17/18
11. 2/3 × 1/5 = 2/15
12. 4/7 × 3/4 = 3/7
13. 1/2 × 2 = 1
14. 3/5 × 4 = 12/5 = 2 2/5
15. 4/9 ÷ 2/3 = 4/9 × 3/2 = 2/3
16. 8/13 × 2/3 = 16/39
17. 12/15 × 3/5 = 36/75
18. 20/25 ÷ 4/5 = 20/25 × 5/4 = 4/5 × 5/4 = 1
19. 7/8 × 2/5 = 7/4 × 1/5 = 7/20
20. 14/21 ÷ 2/7 = 14/21 × 7/2 = 2/3 × 7/2 = 7/3 = 2 1/3

Decimals

1. 0.23 + 3.4 = 3.63
2. 5.75 _ 2.05 = 3.7
3. 6.1 _ 1.6 = 4.5
4. 0.018 + 0.045 = 0.063
5. 468.75 _ 192.5 = 276.25
6. 2.3 × 3.2 = 7.36
7. 0.007 × 2.18 = 0.01526
8. 5.2 ÷ 1.4 = 3.7143
9. 12.26 ÷ 0.04 = 306.5
10. 4.0 × 0.25 = 1

Fraction/Decimal Conversions

1. 1/2 = 0.5
2. 2/5 = 0.4
3. 5/8 = 0.625
4. 12/25 = 0.48
5. 13/39 = $0.\overline{3}$
6. 7/16 = 0.4375

7. 0.125 = 125/1000 = 1/8
8. 0.6666 = 2/3
9. 4.25 = 4 25/100 = 4¼
10. 0.2 = 2/10 =1/5

Percent

1. 0.5 = 50%
2. 0.782 = 78.2%
3. 1.1 = 110%
4. 0.06 = 6%
5. 0.049 = 4.9%
6. 0.0055 = 0.55%

7. 65% = 0.65
8. 0.25% = 0.0025
9. 300% = 3
10. 0.09% = 0.0009

Signed Numbers

1. (-28) + (-51) = -79
2. (-2) + (-5) = -7
3. 40 + (-21) = 19
4. -87 + 50 = -37
5. 48 + (-27) = 21
6. 56 - (-5) = 61
7. 81 - 4 = 77
8. -48 - (-2) = -46
9. -4(5) = -20
10. 6/(-3) = -2
11. 4 (-5) = -20
12. (-6)/(-3) = 2
13. (-6)/3 = -2
14. (-8)(-5) = 40
15. (-7)(6) = -42

Exponents

1. $(3^2)(3^3) = 3^5$
2. $7^5/7^3 = 7^2$
3. $(10^5)(10^6) = 10^{11}$
4. $(10^6)(10^{-4}) = 10^2$
5. $6^{-4}/6^{-3} = 6^{-1}$
6. $6^{-8}/6^3 = 6^{-11}$

Square Roots

1. $\sqrt{16} = 4$
2. $-\sqrt{81} = -9$
3. $\sqrt{144} = 12$
4. $\sqrt{15^2} = 15$
5. $(\sqrt{6})^2 = 6$
6. $-\sqrt{400} = -20$
7. $\sqrt{\frac{1}{64}} = \frac{1}{8}$
8. $\sqrt{9 \cdot 49} = \sqrt{3^2 \cdot 7^2} = \sqrt{3^2} \cdot \sqrt{7^2} = 3 \cdot 7 = 21$
9. $\sqrt{\frac{81}{36}} = \frac{\sqrt{81}}{\sqrt{36}} = \frac{\sqrt{9^2}}{\sqrt{6^2}} = \frac{9}{6} = \frac{3}{2}$
10. $-\sqrt{625} = -\sqrt{25^2} = -25$

Scientific Notation

1. $(2 \times 10^{-2})(3 \times 10^{-2}) = 6 \times 10^{-4}$
2. $(6 \times 10^{-8})/(3 \times 10^3) = 2 \times 10^{-11}$
3. $(9 \times 10^4)(-1 \times 10^{-2}) = -9 \times 10^2$
4. $(3 \times 10^{-7})(9 \times 10^2) = 2.7 \times 10^{-4}$
5. (7E2)(6E4) = 4.2E7
6. (5E-3)/(5E-2) = 1E-1

Order of Operations

1. 5 + (-3) - (-2) - 6 = 5 + 6 - 6 = 5
2. 18 - [52 ÷ (7 + 6)] = 18 - (52 ÷ 13) = 18 - 4 = 14
3. 19 - 7 + 12 - 2 ÷ 8 = 12 + 24 ÷ 8 = 12 + 3 + 15
4. 2^3 - 20 ÷ 4 + 4 - 3 = 8 - 5 + 12 = 3 + 12 = 15
5. $10 + 6(0.5)^3 = 10 + 6(0.125) = 10 + 0.75 = 10.75$
6. $3^3 + 10 \div 5 = 27 + 2 = 29$
7. $(8 + 4 - 3)^2 = (8 + 12)^2 = 20^2 = 400$

8. $7(4^2 - 10) \div (12 - \frac{3}{4}) = 7(16 - 10) \div 9 = 7(6) \div 9 = 42 \div 9 = 4.667$
9. $7(6 - 2^2) = 7(6 - 4) = 7(2) = 14$
10. $(57 - 2^5)^{1/2} = (57 - 32)^{1/2} = 25^{1/2} = 5$

Algebra

1.
$$x + 3 = 10$$
$$x + 3 - 3 = 10 - 3$$
$$x = 7$$

2.
$$5 + z = 8$$
$$5 + z - 5 = 8 - 5$$
$$z = 3$$

3.
$$\frac{y}{4} = 2$$
$$4 \cdot \frac{y}{4} = 2 \cdot 4$$
$$y = 8$$

4.
$$\frac{r}{2} = 6$$
$$2 \cdot \frac{r}{2} = 6 \cdot 2$$
$$r = 12$$

5.
$$5(j + 5) = 45$$
$$\frac{5(j + 5)}{5} = \frac{45}{5}$$
$$j + 5 = 9$$
$$j + 5 - 5 = 9 - 5$$
$$j = 4$$

6.
$$5d = 25$$
$$\frac{5d}{5} = \frac{25}{5}$$
$$d = 5$$

7.
$$9n^2 = 81$$
$$\frac{9n^2}{9} = \frac{81}{9}$$
$$n^2 = 9$$
$$\sqrt{n^2} = \sqrt{9}$$
$$n = 3$$

8.
$$a+6-6a=-14$$
$$6-5a=-14$$
$$6-5a-6=-14$$
$$-5a=-20$$
$$\frac{-5a}{-5}=\frac{-20}{-5}$$
$$a=4$$

9.
$$a^2b=c^2d$$
$$\frac{a^2b}{b}=\frac{c^2d}{b}$$
$$a^2=\frac{c^2d}{b}$$
$$\sqrt{a^2}=\sqrt{\frac{c^2d}{b}}$$
$$a=\sqrt{\frac{c^2d}{b}}$$

10.
$$\frac{b}{a}=\frac{c}{d}$$
$$a\cdot\frac{b}{a}=\frac{c}{d}\cdot a$$
$$b=\frac{ca}{d}$$
$$d\cdot b=\frac{ca}{d}\cdot d$$
$$db=ca$$
$$\frac{db}{c}=\frac{ca}{c}$$
$$\frac{db}{c}=a$$

11. $3x+14y-xy$ where x = 5, y = 2

3(5) + 14(2) – 5(2)
15 + 28 – 10
43-10
33

12. $\frac{4s+1}{6t+s}$ where $s = -3$, $t = 10$

$$\frac{4(-3)+1}{6(10)+(-3)}$$

$$\frac{-12+1}{60+(-3)}$$

$$\frac{-11}{57}$$

13. $\frac{16a+5b}{1-4a}$ where $a = -1$, $b = 5$

$$\frac{16(-1)+5(5)}{1-4(-1)}$$

$$\frac{-16+25}{1+4}$$

$$\frac{9}{5}$$

$$1\frac{4}{5}$$

14. $3i+\frac{j}{1+k}=0$ where $k = 2$, $j = -12$, solve for i

$$3i+\frac{-12}{1+2}=0$$

$$3i-4=0$$

$$3i=4$$

$$i=\frac{4}{3}$$

$$i=1\frac{1}{3}$$

15. $7(2m - \frac{3}{4}n) - l - 10$ where $m - \frac{1}{2}\ n - 8$, solve for l

$7[2(\frac{1}{2}) - \frac{3}{4}(8)] - l - 10$

$7(1 - 6) - l - 10$

$7(-5) - l - 10$

$-35 - l - 10$

$l - 45$

Logarithms

1. log 6.40 = 0.8062
2. log 0.5 = _0.301
3. $\log^{-1} 16 = 1 \times 10^{16}$
4. $\log^{-1} 3.7846 = 6089.76$
5. ln 86 = 4.45
6. ln 0.5 = _0.693
7. $\ln^{-1} 0.695 = 2.004$
8. $\ln^{-1} 1 = e = 2.7182 \ldots$

9.
$$\begin{aligned} 5 &= 4^x \\ \log 5 &= \log [4^x] \\ \log 5 &= (\log 4)(x) \\ \frac{\log 5}{\log 4} &= x \\ \frac{0.69897}{0.60206} &= x \\ 1.161 &= x \end{aligned}$$

10.
$$\begin{aligned} 23 &= 6^t \\ \log 23 &= \log [6^t] \\ \log 23 &= (\log 6)(t) \\ \frac{\log 23}{\log 6} &= t \\ \frac{1.36173}{0.77815} &= t \\ 1.74995 &= x \end{aligned}$$

11.
$$\begin{aligned} 9 &= 22(3^y) \\ \frac{9}{22} &= 3^y \\ \log \frac{9}{22} &= \log [3^y] \\ \log \frac{9}{22} &= (\log 3)(y) \\ \frac{\log \frac{9}{22}}{\log 3} &= y \\ \frac{-0.38818}{0.47712} &= y \\ -0.8136 &= y \end{aligned}$$

12.

$$
\begin{aligned}
50 &= 2000\left(\tfrac{1}{2}\right)^n \\
\frac{50}{2000} &= \left(\tfrac{1}{2}\right)^n \\
0.025 &= (0.5)^n \\
\log 0.025 &= \log\left[0.5^n\right] \\
\log 0.025 &= (\log 0.5)n \\
\frac{\log 0.025}{\log 0.5} &= n \\
\frac{-1.60206}{-0.30103} &= n \\
5.3219 &= n
\end{aligned}
$$

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Course Title: **Radiological Control Technician**
Module Title: **Unit Analysis & Conversion**
Module Number: **1.02**

Objectives :

1.02.01 Identify the commonly used unit systems of measurement and the base units for mass, length, and time in each system.

1.02.02 Identify the values and abbreviations for SI prefixes.

1.02.03 Given a measurement and the appropriate conversion factor(s) or conversion factor table, convert the measurement to the specified units.

1.02.04 Using the formula provided, convert a given temperature measurement to specified units.

INTRODUCTION

A working knowledge of the unit analysis and conversion process is necessary for the Radiological Control Technician. It is useful for air and water sample activity calculations, contamination calculations, and many other applications. This lesson will introduce the International System of Units (SI), the prefixes used with SI units, and the unit analysis and conversion process. Many calculations accomplished in radiological control are actually unit conversions, not complex calculations involving formulas that must be memorized.

REFERENCES:

1. "Health Physics and Radiological Health Handbook"; Shleien; 1992.
2. DOE-HDBK-1010-92 (June 1992) "Classical Physics" DOE Fundamental Handbook; US Department of Energy.
3. "Chart of the Nuclides"; Sixteenth Edition, Knolls Atomic; 2003.

UNITS AND MEASUREMENTS

Units are used in expressing physical quantities or *measurements*, i.e., length, mass, etc. All measurements are actually relative in the sense that they are comparisons with some standard unit of measurement. Two items are necessary to express these physical quantities: a <u>number</u> which expresses the magnitude and a <u>unit</u> which expresses the dimension. A number and a unit must both be present to define a measurement. Measurements are algebraic quantities and as such may be mathematically manipulated subject to algebraic rules.

Fundamental Quantities

All measurements or physical quantities can be expressed in terms of three fundamental quantities. They are called fundamental quantities because they are dimensionally independent. They are:

- *Length* (L)
- *Mass* (M) (not the same as weight)
- *Time* (T)

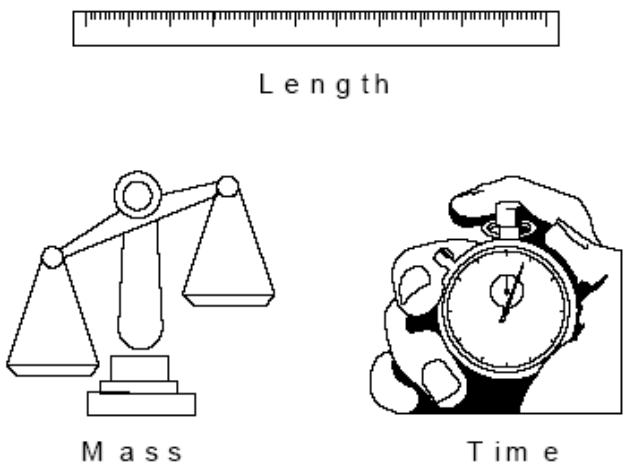

Figure 1. Fundamental Units

Derived Quantities

Other quantities are derived from the fundamental quantities. These *derived* quantities are formed by multiplication and/or division of fundamental quantities. For example:

- Area is the product of *length* times *length* (width), which is L × L, or L^2.
- Volume is area times length, which is *length* times *length* times *length*, or L^3.
- Velocity is expressed in *length* per unit *time*, or L/T.
- Density is expressed in *mass* per unit volume, or M/L^3.

1.02.01	*Identify the commonly used unit systems of measurements and the base units for mass, length, and time in each system.*

SYSTEMS OF UNITS

The units by which physical quantities are measured are established in accordance with an agreed standard. Measurements made are thereby based on the original standard which the unit represents. The various units that are established, then, form a *system* by which all measurements can be made.

English System

The system that has historically been used in the United States is the English System, sometimes called the English Engineering System (EES). Though no longer used in England, many of the units in this system have been used for centuries and were originally based on common objects or human body parts, such as the foot or yard. Though practical then, the standards for these units were variable as the standard varied from object to object, or from person to person. The base units for length, mass, and time in the English system are the foot, pound, and second, respectively.

Even though fixed standards have since been established for these antiquated units, no uniform correlation exists between units established for the same quantity. For example, in measuring relatively small lengths there are inches, feet, and yards. There are twelve inches in a foot, and yet there are only three feet in a yard. This lack of uniformity makes conversion from one unit to another confusing as well as cumbersome. However, in the U.S., this system is still the primary system used in business and commerce.

Table 1. English System Base Units

Physical Quantity	Unit	Abbr.
Length:	foot	ft.
Mass:	pound	lb.
Time:	second	sec.

International System of Units (SI)

Since the exchange of scientific information is world-wide today, international committees have been set up to standardize the names and symbols for physical quantities. In 1960, the **International System of Units** (abbreviated SI from the French name Le **S**ystème **I**nternationale d'Unites) was adopted by the 11th General Conference of Weights and Measures (CGPM). The SI, or modernized **metric system**, is based on the decimal (base 10) numbering system. First devised in France around the time of the French Revolution, the metric system has since been refined and expanded so as to establish a practical system of units of measurement suitable for adoption by all countries. The SI system consists of a set of specifically defined units and prefixes that serve as an internationally accepted system of measurement. Nearly all countries in the world use metric or SI units for business and commerce as well as for scientific applications.

1.02.02 Identify the values and abbreviations for SI prefixes.

SI Prefixes

The SI system is completely decimalized and uses prefixes for the base units of *meter* (m) and *gram* (g), as well as for derived units, such as the *liter* (l) which equals 1000 cm^3.

SI prefixes are used with units for various magnitudes associated with the measurement being made. Units with a prefix whose value is a positive power of ten are called *multiples*. Units with a prefix whose value is a negative power of ten are called *submultiples*.

For example, try using a yard stick to measure the size of a frame on film for a camera. Instead you would use inches, because it is a more suitable unit. With the metric system, in order to measure tiny lengths, such as film size, the prefix *milli-* can be attached to the meter unit to make a millimeter, or 1/1000 of a meter. A millimeter is much smaller and is ideal in this situation. On the other hand, we would use a prefix like *kilo-* for measuring distances traveled in a car. A *kilometer* would be more suited for these large distances than the meter.

Table 2. SI Prefixes

PREFIX	FACTOR	SYMBOL	PREFIX	FACTOR	SYMBOL
yotta	10^{24}	Y	deci	10^{-1}	d
zetta	10^{21}	Z	centi	10^{-2}	c
exa	10^{18}	E	milli	10^{-3}	m
peta	10^{15}	P	micro	10^{-6}	µ
tera	10^{12}	T	nano	10^{-9}	n
giga	10^{9}	G	pico	10^{-12}	p
mega	10^{6}	M	femto	10^{-15}	f
kilo	10^{3}	k	atto	10^{-18}	a
hecto	10^{2}	h	zepto	10^{-21}	z
deka	10^{1}	da	yocto	10^{-24}	y

Prior to the adoption of the SI system, two groups of units were commonly used for the quantities length, mass, and time: **MKS** (for meter-kilogram-second) and **CGS** (for centimeter-gram-second).

Table 3. Metric Subsystems

Physical Quantity	CGS	MKS
Length:	centimeter	meter
Mass:	gram	kilogram
Time:	second	second

<u>SI Units</u>

There are seven fundamental physical quantities in the SI system . These are length, mass, time, temperature, electric charge, luminous intensity, and molecular quantity (or amount of substance). In the SI system there is one SI unit for each physical quantity. The SI system base units are those in the metric MKS system. Table 4 lists the seven fundamental quantities and their associated SI unit. The units for these seven fundamental quantities provide the base from which the units for other physical quantities are derived.

For most applications the RCT will only be concerned with the first four quantities as well as the quantities derived from them.

Radiological Units

In the SI system, there are derived units for quantities used for radiological control. These are the becquerel, the gray, and the sievert. The SI unit of activity is the becquerel, which is the activity of a radionuclide decaying at the rate of one spontaneous nuclear transition per second. The gray is the unit of absorbed dose, which is the energy per unit mass imparted to matter by ionizing radiation, with the units of one joule per kilogram. The unit for dose equivalence is the sievert, which has the units of joule per kilogram. These quantities and their applications will be discussed in detail in Lesson 1.06.

Other units

There are several other SI derived units that are not listed in Table 4. It should be noted that the SI system is evolving and that there will be changes from time to time. The standards for some fundamental units have changed in recent years and may change again as technology improves our ability to measure even more accurately.

Table 4. International System (SI) Units

Physical Quantity	Unit	Symbol	Dimensions
	Base units		
Length:	meter	m	m
Mass:	kilogram	kg	kg
Time:	second	s or sec.	s
Temperature:	kelvin	K	K or °K
Electric current:	ampere	A or amp	A or (C/s)
Luminous intensity:	candela	cd	cd
Molecular quantity:	mole	mol	mol
	Selected derived units		
Volume:	cubic meter	m^3	m^3
Force:	newton	N	$kg \cdot m/s^2$
Work/Energy:	joule	J	N·m
Power:	watt	W	J/s
Pressure:	pascal	Pa	N/m^2
Electric charge:	coulomb	C	A·s
Electric potential:	volt	V	J/C
Electric resistance:	ohm	Σ	V/A
Frequency:	hertz	Hz	s^{-1}
Activity:	becquerel	Bq	disintegration/s
Absorbed dose:	gray	Gy	J/kg
Equivalent dose:	sievert	Sv	$Gy \cdot W_R$

1.02.03	*Given a measurement and the appropriate conversion factor(s) or conversion factor table, convert the measurement to the specified units.*

UNIT ANALYSIS AND CONVERSION PROCESS

Units and the Rules of Algebra

Remember that a measurement consists of a number and a unit. When working problems with measurements, it should be noted that the measurement units are subject to the same algebraic rules as the values. Some examples are provided below.

$$(cm)\times(cm) = cm^2$$

$$\frac{ft^3}{ft} = ft^2$$

$$\frac{1}{yr} = yr^{-1}$$

As a result, measurements can be multiplied, divided, etc., in order to convert to a different system of units. Obviously, in order to do this, the units must be the same. For example, a square measures one foot in length and 18 inches in width. To find the area of the square in square inches we must multiply the length by the width. However, when the measurements are in different units, and cannot be multiplied directly.

We can convert feet to inches. We know that there are 12 inches in one foot. We can use this ratio to convert 1 foot to 12 inches. Then we can then calculate the area as 12 inches × 18 inches, which equals 216 in^2, which is a valid measurement.

Steps for Unit Analysis and Conversion

1) Determine given unit(s) and desired unit(s).

2) Build (or obtain) conversion factor(s) -- see Conversion Tables at end of lesson

A conversion factor is a ratio of two equivalent physical quantities expressed in different units. *When expressed as a fraction, the value of all conversion factors is 1*. Because a conversion factor equals 1, it does not matter which value is placed in the numerator or denominator of the fraction.

Examples of conversion factors are:

$$\frac{365days}{1year} \qquad \frac{12inches}{1\,foot} \qquad \frac{1foot^3}{2.832E4cm^3}$$

Building conversion factors involving the metric prefixes for the same unit can be tricky. This involves the conversion of a base unit to, or from, a subunit or superunit.

To do this, use the following steps: Example: 1 gram to milligrams

a) Place the base unit in the numerator and the subunit/ superunit in the denominator (or vice versa):

$$\frac{g}{mg}$$

b) Place a 1 in front of the subunit/superunit:

$$\frac{g}{1mg}$$

c) Place the value of the prefix on the subunit/ superunit in front of the base unit:

m (*milli*-) = 10^{-3} or 1E

$$\frac{1E-3g}{1mg}$$

Also remember that algebraic manipulation can be used when working with metric prefixes and bases. For example, 1 centimeter = 10^{-2} meters. This means that 1 meter = $1/10^{-2}$ centimeters, or 100 cm. Therefore, the two conversion factors below are equal:

$$\frac{1E-2m}{1cm} = \frac{1m}{100cm}$$

3) Set up an equation by multiplying the given units by the conversion factor(s) to obtain desired unit(s).

When a measurement is multiplied by a conversion factor, the unit(s) (and probably the magnitude) will change; however, the actual measurement itself does not change. For example, 1 ft and 12 inches are still the same length; only different units are used to express the measurement.

By using a "ladder" or "train tracks," a series of conversions can be accomplished in order to get to the desired unit(s). By properly arranging the numerator and denominator of the conversion factor(s), given and intermediate units will cancel out by multiplication or division, leaving the desired units. Some examples of the unit analysis and conversion process follow:

EXAMPLE 1.

Convert 3 years to seconds.

Step 1 - Determine given and desired unit(s):

Given units: years
Desired units: seconds.

Step 2 - Build/obtain conversion factor(s):

We can use multiple conversion factors to accomplish this problem:

1 year = 365.25 days
1 day = 24 hours
1 hour = 60 minutes
1 minute = 60 seconds

Step 3 - Analyze and cancel given and intermediate units. Perform multiplication and division of numbers:

$$\left(\frac{3years}{}\right)\left(\frac{365.25days}{1year}\right)\left(\frac{24hours}{1day}\right)\left(\frac{60minutes}{1hour}\right)\left(\frac{60seconds}{1minute}\right)=94,672,800\,\text{sec}.$$

Unit analysis and conversion process follow:

EXAMPLE 2.

What is the activity of a solution in $\frac{\mu Ci}{ml}$ if it has 2000 $\frac{dpm}{gallon}$?

Step 1 - Determine given and desired unit(s):

Given units: $\frac{dpm}{gallon}$

Desired units: $\frac{\mu Ci}{ml}$

Step 2 - Build conversion factor(s):

1 liter = 0.26418 gallons
1 dpm = 4.5 E-07 μCi
1 liter = 1000 ml

Step 3 - Analyze and cancel given and intermediate units. Perform multiplication and division of numbers.

$$\left(\frac{2000dpm}{gal}\right)\left(\frac{4.5E-7\mu Ci}{1dpm}\right)\left(\frac{0.26418gal}{1\ell}\right)\left(\frac{1\ell}{1,000ml}\right)=2.38E-7\frac{\mu Ci}{ml}$$

Practical exercises and their solutions are provided at the end of this lesson.

1.02.04	*Using the formula provided, convert a given temperature measurement to specified units.*

TEMPERATURE MEASUREMENTS AND CONVERSIONS

Temperature measurements are made to determine the amount of heat flow in an environment. To measure temperature it is necessary to establish relative scales of comparison. Three temperature scales are in common use today. The general temperature measurements we use on a day-to-day basis in the United States are based on the **Fahrenheit** scale. In science, the **Celsius** scale and the **Kelvin** scale are used. Figure 2 shows a comparison of the three scales.

The Fahrenheit scale, named for its developer, was devised in the early 1700's. This scale was originally based on the temperatures of human blood and salt-water, and later on the freezing and boiling points of water. Today, the Fahrenheit scale is a secondary scale defined with reference to the other two scientific scales. The symbol °F is used to represent a degree on the Fahrenheit scale.

About thirty years after the Fahrenheit scale was adopted, Anders Celsius, a Swedish astronomer, suggested that it would be simpler to use a temperature scale divided into one hundred degrees between the freezing and boiling points of water. For many years his scale was called the **centigrade** scale. In 1948 an international conference of scientists re-named it the Celsius scale in honor of its inventor. The Celsius degree, °C, was defined as 1/100 of the temperature difference between the freezing point and boiling point of water.

In the 19th century, an English scientist, Lord Kelvin, established a more fundamental temperature scale that used the lowest possible temperature as a reference point for the beginning of the scale. The lowest possible temperature, sometimes called *absolute zero*, was established as 0 K (zero Kelvin). This temperature is 273.15°C below zero, or -273.15°C. Accordingly, the Kelvin degree, K, was chosen to be the same as a Celsius degree so that there would be a simple relationship between the two scales.

Note that the degree sign (°) is not used when stating a temperature on the Kelvin scale. Temperature is stated simply as Kelvin (K). The Kelvin was adopted by the 10th Conference of Weights and Measures in 1954, and is the SI unit of thermodynamic temperature. Note that the degree Celsius (°C) is the SI unit for expressing Celsius temperature and temperature intervals. The temperature interval one degree Celsius equals one kelvin exactly. Thus, 0°C = 273.15 K by definition.

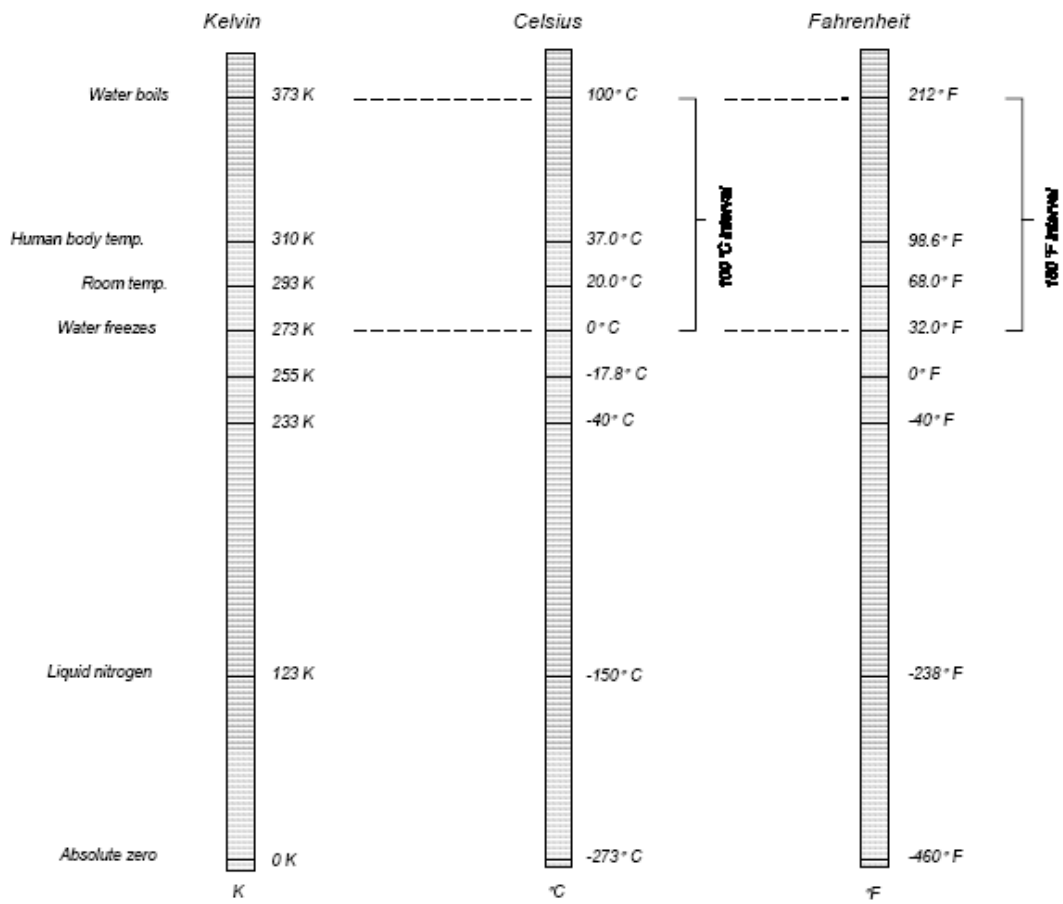

Figure 2. Comparison of Kelvin, Celsius and Fahrenheit scales.

To convert from one unit system to another, the following formulas are used:

Table 5. Equations for Temperature Conversions

°F to °C	$°C = \frac{(°F - 32)}{1.8}$ or $°C = (°F - 32)\left(\frac{5}{9}\right)$
°C to °F	$°F = 1.8(°C) + 32$ or $°F = \left(\frac{9}{5}\right)(°C) + 32$

°C to K	$K = °C + 273.15$

EXAMPLE 3.

Convert 65° Fahrenheit to Celsius.

$$°C = \frac{(65°F - 32)}{1.8}$$

$$°C = \frac{33}{1.8}$$

$$°C = 18.3°C$$

PRACTICAL EXERCISES:

Convert the following measurements:

1. 67 mm = _____ feet.

2. 1843 ounces = _____ kg.

3. 3500 microsieverts (μSv) = _____ millirem (mrem).

4. 0.007 years = _____ minutes.

5. 5000 disintegrations per minute (dpm) = _____ millicuries (mCi).

6. 2350 micrometer (µm) = _____ inches.

7. 2.5E-4 ergs = _____ keV.

8. 205 °F = _____ K.

9. 2E-3 rad = _____ milligray (mGy).

10. –25 °C = _____ °F.

Use unit analysis and conversion to solve the following problems.

11. Light travels at 186,000 miles per second. How many feet will light travel in one minute?

12. A worker earns a monthly salary of $2500. If the worker gets paid every two weeks and works no overtime, what will be the gross amount for a given pay period?

13. An air sampler has run for 18 hours, 15 minutes at 60 liters per minute. When collected and analyzed the sample reads 7685 disintegrations per minute (dpm). What is the concentration of the sample in microcuries/cm^3?

PRACTICAL EXERCISE SOLUTIONS:

1. 67 mm = _____ feet.

$$\left(\frac{67mm}{1}\right)\left(\frac{1m}{1E3mm}\right)\left(\frac{3.2808\,ft}{1m}\right)=0.22\,ft$$

2. 1843 ounces = _____ kg.

$$\left(\frac{1843oz}{1}\right)\left(\frac{28.35g}{1}oz\right)\left(\frac{1kg}{1E3g}\right)=52.25kg$$

3. 3500 microsieverts (μSv) = _____ millirem (mrem).

$$\left(\frac{3.5E3\mu Sv}{1}\right)\left(\frac{1Sv}{1E6\mu Sv}\right)\left(\frac{1E2rem}{1Sv}\right)\left(\frac{1E3mrem}{1rem}\right)=3.5E2mrem=350mrem$$

4. 0.007 years = _____ minutes.

$$\left(\frac{0.007year}{1}\right)\left(\frac{365.25}{1year}\right)\left(\frac{24hours}{1day}\right)\left(\frac{60minutes}{1hour}\right)=3681.72minutes$$

5. 5000 dis./min. = _____ millicuries (mCi).

$$\left(\frac{5E3dis}{\min}\right)\left(\frac{1Ci}{2.22E12\frac{dis}{\min}}\right)\left(\frac{1E3mCi}{1ci}\right)=2.25E-6mCi$$

6. 2350 micrometer (μm) = _____ inch.

$$\left(\frac{2350\mu}{1}\right)\left(\frac{3.937E-5inches}{1\mu}\right)=0.0925inches=9.25E-2inch$$

7. 2.5E-4 ergs = _____ keV.

$$\left(\frac{2.5E-4ergs}{1}\right)\left(\frac{6.2148E11}{1erg}\right)\left(\frac{1keV}{1E3eV}\right)=1.55E5keV$$

8. 205 EF = _____ K.

$$°C=\frac{(205°F-32)}{1.8}=96.1°C$$

$$K=96.1°C+273.16=369.27K$$

9. 2E-3 rad = _____ milligray (mGy).

$$\left(\frac{2E-3rad}{1}\right)\left(\frac{0.01Gy}{1rad}\right)\left(\frac{1E3mGys}{1Gy}\right)=2E-2mGy=0.02mGy$$

10. –25 °C = _____ °F.

$$°F=(-25°C)1.8+32=-13°F$$

Use unit analysis and conversion to solve the following:

11. Light travels at 186,000 miles per second. How many feet will light travel in one minute?

$$\left(\frac{186,000 miles}{\sec}\right)\left(\frac{5280\,ft}{1 mile}\right)\left(\frac{60\sec}{1 minute}\right) = 5.89E10\frac{ft}{\min}$$

12. A worker earns a monthly salary of $2500. If the worker gets paid every two weeks and works no overtime, what will be the gross amount for a given pay period?

$$\left(\frac{2500 dollars}{months}\right)\left(\frac{12 months}{1 year}\right)\left(\frac{1 year}{52 weeks}\right)\left(\frac{2 weeks}{payperiod}\right) = 1153.85\frac{dollars}{payperiod}$$

13. An air sampler has run for 18 hours, 15 minutes at 60 liters per minute. When collected and analyzed the sample reads 7685 dis./min. What is the concentration of the sample in microcuries/cm^3?

$$\left(\frac{15 minutes}{1}\right)\left(\frac{1 hour}{60 minutes}\right) = 0.25 hour$$

18 hours + 0.25 hours = 18.25 hours

$$\left(\frac{18.25 hours}{1}\right)\left(\frac{60 minutes}{1 hour}\right)\left(\frac{60 l}{1 minute}\right) = 65,700 l$$

$$\left(\frac{7685 dpm}{6.57E4 l}\right)\left(\frac{1 Ci}{2.22E12 dpm}\right)\left(\frac{1E6 \mu Ci}{1 Ci}\right)\left(\frac{1 l}{1E3 ml}\right)\left(\frac{0.99997 ml}{1 cc}\right) = 5.26E-11\frac{\mu Ci}{cc}$$

INSTRUCTIONS FOR USING CONVERSION FACTOR TABLES

The tables that follow include conversion factors that are useful to the RCT. They are useful in making a single conversion from one unit to another by using the guide arrows at the top of the page in accordance with the direction of the conversion. However, when using the tables to develop equivalent fractions for use in unit analysis equations, a better understanding of how to read the conversion factors given in the table is required.

The conversions in the table have been arranged by section in the order of fundamental units, followed by derived units:

Length
Mass
Time
Area
Volume
Density
Radiological
Energy
Fission
Miscellaneous (Temperature, etc.)

The easiest way to read a conversion from the table is done as follows. Reading *left to right,* "one (1) of the units in the left column is equal to the number in the center column of the unit in the right column." For example, look at the first conversion listed under **Length**. This conversion would be read from left to right as "1 angstrom is equal to E-8 centimeters," or

$$1\text{Å} = 10^{-8}\ centimeters \Rightarrow \frac{1\ \text{Å}}{10^{-8}\ centimeters}$$

Another conversion would be read from left to right as "1 millimeter (mm) is equal to 1E-1 centimeters," or *1 mm = 0.1 cm*. This method can be applied to any of the conversions listed in these tables when reading *left to right*.

If reading *right to left*, the conversion should be read as "one (1) of the unit in the right column is equal to the inverse of (1 over) the number in the center column of the unit in the left column." For example, using the conversion shown previously, the conversion reading right to left would be "1 inch is equal to the inverse of 3.937E-5 (1/3.937E-5) micrometers," or

$$1inch = \frac{1}{3.937E-5\mu m} = 2.54E4\mu m$$

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Length	
angstroms (Å)	10^{-8}	Cm
Å	10^{-10}	M
micrometer (µm)	10^{-3}	Mm
µm	10^{-4}	Cm
µm	10^{-6}	M
µm	3.937×10^{-5}	in.
mm	10^{-1}	Cm
cm	0.3937	in.
cm	3.2808×10^{-2}	Ft
cm	10^{-2}	M
m	39.370	in.
m	3.2808	Ft
m	1.0936	Yd
m	10^{-3}	Km
m	6.2137×10^{-4}	Miles
km	0.62137	Miles
mils	10^{-3}	in.
mils	2.540×10^{-3}	Cm
in.	10^{3}	Mils
in.	2.5400	Cm
ft	30.480	Cm
rods	5.500	Yd
miles	5280	Ft
miles	1760	Yd
miles	1.6094	Km

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Mass	
mg	10^{-3}	G
mg	3.527×10^{-5}	oz avdp
mg	1.543×10^{-2}	Grains
g	3.527×10^{-2}	oz avdp
g	10^{-3}	Kg
g	980.7	Dynes
g	2.205×10^{-3}	Lb
kg	2.205	Lb
kg	0.0685	Slugs
kg	9.807×10^{5}	Dynes
lb	4.448×10^{5}	Dynes
lb	453.592	G
lb	0.4536	Kg
lb	16	oz avdp
lb	0.0311	Slugs
dynes	1.020×10^{-3}	G
dynes	2.248×10^{-6}	Lb
u (unified--^{12}C scale)	1.66043×10^{-27}	Kg
amu (physical--^{16}0 scale)	1.65980×10^{-27}	Kg
oz	28.35	G
oz	6.25×10^{-2}	Lb

Note: Mass to energy conversions under miscellaneous

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Time	
days	86,400	Sec
days	1440	Min
days	24	Hours
years	3.15576×10^{7}	Sec
years	525,960	Min
years	8766	Hr
years	365.25	Days
	Area	
barns	10^{-24}	cm^2
circular mils	7.854×10^{-7}	$in.^2$
cm^2	10^{24}	Barns
cm^2	0.1550	$in.^2$
cm^2	1.076×10^{-3}	ft^2
cm^2	10^{-4}	m^2
ft^2	929.0	cm^2
ft^2	144	in^2
ft^2	9.290×10^{-2}	m^2
$in.^2$	6.452	cm^2
$in.^2$	6.944×10^{-3}	ft^2
$in.^2$	6.452×10^{-4}	m^2
m^2	1550	$in.^2$
m^2	10.76	ft^2
m^2	1.196	yd^2
m^2	3.861×10^{-7}	sq mi

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Volume	
cm^3 (cc)	0.99997	Ml
cm^3	6.1023×10^{-2}	$in.^3$
cm^3	10^{-6}	m^3
cm^3	9.9997×10^{-4}	Liters
cm^3	3.5314×10^{-5}	ft^3
m^3	35.314	ft^3
m^3	2.642×10^{2}	Gal
m^3	9.9997×10^{2}	Liters
$in.^3$	16.387	cm^3
$in.^3$	5.787×10^{-4}	ft^3
$in.^3$	1.639×10^{-2}	Liters
$in.^3$	4.329×10^{-3}	Gal
ft^3	2.832×10^{-2}	m^3
ft^3	7.481	Gal
ft^3	28.32	Liters
ft^3	1728	$in.^3$
gal (U.S.)	231.0	$in.^3$
gal	0.13368	ft^3
liters	33.8147	fluid oz
liters	1.05671	Quarts
liters	0.26418	Gal
gm moles (gas)	22.4	liters (s.t.p.)

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Density	
cm^3/g	1.602×10^{-2}	ft^3/lb
ft^3/lb	62.43	cm^3/g
g/cm^3	62.43	lb/ft^3
lb/ft^3	1.602×10^{-2}	g/cm^3
$lb/in.^3$	27.68	g/cm^3
lb/gal	0.1198	g/cm^3
	Radiological Units	
becquerel	2.703×10^{-11}	Curies
curies	3.700×10^{10}	dis/sec
curies	2.220×10^{12}	dis/min
curies	10^3	Millicuries
curies	10^6	Microcuries
curies	10^{12}	Picocuries
curies	10^{-3}	Kilocuries
curies	3.700×10^{10}	Becquerel
dis/min	4.505×10^{-10}	Millicuries
dis/min	4.505×10^{-7}	Microcuries
dis/sec	2.703×10^{-8}	Millicuries
dis/sec	2.703×10^{-5}	Microcuries
kilocuries	10^3	Curies
microcuries	3.700×10^4	dis/sec
microcuries	2.220×10^6	dis/min
millicuries	3.700×10^7	dis/sec
millicuries	2.220×10^9	dis/min
R	2.58×10^{-4}	C/kg of air
R	1	esu/cm^3 of air (s.t.p.)
R	2.082×10^9	ion prs/cm^3 of air (s.t.p.)

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Radiological Units (continued)	
R	1.610×10^{12}	ion prs/g of air
R (33.7 eV/ion pr.)	7.02×10^{4}	MeV/cm^3 of air (s.t.p.)
R (33.7 eV/ion pr.)	5.43×10^{7}	MeV/g of air
R (33.7 eV/ion pr.)	86.9	ergs/g of air
R (33.7 eV/ion pr.)	2.08×10^{-6}	g-cal/g of air
R (33.7 eV/ion pr.)	.98	ergs/g of soft tissue
rads	0.01	Gray
rads	0.01	J/kg
rads	100	ergs/g
rads	8.071×10^{4}	MeV/cm^3 or air (s.t.p.)
rads	6.242×10^{7}	MeV/g
rads	10^{-5}	watt-sec/g
rads (33.7 eV/ion pr.)	2.39×10^{9}	ion prs/cm^3 of air (s.t.p.)
gray	100	Rad
rem	0.01	Sievert
sievert	100	Rem
µCi/^{3} (µCi/ml)	2.22×10^{12}	dpm/m^3
µCi/cm^3	2.22×10^{9}	dpm/liter
dpm/m^3	0.4505	pCi/m^3
	Energy	
Btu	1.0548×10^{3}	joules (absolute)
Btu	0.25198	kg-cal
Btu	1.0548×10^{10}	Ergs
Btu	2.930×10^{-4}	kW-hr
Btu/lb	0.556	g-cal/g
eV	1.6021×10^{-12}	Ergs

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Energy (continued)	
eV	1.6021×10^{-19}	joules (abs)
eV	10^{-3}	keV
eV	10^{-6}	MeV
ergs	10^{-7}	joules (abs)
ergs	6.2418×10^{5}	MeV
ergs	6.2418×10^{11}	eV
ergs	1.0	dyne-cm
ergs	9.480×10^{-11}	Btu
ergs	7.375×10^{-8}	ft-lb
ergs	2.390×10^{-8}	g-cal
ergs	1.020×10^{-3}	g-cm
gm-calories	3.968×10^{-3}	Btu
gm-calories	4.186×10^{7}	Ergs
joules (abs)	10^{7}	Ergs
joules (abs)	0.7376	ft-lb
joules (abs)	9.480×10^{-4}	Btu
g-cal/g	1.8	Btu/lb
kg-cal	3.968	Btu
kg-cal	3.087×10^{3}	ft-lb
ft-lb	1.356	joules (abs)
ft-lb	3.239×10^{-4}	kg-cal
kW-hr	2.247×10^{19}	MeV
kW-hr	3.60×10^{13}	Ergs
MeV	1.6021×10^{-6}	Ergs

Note: Mass to energy conversions under miscellaneous

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Fission	
Btu	1.28×10^{-8}	grams ^{235}U fissioned[b]
Btu	1.53×10^{-8}	grams ^{235}U destroyed[b,c]
Btu	3.29×10^{13}	Fissions
fission of 1 g ^{235}U	1	megawatt-days
fissions	8.9058×10^{-18}	kilowatt-hours
fissions[b]	3.204×10^{-4}	Ergs
kilowatt-hours	2.7865×10^{17}	^{235}U fission neutrons
kilowatts per kilogram ^{235}U	2.43×10^{10}	average thermal neutron flu× in fuel[b,d]
megawatt-days per ton U	1.174×10^{-4}	% U atoms fissioned[e]
megawatts per ton U	$2.68 \times 10^{10}/E$[f]	average thermal neutron flu× in fuel[b]
neutrons per kilobarn	1×10^{21}	neutrons/cm^2
watts	3.121×10^{10}	fissions/sec

[b] At 200 MeV/fission.

[c] Thermal neutron spectrum ($\alpha = 0.193$).

[d] δ(fission = 500 barns).

[e] At 200 MeV fission, in ^{235}U-^{238}U mi×ture of low ^{235}U content.

[f] E = enrichment in grams ^{235}U/gram total. No other fissionable isotope present.

Multiply # of to obtain # of	**by by**	**to obtain # of Divide # of**
	Miscellaneous	
radians	57.296	Degrees
eV	1.78258×10^{-33}	Grams
eV	1.07356×10^{-9}	U
erg	1.11265×10^{-21}	Grams
proton masses	938.256	MeV
neutron masses	939.550	MeV
electron masses	511.006	keV
u (amu on ^{12}C scale)	931.478	MeV

Temperature

$$°C = \frac{(°F - 32)}{1.8}$$

$$°C = (°F - 32)\left(\frac{5}{9}\right)$$

$$°F = 1.8(°C) + 32$$

$$°F = \left(\frac{9}{5}\right)(°C) + 32$$

$$°K = °C + 273.16$$

Wavelength to Energy Conversion

keV = 12.40/Å
eV = 1.240×10^{-6}/m

Course Title: **Radiological Control Technician**
Module Title: **Physical Sciences**
Module Number: **1.03**

Objectives :

1.03.01 Define the following terms as they relate to physics:
a. Work
b. Force
c. Energy

1.03.02 Identify and describe four forms of energy.

1.03.03 State the Law of Conservation of Energy.

1.03.04 Distinguish between a solid, a liquid, and a gas in terms of shape and volume.

1.03.05 Identify the basic structure of the atom, including the characteristics of subatomic particles.

1.03.06 Define the following terms:
a. Atomic number
b. Mass number
c. Atomic mass
d. Atomic weight

1.03.07 Identify what each symbol represents in the X notation.

1.03.08 State the mode of arrangement of the elements in the Periodic Table.

1.03.09 Identify periods and groups in the Periodic Table in terms of their layout.

1.03.10 Define the terms as they relate to atomic structure:
a. Valence shell
b. Valence electron

INTRODUCTION

This lesson introduces the RCT to the concepts of energy, work, and the physical states of matter. Knowledge of these topics is important to the RCT as he or she works in environments where materials can undergo changes in state, resulting in changes in the work environment.

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1.03.01 Define the following terms as they relate to physics:

a. Work
b. Force
c. Energy

WORK & FORCE

Physics is the branch of science that describes the properties, changes, and interactions of energy and matter. This unit will serve as a brief introduction to some of the concepts of physics as they apply to the situations that may be encountered by RCTs. Energy can be understood by relating it to another physical concept - work.

The word *work* has a variety of meanings in everyday language. In physics, however, work is specifically defined as a force acting through a distance. Simply put, a *force* is a push or a pull. A more technical definition of force is **any action on an object that can cause the object to change speed or direction**.

Units

Force is derived as the product of mass and acceleration (see equation below). The SI derived unit of force is the *newton* (***N***). It is defined as the force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one meter per second squared; that is:

$$N = \frac{kg \times m}{s^2}$$

As we said before, work is what is accomplished by the action of a force when it makes an object move through a distance. Mathematically, work is expressed as the product of a displacement and the force in the direction of the displacement; that is:

$$\boldsymbol{W = Fd}$$

where:
W = Work
F = Force (newtons)
d = Distance (meters)

For example, a horse works by exerting a physical force (muscle movement) to move a carriage. As the horse pulls, the carriage moves forward in the direction that the horse is pulling. Work is also done by an outside force (energy) to remove an electron from its orbit around the nucleus of an atom.

The SI derived unit of work is the *joule* (J). One joule of work is performed when a force of one newton is exerted through a distance of one meter. Thus:

$$J = N \times m$$

By this definition, work can only be performed when the force causes an object to be moved. This means that if the distance is zero then no work has been performed, even though a force has been applied. For example, if you stand at rest holding a bag of groceries in your hands, you do no work on it; your arms may become tired (and indeed energy is being expended by your muscles), but because the bag is not moved through a distance (d = 0), no work is performed (W = 0).

ENERGY

Energy (E) is defined as the **ability to do work.** Energy and work are closely related, but they are not the same thing. The relationship is that it takes energy to do work, and work can generate energy. This energy will be found in various forms.

1.03.02	*Identify and describe four forms of energy.*

Kinetic Energy

Kinetic energy describes the **energy of motion** an object possesses. For example, a moving airplane possesses kinetic energy.

$$E_K = \frac{1}{2}mv^2$$

where: m = mass
v = velocity

Potential Energy

Potential energy (gravitational) indicates how much **energy is stored as a result of the position** or the configuration of an object. For example, water at the top of a waterfall possesses potential energy.

$$E_P = mgh$$

where: m = mass
g = free fall acceleration
h = vertical distance

Thermal Energy

Thermal energy, or heat, describes the energy that results from the **random motion of molecules**. (*Molecules* are groups of atoms held together by strong forces called chemical bonds.) For example, steam possesses thermal energy.

Chemical Energy

Chemical energy describes the energy that is d**erived from atomic and molecular interactions in which new substances are produced**. For example, the substances in a dry cell provide energy when they react.

Other Forms of Energy

Other forms of energy, such as *electrical* and *nuclear*, will be described in later lessons. Energy may also appear as *acoustical* (sound) or *radiant* (light) energy.

1.03.03	*State the Law of Conservation of Energy.*

Law of Conservation of Energy

The *Law of Conservation of Energy* states that the **total amount of energy in a closed system remains unchanged**. Stated in other terms, as long as no energy enters or leaves the system, the amount of energy in the system will always be the same, although **it can be converted from one form to another**.

For example, suppose a boulder lies at the bottom of a hill and bulldozer is used to push it to the top. If the dozer puts a certain continuous force on the boulder to keep it moving up the slope and moves it a distance, work has been done. The dozer is able to do this work because its engine burns gasoline, creates heat. The heat is converted into the kinetic energy of the moving bulldozer and the boulder in front of it. Some of this energy

is converted into heat and noise. Some is converted into the potential energy that the dozer and the boulder have gained in going to the top of the hill. If the boulder is allowed to roll

back down the hill again, its potential energy will be converted partly into kinetic energy and partly into heat. The heat is produced by friction as the boulder rolls. Eventually the boulder will come to a stop, when all of its kinetic energy has been converted into heat. It leaves a trail of heat that is soaked up in the surroundings.

Gasoline contains chemical energy that is released in the form of heat when a chemical reaction (burning) with oxygen occurs. This energy comes from the breaking and making of bonds between atoms. New products, carbon dioxide and water, are formed as the gasoline combines with oxygen. The energy of the burning gasoline produces heat energy which causes the gaseous combustion products to do work on the pistons in the engine. The work results in the bulldozer moving, giving it kinetic energy.

Units of Energy

Energy is expressed in the same units as work, that is, joules (J). The joule is the SI unit of energy. However, because energy can take on many different forms, it is sometimes measured in other units which can be converted to joules. Some of these units are mentioned below.

Thermal Energy

Thermal energy is often measured in units of **calories** (CGS) or British Thermal Units or **BTU**s (English).

- A **calorie** is the amount of heat needed to raise the temperature of 1 gram of water by 1 °C. One calorie is equal to 4.18605 joules.
- A **BTU** is the amount of heat needed to raise the temperature of 1 pound of water by 1 °F. One BTU is equal to 1.055E3 joules.

Electrical Energy

Electrical energy is sometimes expressed in units of kilowatt-hours. One kw-hr is equal to 3.6E6 joules

A very small unit used to describe the energy of atomic and subatomic size particles is the *electron volt* (eV). One electron volt is the **amount of energy acquired by an electron when it moves through a potential of one volt**. For example, it takes about 15.8 eV of energy to remove an electron from an argon atom. Superunits such as kiloelectron volt (keV) and megaelectron volt (MeV) are used to indicate the energies of various ionizing radiations.

Work-Energy Relationship

When work is done **by** a system or object, it expends energy. For example, when the gaseous combustion products in an automobile engine push against the pistons, the gas loses energy. The chemical energy stored in the gasoline is used to do work so that the car will move.

When work is done **on** a system or object, it acquires energy. The work done on the car by the combustion of the gasoline causes the car to move, giving it more kinetic energy. When energy is converted to work or changed into another form of energy, the total amount of energy remains constant. Although it may appear that an energy loss has occurred, all of the original energy can be accounted for.

Consider again the automobile engine. The energy stored in the gasoline is converted to heat energy, some of which is eventually converted to kinetic energy. The remainder of the heat energy is removed by the engine's cooling system. The motion of the engine parts creates friction, heat energy, which is also removed by the engine's cooling system. As the car travels, it encounters resistance with the air. If no acceleration occurs, the car will slow down as the kinetic energy is converted to friction or heat energy. The contact of the tires on the road converts some of the available kinetic energy to heat energy (friction), slowing down the car. A significant amount of the energy stored in the gasoline is dissipated as wasted heat energy.

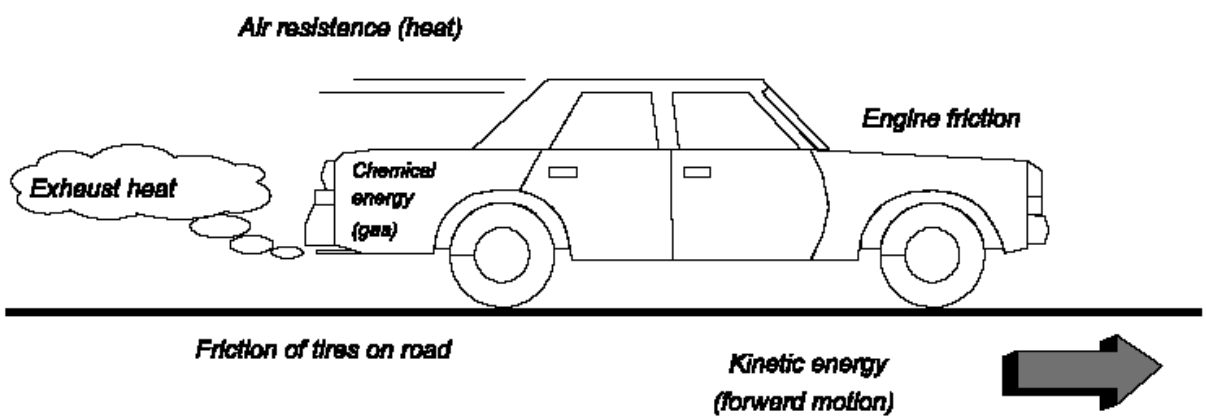

Figure 1. Energy Conversion in an Automobile

Energy-mass relationship

Energy can also be converted into mass and mass converted into energy. This will be discussed further in section 1.04 "Nuclear Sciences."

1.03.03 Distinguish between a solid, a liquid, and a gas in terms of shape and volume.

ENERGY AND CHANGE OF STATE

Matter is anything that has mass and takes up space. All matter is made up of atoms and molecules which are the building blocks used to form all kinds of different substances. These atoms and molecules are in constant random motion. Because of this motion they have thermal energy. The amount of energy depends on the temperature and determines the *state* or *phase* of the substance. There are three states of matter, *solid*, *liquid* and *gas*.

Any substance can exist in any of the three states, but there is generally one state which predominates under normal conditions (temperature and pressure). Take water, for example. At normal temperatures, water is in the liquid state. In the solid state, water is called ice. The gaseous state of water is called steam or water vapor. It's all still water, just in different states. Table 1 provides a summary of these three states in terms of shape and volume.

Table 1. States of Matter Compared

State	Shape	Volume
Solid	definite	definite
Liquid	indefinite	definite
Gas	indefinite	indefinite

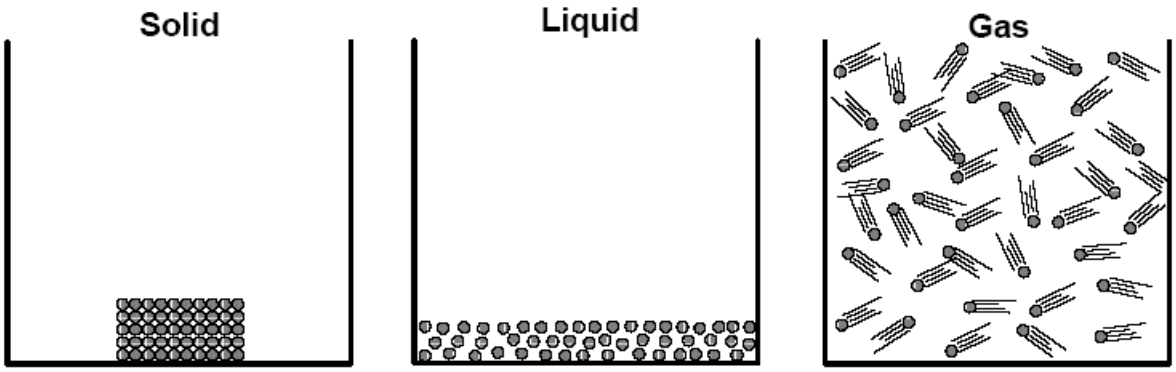

Figure 2. States of Matter

Solid State

A *solid* has definite shape and volume. The solid state differs from the liquid and gaseous states in that:

- The molecules or ions of a solid are held in place by strong attractive forces.
- The molecules have thermal energy, but the energy is not sufficient to overcome the attractive forces.
- The molecules of a solid are arranged in an orderly, fixed pattern.

The rigid arrangement of molecules causes the solid to have a definite shape and a definite volume.

Liquid State

When heat is added to a substance, the molecules acquire more energy, which causes them to break free of their fixed crystalline arrangement. As a solid is heated, its temperature rises until the change of state from solid to liquid occurs.

The volume of a *liquid* is definite since the molecules are very close to each other, with almost no space in between. Consequently, liquids can undergo a negligible amount of compression. However, the attractive forces between the molecules are not strong enough to hold the liquid in a definite shape. For this reason a liquid takes the shape of its container.

High energy molecules near the surface of a liquid can overcome the attractive forces of other molecules. These molecules transfer from the liquid state to the gaseous state. If energy (heat) is removed from the liquid, the kinetic energy of the molecules decreases

and the attractive forces can hold the molecules in fixed positions. When compared with the kinetic energy, the attractive forces are not strong enough to hold the molecules in fixed positions, forming a solid.

Gaseous State

If the temperature of a liquid is increased sufficiently, it boils, that is, molecules change to the gaseous state and escape from the surface. Eventually, all of the liquid will become a gas. A *gas* has both indefinite shape and indefinite volume. A large space exists between gas molecules because of their high thermal energy. This allows for even more compression of a substance in the gaseous state.

1.03.03	*Identify the basic structure of the atom, including the characteristics of subatomic particles.*

THE ATOM

The Bohr Model

As stated previously, the fundamental building block of matter is the *atom*. The basic atomic model, as described by Ernest Rutherford and Niels Bohr in 1911, consists of a positively charged core surrounded by negatively-charged shells. The central core, called the nucleus, contains *protons* and *neutrons*. Nuclear forces hold the nucleus together. The shells are formed by *electrons* which exist in structured orbits around the nucleus. Below is a summary of the three primary subatomic particles which are the constituent parts of the atom.

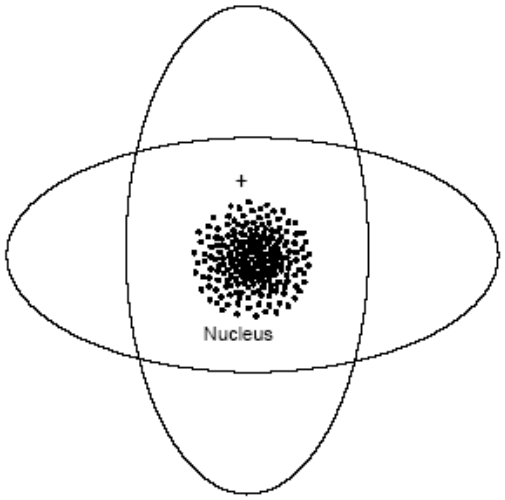

Figure 3. Atomic Model

Protons

- Positively charged (+1)
- Mass: 1.6726E-24 gm or 1.007276470 amu
- Each *element* is **determined by the number of protons** in its nucleus. All atoms of the same element have the same number of protons.

Neutrons

- Neutrally charged (0)
- Mass: 1.6749E-24 gm or 1.008665012 amu
- The number of neutrons determines the *isotope* of an element. Isotopes are atoms which have the same number of protons (therefore, of the same element) but different number of neutrons. This does not affect the chemical properties of the element.

Electrons

- Negatively charged (-1)
- Small mass: 9.1085E-28 gm or 0.00054858026 amu (1/1840 of a proton)
  Because the mass of an electron is so small as compared to that of a proton or neutron, virtually the entire mass of an atom is furnished by the nucleus.
- The number of electrons is normally equal to the number of protons. Therefore, the atom is electrically neutral.
- The number of electrons in the outermost shell determines the chemical behavior or properties of the atom.

THE ELEMENTS

Even though all atoms have the same basic structure, not all atoms are the same. There are over a hundred different types of atoms. These different types of atoms are known as *elements*. The atoms of a given element are alike but have different properties than the atoms of other elements.

Elements are the simplest forms of matter. They can exist alone or in various combinations. Different elements can chemically combine to form *molecules* or molecular *compounds*. For example, water is a compound, consisting of water molecules. These molecules can be

decomposed into the elements hydrogen and oxygen. The elements hydrogen and oxygen are fundamental forms of matter. They cannot be further separated into simpler chemicals.

Chemical Names

Currently, there are over 110 named elements. Table 2 lists the elements and their symbols. Some have been known for many centuries, while others have only been discovered in the last 15 or 20 years. Each element has a unique name. The names of the elements have a variety of origins. Some elements were named for their color or other physical characteristics. Others were named after persons, places, planets or mythological figures.

For example, the name chromium comes from the Greek word *chroma*, which means "color." Chromium is found naturally in compounds used as pigments. The elements curium, einsteinium, and fermium were named after famous nuclear physicists. Germanium, polonium and americium, were named after countries. Uranium, neptunium and plutonium are named in sequence for the three celestial bodies Uranus, Neptune and Pluto.

Chemical Symbols

For convenience, elements have a *symbol* which is used as a shorthand for writing the names of elements. The symbol for an element is either one or two letters taken from the name of the element (see Table 2). Note that some have symbols that are based on the historical name of the element. For example, the symbols for silver and gold are Ag and Au respectively. These come from the old Latin names *argentum* and *aurum*. The symbol for mercury, Hg, comes from the Greek *hydrargyros* which means "liquid silver."

Element	Symbol	Z	Element	Symbol	Z	Element	Symbol	Z
Actinium	Ac	89	Hafnium	Hf	72	Promethium	Pm	61
Aluminum	Al	13	Hassium	Hs	108	Protactinium	Pa	91
Americium	Am	95	Helium	He	2	Radium	Ra	88
Antimony	Sb	51	Holmium	Ho	67	Radon	Rn	86
Argon	Ar	18	Hydrogen	H	1	Rhenium	Re	75
Arsenic	As	33	Indium	In	49	Rhodium	Rh	45
Astatine	At	85	Iodine	I	53	Rubidium	Rb	37
Barium	Ba	56	Iridium	Ir	77	Ruthenium	Ru	44
Berkelium	Bk	97	Iron	Fe	26	Rutherfordium	Rf	104
Beryllium	Be	4	Krypton	Kr	36	Samarium	Sm	62
Bismuth	Bi	83	Lanthanum	La	57	Scandium	Sc	21
Bohrium	Bh	107	Lawrencium	Lw	103	Seaborgium	Sg	106
Boron	B	5	Lead	Pb	82	Selenium	Se	34
Bromine	Br	35	Lithium	Li	3	Silicon	Si	14
Cadmium	Cd	48	Lutetium	Lu	71	Silver	Ag	47
Calcium	Ca	20	Magnesium	Mg	12	Sodium	Na	11
Californium	Cf	98	Manganese	Mn	25	Strontium	Sr	38
Carbon	C	6	Meitnerium	Mt	109	Sulfur	S	16
Cerium	Ce	58	Mendelevium	Md	101	Tantalum	Ta	73
Cesium	Cs	55	Mercury	Hg	80	Technetium	Tc	43
Chlorine	Cl	17	Molybdenum	Mo	42	Tellurium	Te	52
Chromium	Cr	24	Neodymium	Nd	60	Terbium	Tb	65
Cobalt	Co	27	Neon	Ne	10	Thallium	Tl	81
Copper	Cu	29	Neptunium	Np	93	Thorium	Th	90
Curium	Cm	96	Nickel	Ni	28	Thulium	Tm	69
Dubnium	Db	105	Niobium	Nb	41	Tin	Sn	50
Dysprosium	Dy	66	Nitrogen	N	7	Titanium	Ti	22
Einsteinium	Es	99	Nobelium	No	102	Tungsten	W	74
Erbium	Er	68	Osmium	Os	76	Uranium	U	92
Europium	Eu	63	Oxygen	O	8	Vanadium	V	23
Fermium	Fm	100	Palladium	Pd	46	Xenon	Xe	54
Fluorine	F	9	Phosphorus	P	15	Ytterbium	Yb	70
Francium	Fr	87	Platinum	Pt	78	Yttrium	Y	39
Gadolinium	Gd	64	Plutonium	Pu	94	Zinc	Zn	30
Gallium	Ga	31	Polonium	Po	84	Zirconium	Zr	40
Germanium	Ge	32	Potassium	K	19			
Gold	Au	79	Praseodymium	Pr	59			

1.03.03 Define the following terms:

a) Atomic number
b) Mass number
c) Atomic mass
d) Atomic weight

Atomic Number

The **number of protons** in the nucleus of an element is called the *atomic number*. All atoms of a particular element have the same atomic number. Atomic numbers are integers. For example, a hydrogen atom has one proton in the nucleus. Therefore, the atomic number of hydrogen is 1. A helium atom has two protons in the nucleus, which means that its atomic number is 2. Uranium has 92 protons in the nucleus and, therefore, has an atomic number of 92. Atomic number is often represented by the symbol **Z**.

Mass Number

The total **number of protons plus neutrons** in the nucleus of a particular isotope of an element is called the *mass number*. It is the integer nearest to the mass of the atom of concern. Since a proton has a mass of 1.0073 amu, we will give a proton a mass number of 1. The mass number of a neutron would also be 1, since its mass is 1.0087 amu. So, by adding the number of protons and the number of neutrons we can determine the mass number of the atom of concern.

For example, a normal hydrogen atom has 1 proton, but no neutrons. Therefore, its mass number is 1. A helium atom has 2 protons and 2 neutrons, which means that it has a mass number of 4. If a uranium isotope has 146 neutrons then it has a mass number of 238 (92 + 146), while if it only has 143 neutrons its mass number would be 235.

The mass number can be used with the name of the element to identify which isotope of an element we are referring to. If we are referring to the isotope of uranium that has a mass number of 238, we can write it as Uranium-238. If we are referring to the isotope of mass number 235, we write it as Uranium-235. Often, this expression is shortened by using the chemical symbol instead of the full name of the element, as in U-238 or U-235.

Atomic Mass

The **actual mass of an atom of a particular isotope** is called its *atomic mass*. The units are expressed in Atomic Mass Units (AMU). AMUs are based on 1/12 of the mass of a Carbon-12 atom (1.660E-24 gm). In other words, the mass of one C-12 atom is exactly 12 amu.

For example, the mass of a hydrogen atom is 1.007825 amu (1 proton + 1 electron = 1.00727647 + 0.00054858026) . The mass of a Uranium-238 atom in amu is 238.0508, while the mass of a U-235 atom is only 235.0439. Notice that atomic masses are very accurate and are written as decimals.

Atomic Weight

The weighted average of the isotopic masses of an element, based on the percent abundance of its naturally occurring isotopes, is called the *atomic weight*. The atomic weight is expressed in AMU and is used mainly in calculations of chemical reactions.

Since AMUs are based on Carbon-12, one may wonder why the Periodic Table (see Figure 5) shows the atomic weight of Carbon as 12.011, and not exactly 12. The explanation is simple and will help to clarify the difference between the atomic weight of an element and the atomic mass of an isotope of that element.

Carbon, as it occurs in nature, is a mixture of two isotopes: about 98.9% of all carbon atoms are C-12, while the abundance of C-13 atoms is 1.1% (a total of 100%). The presence of these heavier Carbon atoms explains why the atomic weight of carbon is slightly more than 12. The atomic weight of an element is a "weighted average" (no pun intended). This average is determined by finding the sum of the mass of each isotope multiplied by its percent abundance. If the atomic mass of C-12 is 12.00, and the atomic mass of C-13 is 13.00, we can determine the atomic weight of carbon:

$$12.00(0.989) + 13.00(0.011) = 11.868 + 0.143 = 12.011 \text{ amu}$$

With the understanding of these concepts, we can discuss the Periodic Table of the Elements and the information it provides.

1.03.07 Identify what each symbol represents in the ${}^{A}_{Z}X$ notation.

NUCLIDE NOTATION

The format for representing a specific combination of protons and neutrons is to use its nuclear symbol. This is done by using the standard chemical symbol, with the atomic number written as a subscript at the lower left of the symbol, and the mass number written as a superscript at the upper left of the symbol:

$$^{A}_{Z}X$$

where: **X** = Symbol for element
Z = Atomic number: number of protons
A = Mass number: number of protons (Z) plus number of neutrons (N); therefore: $A = Z + N$

For example, the notation for Uranium-238 would be $^{238}_{92}U$.

1.03.08	*State the mode of arrangement of the elements in the Periodic Table.*
1.03.09	*Identify periods and groups in the Periodic Table in terms of their layout.*

MODERN PERIODIC TABLE

The modern Periodic Table (see Figure 5) **is an arrangement of the elements in order of increasing atomic number**. A comparison of the properties for selected elements will illustrate that there is a predictable, recurring pattern, or *periodicity*. This observation is summarized in the *Periodic Law*, which states that the properties of the elements are repetitive or recurring functions of their atomic numbers.

Data about each element in the Periodic Table are presented in a column and row format. The **rows or horizontal sections** in the Periodic Table are called *periods*. The **columns or vertical sections** are called *groups* or *families* because they "behave" chemically similar; that is they have similar chemical properties.

Since the number of electrons is equal to the number of protons, the **structure of the Periodic Table directly relates to the number and arrangement of electrons** in the atom (see Table 3). Figure 4 below gives a simple illustration of the electron shells described in the Bohr model of the atom.

Electrons orbit around the nucleus in structured *shells*, designated sequentially as 1 through 7 (K through Q) from inside out. Shells represent groups of energy states called *orbitals*. The higher the energy of the orbital the greater the distance from the nucleus. The lowest energy state is in the innermost shell (K).

The number of orbitals in a shell is the square of the shell number (n). The maximum number of electrons which can occupy an orbital is 2. Therefore, each shell can hold a maximum of $2n^2$ electrons. For example, for the L shell the maximum number of electrons would be 8:

L-shell: n = 2 $\rightarrow\rightarrow\rightarrow\rightarrow$ $2(2^2) = 8$

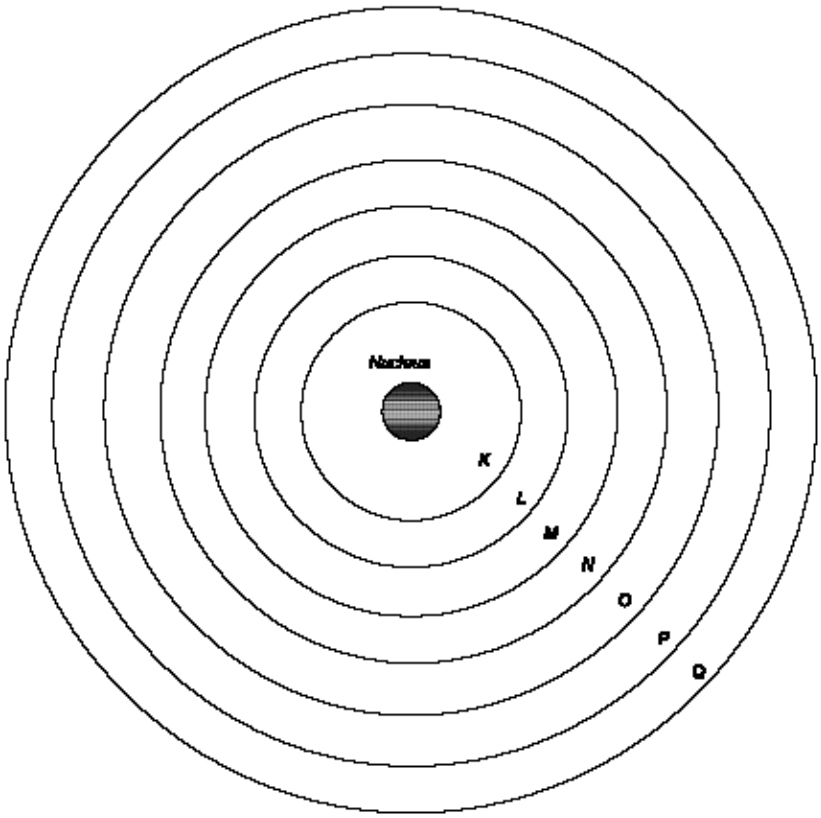

Figure 4. Electron Shells

Figure 5. Periodic Table of the Elements

Atomic Weight: 83.80 — Symbol: Kr — Atomic Number: 36

Solid
Liquid
Gas
Synthetic

NOBLE GAS

Metalloid Line

1.0080 1 H	IIA											IIIB	IVB	VB	VIB		4.00260 He
6.941 3 Li	9.01218 4 Be											10.81 5 B	12.011 6 C	14.0067 7 N	15.9994 8 O	18.9984 9 F	20.179 10 Ne
22.98977 11 Na	24.305 12 Mg	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	26.98154 13 Al	28.0855 14 Si	30.97376 15 P	32.06 16 S	32.06 17 Cl	39.948 18 Ar
39.0983 19 K	40.08 20 Ca	41.9559 21 Sc	47.90 22 Ti	50.9415 23 V	51.996 24 Cr	54.9380 25 Mn	55.847 26 Fe	58.933 27 Co	58.70 28 Ni	63.546 29 Cu	65.38 30 Zn	69.72 31 Ga	72.59 32 Ge	74.9216 33 As	78.96 34 Se	79.904 35 Br	83.80 36 Kr
85.4678 37 Rb	87.62 38 Sr	88.9059 39 Y	91.22 40 Zr	92.9064 41 Nb	95.94 42 Mo	(98) 43 Tc	101.07 44 Ru	102.905 45 Rh	106.4 46 Pd	107.868 47 Ag	112.41 48 Cd	114.82 49 In	118.69 50 Sn	121.75 51 Sb	127.60 52 Te	126.9045 53 I	131.30 54 Xe
132.9054 55 Cs	137.33 56 Ba	138.9055 57 La	178.49 72 Hf	180.9479 73 Ta	183.85 74 W	186.207 75 Re	190.2 76 Os	192.22 77 Ir	195.09 78 Pt	196.966 79 Au	200.59 80 Hg	204.37 81 Tl	207.2 82 Pb	208.9804 83 Bi	(209) 84 Po	(210) 85 At	(222) 86 Rn
(223) 87 Fr	226.0254 88 Ra	227.0278 89 Ac	(261) 104 Rf	(262) 105 Db	(263) 106 Sg	(264) 107 Bh	(265) 108 Hs	(266) 109 Mt									

★	140.12 58 Ce	140.9077 59 Pr	144.24 60 Nd	(145) 61 Pm	150.4 62 Sm	151.96 63 Eu	157.25 64 Gd	158.925 65 Tb	162.50 66 Dy	164.9304 67 Ho	167.26 68 Er	168.9342 69 Tm	173.04 70 Yb	174.967 71 Lu
★★	232.0381 90 Th	231.0359 91 Pa	238.029 92 U	237.0482 93 Np	(244) 94 Pu	(243) 95 Am	(247) 96 Cm	(247) 97 Bk	(251) 98 Cf	(252) 99 Es	(257) 100 Fm	(258) 101 Md	(259) 102 No	(260) 103 Lr

Z	Element	K	L	M	N	O
1	Hydrogen	1				
2	Helium	2				
3	Lithium	2	1			
4	Beryllium	2	2			
5	Boron	2	3			
6	Carbon	2	4			
7	Nitrogen	2	5			
8	Oxygen	2	6			
9	Fluorine	2	7			
10	Neon	2	8			
11	Sodium	2	8	1		
12	Magnesium	2	8	2		
13	Aluminum	2	8	3		
14	Silicon	2	8	4		
15	Phosphorus	2	8	5		
16	Sulfur	2	8	6		
17	Chlorine	2	8	7		
18	Argon	2	8	8		
19	Potassium	2	8	8	1	
20	Calcium	2	8	8	2	
21	Scandium	2	8	9	2	
22	Titanium	2	8	10	2	
23	Vanadium	2	8	11	2	
24	Chromium	2	8	13	1	
25	Manganese	2	8	13	2	
26	Iron	2	8	14	2	
27	Cobalt	2	8	15	2	
28	Nickel	2	8	16	2	
29	Copper	2	8	18	1	
30	Zinc	2	8	18	2	
31	Gallium	2	8	18	3	
32	Germanium	2	8	18	4	
33	Arsenic	2	8	18	5	
34	Selenium	2	8	18	6	
35	Bromine	2	8	18	7	
36	Krypton	2	8	18	8	
37	Rubidium	2	8	18	8	1
38	Strontium	2	8	18	8	2
39	Yttrium	2	8	18	9	2
40	Zirconium	2	8	18	10	2
41	Niobium	2	8	18	12	1
42	Molybdenum	2	8	18	13	1
43	Technetium	2	8	18	13	2
44	Ruthenium	2	8	18	15	1
45	Rhodium	2	8	18	16	1
46	Palladium	2	8	18	18	0
47	Silver	2	8	18	18	1
48	Cadmium	2	8	18	18	2
49	Indium	2	8	18	18	3
50	Tin	2	8	18	18	4
51	Antimony	2	8	18	18	5
52	Tellurium	2	8	18	18	6
53	Iodine	2	8	18	18	7
54	Xenon	2	8	18	18	8

Z	Element	K	L	M	N	O	P	Q
55	Cesium	2	8	18	18	8	1	
56	Barium	2	8	18	18	8	2	
57	Lanthanum	2	8	18	18	9	2	
58	Cerium	2	8	18	20	8	2	
59	Praseodymium	2	8	18	21	8	2	
60	Neodymium	2	8	18	22	8	2	
61	Promethium	2	8	18	23	8	2	
62	Samarium	2	8	18	24	8	2	
63	Europium	2	8	18	25	8	2	
64	Gadolinium	2	8	18	25	9	2	
65	Terbium	2	8	18	27	8	2	
66	Dysprosium	2	8	18	28	8	2	
67	Holmium	2	8	18	29	8	2	
68	Erbium	2	8	18	30	8	2	
69	Thulium	2	8	18	31	8	2	
70	Ytterbium	2	8	18	32	8	2	
71	Lutetium	2	8	18	32	9	2	
72	Hafnium	2	8	18	32	10	2	
73	Tantalum	2	8	18	32	11	2	
74	Tungsten	2	8	18	32	12	2	
75	Rhenium	2	8	18	32	13	2	
76	Osmium	2	8	18	32	14	2	
77	Iridium	2	8	18	32	15	2	
78	Platinum	2	8	18	32	16	2	
79	Gold	2	8	18	32	18	1	
80	Mercury	2	8	18	32	18	2	
81	Thallium	2	8	18	32	18	3	
82	Lead	2	8	18	32	18	4	
83	Bismuth	2	8	18	32	18	5	
84	Polonium	2	8	18	32	18	6	
85	Astatine	2	8	18	32	18	7	
86	Radon	2	8	18	32	18	8	
87	Francium	2	8	18	32	18	8	1
88	Radium	2	8	18	32	18	8	2
89	Actinium	2	8	18	32	18	9	2
90	Thorium	2	8	18	32	18	10	2
91	Protactinium	2	8	18	32	20	9	2
92	Uranium	2	8	18	32	21	9	2
93	Neptunium	2	8	18	32	22	9	2
94	Plutonium	2	8	18	32	24	8	2
95	Americium	2	8	18	32	25	8	2
96	Curium	2	8	18	32	25	9	2
97	Berkelium	2	8	18	32	27	8	2
98	Californium	2	8	18	32	28	8	2
99	Einsteinium	2	8	18	32	29	8	2
100	Fermium	2	8	18	32	30	8	2
101	Mendelevium	2	8	18	32	31	8	2
102	Nobelium	2	8	18	32	32	8	2
103	Lawrencium	2	8	18	32	32	9	2
104	Rutherfordium	2	8	18	32	32	10	2
105	Dubnium	2	8	18	32	32	11	2
106	Seaborgium	2	8	18	32	32	12	2
107	Bohrium	2	8	18	32	32	13	2
109	Meitnerium	2	8	18	32	32	15	2

1.03.10 Define the terms as they relate to atomic structure:

a) Valence shell
b) Valence electron

The highest occupied energy level in a ground-state atom is called its *valence shell*. Therefore, the electrons contained in it are called *valence electrons*. The rows or periods in the Periodic Table correspond to the electron shells. The elements contained in first period have their valence electrons in the first energy level or K-shell. The elements contained in the second period have their outer or valence shell electrons in the second energy level or L-shell, and so on. The pattern continues down the table.

The number of electrons in the valence shell determines the chemical properties or "behavior" of the atom. The valence shell can have a maximum of eight electrons, except for the K-shell which can only have two. Atoms are chemically stable when the valence shell has no vacancies; that is, they "prefer" to have a full valence shell. Atoms of elements toward the right of the Periodic Table seem to lack only one or two electrons. These will "look" for ways to gain electrons in order to fill their valence shell. Atoms of elements on the left side of the table seem to have an excess of one or two electrons. These will tend to find ways to lose these excess electrons so that the full lower shell will be the valence shell.

The outcome is that certain atoms will combine with other atoms in order to fill their valence shells. This combination that occurs is called a *chemical bond*, and results in the formation of a *molecule*. The bond is accomplished by "sharing" or "giving up" valence electrons, thus forming a molecule whose chemical properties are different than those of the individual element atoms.

A good example is table salt. Salt is a 1:1 combination of sodium and chlorine; that is, a salt molecule is formed when one sodium atom bonds with one chlorine atom. If we look at Table 3, we can see that sodium (Na) has 1 electron in its outermost shell. Chlorine (Cl) needs one electron to complete its valence shell. The sodium atom "gives up" its extra electron to the chlorine atom who then "thinks" that its valence shell is full. Because the sodium atom has one less electron, the atom now has a net positive charge; that is, it has one less electron than it has protons. The chlorine atom now has a net negative charge because it has one more electron than it has protons. The opposite charges of the two *ions* attract and form an *ionic bond*. The bond results in a sodium chloride molecule (NaCl). However, this is just one type of chemical bond between atoms. There are several other types of chemical bonds that can occur, but which are beyond the scope of this lesson.

Note the rightmost column in the Periodic Table. These elements are known as the *noble* or *inert* gases because they all have a full valence shell (see also the underlined elements in Table 3). This means that they "feel" no need to bond with other atoms. Noble gases are thus considered chemically inert and very rarely interact with other elements.

The Quantum Mechanical Model

Over the years, the Bohr model of the atom was found to be inadequate as the principles of quantum mechanics evolved. A newer model, known as the *quantum mechanical model,* describes the electrons arranged in *energy levels* corresponding to the "electron shells" of the Bohr model. In the quantum mechanical model the electron is not viewed as particle in a specific orbit, but rather as an electron cloud in which the negative charge of the electron is spread out within the cloud. These energy levels are referred to as *orbitals* to emphasize that these are not circular "orbits" like those of the Bohr model but rather electron clouds. An *electron cloud* is a representation of the volume about the nucleus in which an electron of a specific energy is likely to be found.

The quantum mechanical model further states that the energy levels are subdivided into *sublevels*, referred to by the letters *s*, *p*, *d*, *f*, etc. An energy level can contain one or more sublevels or orbitals, and a maximum of two electrons can reside in each sublevel. For example, the first energy level contains one **s** sublevel which can accommodate a maximum of two electrons.

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Course Title: **Radiological Control Technician**
Module Title: **Nuclear Physics**
Module Number: **1.04**

Objectives :

1.04.01 Identify the definitions of the following terms:
a. Nucleon
b. Nuclide
c. Isotope

1.04.02 Identify the basic principles of the mass-energy equivalence concept.

1.04.03 Identify the definitions of the following terms:
a. Mass defect
b. Binding energy
c. Binding energy per nucleon

1.04.04 Identify the definitions of the following terms:
a. Fission
b. Criticality
c. Fusion

INTRODUCTION

Nuclear power is made possible by the process of nuclear fission. Fission is but one of a large number of nuclear reactions which can take place. Many reactions other than fission are quite important because they affect the way we deal with all aspects of handling and storing nuclear materials. These reactions include radioactive decay, scattering, and radiative capture. This lesson is designed to provide an understanding of the forces present within an atom.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
2. "Introduction to Health Physics"; Cember, Herman; 4nd ed.; McGraw-Hill Medical; 2008.
3. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago

1.04.01 Identify the definitions of the following terms:

a. Nucleon
b. Nuclide
c. Isotope

NUCLEAR TERMINOLOGY

There are several terms used in the field of nuclear physics that an RCT must understand.

Nucleon

Neutrons and protons are found in the nucleus of an atom, and for this reason are collectively referred to as *nucleons*. A nucleon is defined as a constituent particle of the atomic nucleus, either a neutron or a proton.

Nuclide

A species of atom characterized by the constitution of its nucleus, which is specified by its atomic mass and atomic number (Z), or by its number of protons (Z), number of neutrons (N), and energy content. A listing of all nuclides can be found on the "Chart of the Nuclides," which will be introduced in a later lesson.

Isotope

This term was mentioned in Lesson 1.03 when we discussed the concepts of atomic mass and atomic weight. *Isotopes* are defined as nuclides which have the **same number of protons but different numbers of neutrons**. Therefore, any nuclides which have the same atomic number (i.e. the same element) but different atomic mass numbers are isotopes.

For example, hydrogen has three isotopes, known as *Protium*, *Deuterium* and *Tritium*. Since hydrogen has one proton, any hydrogen atom will have an atomic number of 1. However, the atomic mass numbers of the three isotopes are different: Protium (^{1}H) has an mass number of 1 (1 proton, no neutrons), deuterium (D or ^{2}H) has a mass number of 2 (1 proton, 1 neutron), and tritium (T or ^{3}H) has a mass number of 3 (1 proton, 2 neutrons).

1.04.02 Identify the basic principles of the mass-energy equivalence concept.

MASS-ENERGY EQUIVALENCE

Of fundamental concern in nuclear reactions is the question of whether a given reaction is possible and, if so, how much energy is required to initiate the reaction or is released when the reaction occurs. The key to these questions lies in the relationship between the mass and energy of an object.

The theory that relates the two was proposed by Albert Einstein in 1905. Einstein's special theory of relativity culminated in the famous equation:

$$E = mc^2$$

where: E = Energy
m = mass
c = speed of light

This equation expresses the equivalence of mass and energy, meaning that **mass may be transformed to energy and vice versa**. Because of this equivalence the two are often referred to collectively as *mass-energy*.

The *mass-energy equivalence* theory implies that **mass and energy are interchangeable**. The theory further states that **the mass of an object depends on its speed**. Thus, all matter contains energy by virtue of its mass. It is this energy source that is tapped to obtain nuclear energy.

The Law of Conservation of Energy applies to mass as well as energy, since the two are equivalent. Therefore, in any nuclear reaction the total mass-energy is conserved i.e. mass-energy cannot be created or destroyed. This is of importance when it becomes necessary to calculate the energies of the various types of radiation which accompany the radioactive decay of nuclei.

Pair Annihilation: An Example of Mass to Energy Conversion

An interaction which occurs is *pair annihilation*, where two particles with mass, specifically a *positron* and an electron (negatron), collide and are transformed into two rays (photons) of electromagnetic energy. A positron is essentially an anti-electron, having a positive charge. When a positron collides with an electron, both particles are annihilated and their mass is converted completely to electromagnetic energy. (This interaction will be discussed in Lesson 1.07 "Interactions of Radiation with Matter.")

If the mass of an electron/positron is 0.00054858026 amu, the resulting annihilation energy (radiation) resulting from the collision would be:

$$\frac{2(0.0005485026amu)}{1} \times \frac{931.478MeV}{amu} = 1.022MeV$$

1.04.03	*Identify the definitions of the following terms:* *a. Mass defect* *b. Binding energy* *c. Binding energy per nucleon*

MASS DEFECT AND BINDING ENERGY

With an understanding of the equivalence of mass and energy, we can now examine the principles which lie at the foundation of nuclear power.

Mass Defect

As we said earlier, the mass of an atom comes almost entirely from the nucleus. If a nucleus could be disassembled to its constituent parts, i.e., protons and neutrons, it would be found that the **total mass of the atom is less than the sum of the masses of the individual protons and neutrons**. This is illustrated in Figure 1 below.

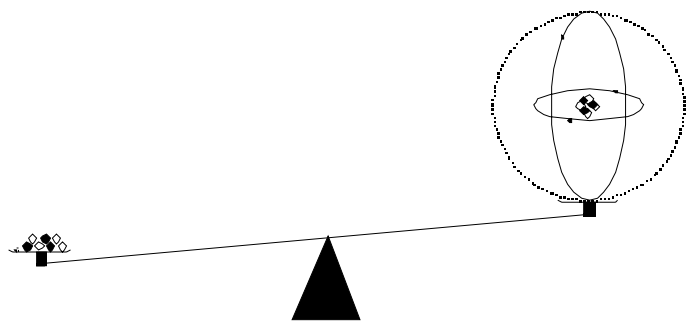

Figure 1. Atomic Scale

This slight difference in mass is known as the *mass defect*, $*$ (pronounced "delta"), and can be computed for each nuclide, using the following equation.

$$* = (Z)(M_p) + (Z)(M_e) + (A\text{-}Z)(M_n) - M_a$$

where:

$*$	=	mass defect
Z	=	atomic number
M_p	=	mass of a proton (1.00728 amu)
M_e	=	mass of a electron (0.000548 amu)
A	=	mass number
M_n	=	mass of a neutron (1.00867 amu)
M_a	=	atomic mass (from Chart of the Nuclides)

For example, consider an isotope of Lithium, Li:

$A = 7$
$Z = 3$
$M = 7.01600$ amu (per Chart of the Nuclides)

Therefore:

$* = (3)(1.00728) + (3)(0.000548) + (7-3)(1.00867) - (7.01600)$
$* = (3.02184) + (0.001644) + (4.03468) - (7.01600)$
$* = (7.058164) - (7.01600)$
$* = 0.042164$ amu

Binding Energy

The mass defect of ${}^{2}_{3}\mathrm{Li}$ is 0.042164 amu. This is the mass that is apparently "missing", but, in fact, has been converted to energy, the energy that binds the lithium atom nucleus together, or its *binding energy*. Binding energy is **the energy equivalent of mass defect**. Note from the Lesson 1.02 Conversion Tables that:

1 amu = 931.478 MeV

So, if we multiply the mass defect by this number we can calculate the binding energy.

$$BE = \left(\frac{0.042164amu}{1}\right)\left(\frac{931.478MeV}{amu}\right) = 39.27MeV$$

From this we have determined the energy converted from mass in the formation of the nucleus. We will see that it is also the energy that must be applied to the nucleus in order to break it apart.

Another important calculation is that of the binding energy of a neutron. This calculation is of significance when the energetics of the *fission* process are considered. For example, when ${}^{235}\mathrm{U}$ absorbs a neutron, the compound nucleus ${}^{236}\mathrm{U}$ is formed (see NUCLEAR FISSION later in this lesson). The change in mass (Δm) is calculated and then converted to its energy equivalent:

$\Delta m = (m_n + m_{U235}) - m_{U236}$
$\Delta m = (1.00867 + 235.0439) - 236.0456$
$\Delta m = 0.0070$ amu

0.0070 amu × 931.5 MeV/amu = 6.52 MeV

Thus, the nucleus possesses an *excitation energy* of 6.52 MeV when ^{235}U absorbs a neutron.

Binding Energy per Nucleon

If the total binding energy of a nucleus is divided by the total number of nucleons in the nucleus, the *binding energy per nucleon* is obtained. This represents the average energy which must be supplied in order to remove a nucleon from the nucleus. For example, using the Li atom as before, the binding energy per nucleon would be calculated as follows:

$$\frac{39.27 MeV}{7 nucleons} = 5.61 MeV per nucleon$$

If the binding energy per nucleon is plotted as a function of mass number (total number of nucleons) for each element, a curve is obtained (see Figure 2). The binding energy per nucleon peaks at about 8.5 MeV for mass numbers 40 - 120 and decreases to about 7.6 MeV per nucleon for uranium.

The binding energy per nucleon decreases with increasing mass number above mass 56 because as more protons are added, the proton-proton repulsion increases faster than the nuclear attraction. Since the repulsive forces are increasing, less energy must be supplied, on the average, to remove a nucleon. That is why there are no *stable* nuclides with mass numbers beyond that of 208.

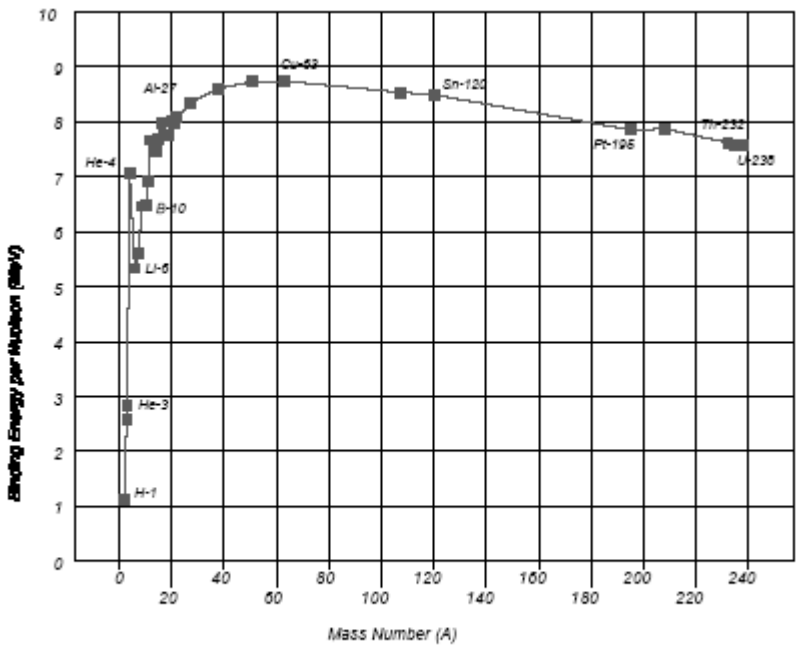

Figure 2. Binding Energy vs. Mass Number

NUCLEAR TRANSFORMATION EQUATIONS

Using the X format, equations can be written which depict a transformation that has occurred in a nucleus or nuclei. Since it is an equation, both sides must be equal. Therefore, the total mass-energy on the left must be equal to the total mass-energy on the right. Keeping in mind that mass and energy are equivalent, any difference in total mass is accounted for as energy released in the transformation. This energy release is called the *Q* value. For example, the *alpha decay* of Radium-226 would be depicted as:

$$^{226}_{88}\mathbf{Ra} \longrightarrow {}^{222}_{86}\mathbf{Rn} + {}^{4}_{2}\boldsymbol{\alpha} + \boldsymbol{Q}$$

The energy release, represented by *Q* in this case, is manifest as the kinetic energy of the high-speed alpha particle, as well as the recoil of the Radon-222 atom.

1.04.04	*Identify the definitions of the following terms:* *a. Fission* *b. Criticality* *c. Fusion*

NUCLEAR FISSION

As we have shown, the nucleus of a single atom could be the source of considerable energy. If the nucleus could be split so as to release this energy it could be used to generate power. Therefore, if the energy from millions of atoms were released it would be a great source of power. This thinking is the basis for nuclear power.

When a free neutron strikes a nucleus, one of the processes which may occur is the *absorption* of the neutron by the nucleus. It has been shown that the absorption of a neutron by a nucleus raises the energy of the system by an amount equal to the binding energy of the neutron. Under some circumstances, this absorption may result in **the splitting of the nucleus into at least two smaller nuclei with an accompanying release of energy**. This process is called *fission*. Two or three neutrons are usually released during this type of transformation.

In order to account for how this process is possible, use is made of the liquid drop model of the nucleus. This model is based on the observation that the nucleus, in many ways, resembles a drop of liquid. The liquid drop is held together by cohesive forces between molecules, and when the drop is deformed the cohesive forces may be insufficient to restore the drop to its original shape. Splitting may occur, although in this case, there would be no release of energy. Figure 3 illustrates this model.

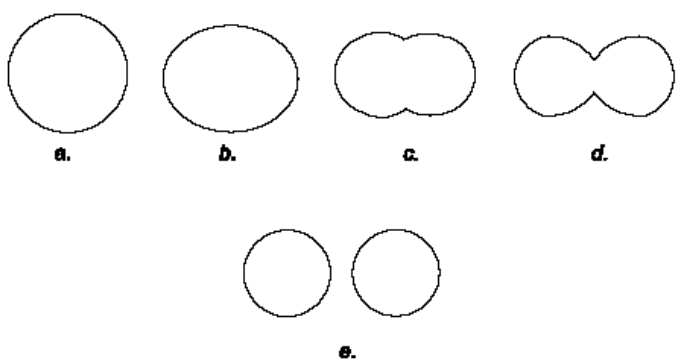

Figure 3. Liquid Drop Model of Fission

The absorption of a neutron raises the energy of the system by an amount equal to the binding energy of the neutron. This energy input causes deformation of the nucleus, but if it is not of sufficient magnitude, the nucleon-nucleon attractive forces will act to return the nucleus to its original shape. If the energy input is sufficiently large, the nucleus may reach a point of separation, and a fission has occurred. The energy required to drive the nucleus to the point of separation is called the *critical energy for fission*, E_c. The values of E_c for various nuclei can be calculated, based on a knowledge of the forces which act to hold the nucleus together.

An example of a fission is shown below, involving neutron absorption by ^{235}U:

$$^{235}_{92}\mathbf{U} + ^{1}_{0}\mathbf{n} \longrightarrow ^{236}_{92}\mathbf{U}^{*} \longrightarrow ^{138}_{56}\mathbf{Ba} + ^{95}_{36}\mathbf{Kr} + 3\left(^{1}_{0}\mathbf{n}\right) + \mathbf{Q}$$

On the average, approximately 200 MeV of energy is released per fission.

The fission process can be "energetically" explained by comparing the critical energy for fission with the amount of energy input, i.e., the neutron binding energy. For ^{238}U and ^{232}Th, the critical energy for fission is greater than the neutron binding energy. Therefore, an additional amount of energy must be supplied in order for fission to occur in these nuclei. This additional energy is in the form of neutron kinetic energy, and confirms the observation that fission occurs in these fissionable nuclei only when the neutron has approximately 1 MeV of kinetic energy.

The situation is quite different for ^{235}U, ^{233}U, and ^{239}Pu. In these cases, the neutron binding energy exceeds the critical energy for fission. Thus, these nuclei may be fissioned by *thermal*, or very low energy, (0.025 eV) neutrons.

As mentioned earlier, the new elements which are formed as a result of the fissioning of an atom are unstable because their N/P ratios are too high. To attain stability, the fission fragments will undergo various transformations depending on the degree of instability. Along with the neutrons immediately released during fission, a highly unstable element may give off several neutrons to try to regain stability. This, of course, makes more neutrons available to cause more fissions and is the basis for the *chain reaction* used to produce nuclear power. The excited fission product nuclei will also give off other forms of radiation in an attempt to achieve a stable status. These include beta and gamma radiation.

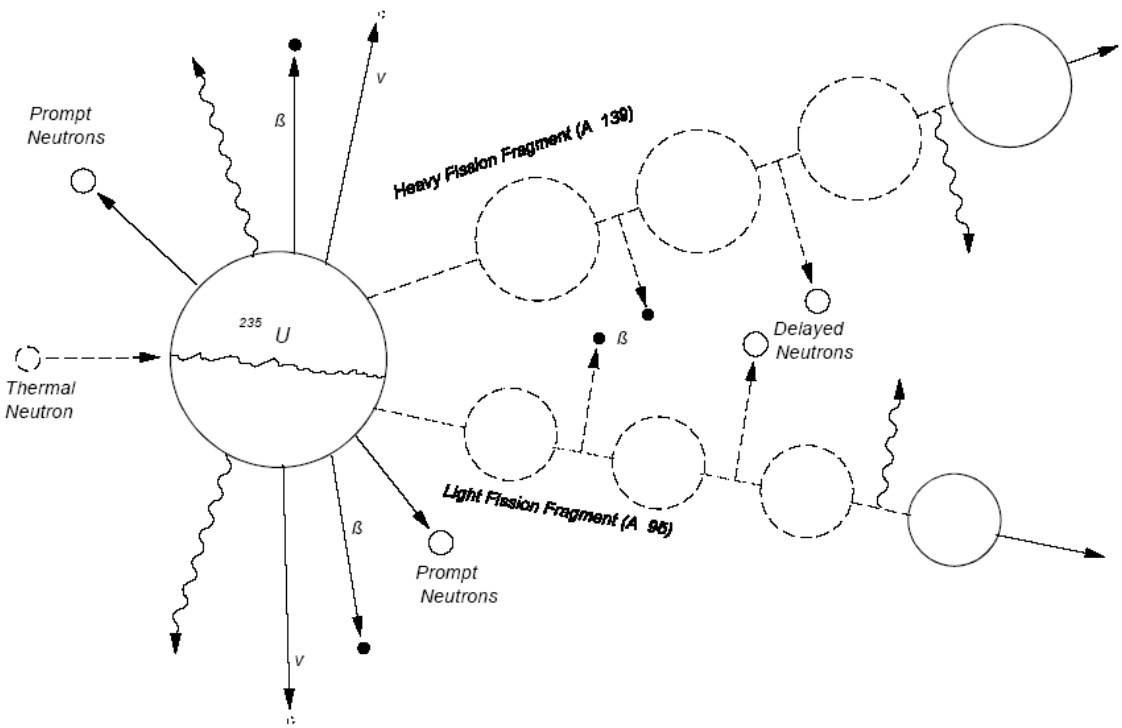

Figure 4. Fission process in ^{235}U initiated by a thermal neutron.

Criticality

Criticality is the condition in which the neutrons produced by fission are equal to the number of neutrons in the previous generation. This means that the neutrons in one generation go on to produce an equal number of fission events, which events in turn produce neutrons that produce another generation of fissions, and so forth. This continuation results in the self-sustained chain reaction mentioned above. Figure 5 gives a simple illustration of the chain reaction that occurs in a criticality.

As one can discern, this reaction requires control. If the population of neutrons remains constant, the chain reaction will be sustained. The system is thus said to be *critical*. However, if too many neutrons escape from the system or are absorbed but do not produce a fission, then the system is said to be *subcritical* and the chain reaction will eventually stop.

On the other hand, if the two or three neutrons produced in one fission each go on to produce another fission, the number of fissions and the production of neutrons will increase exponentially. In this case the chain reaction is said to be *supercritical*.

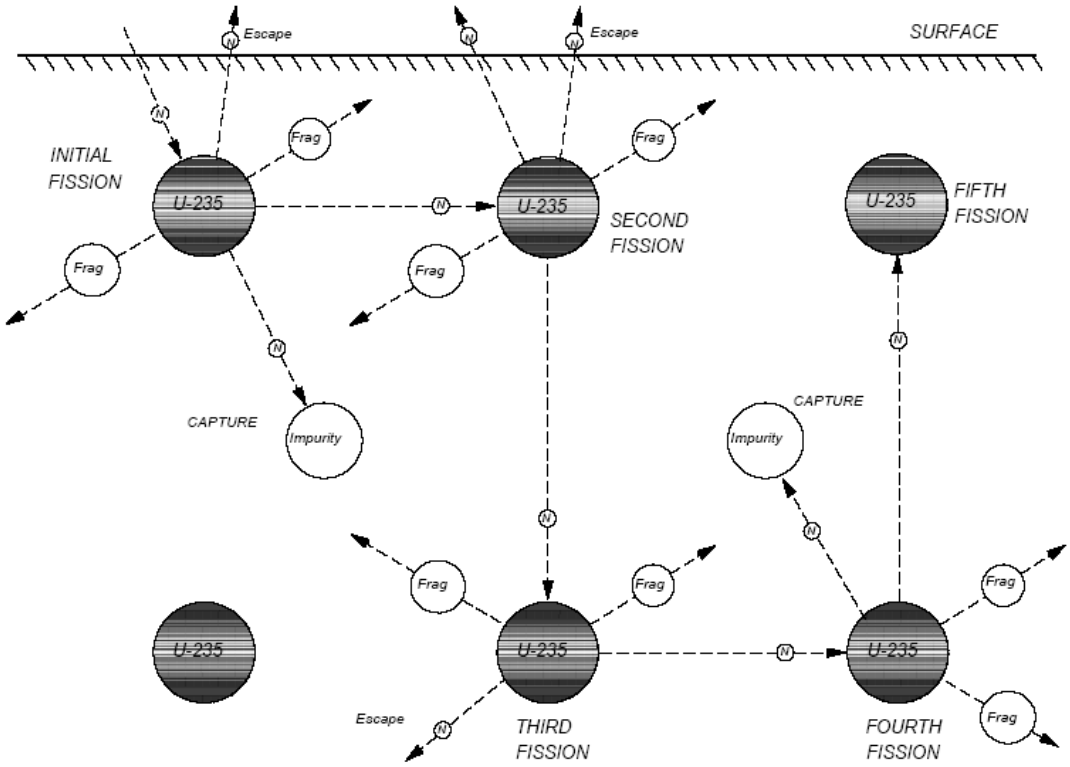

Figure 5. Self-sustaining Chain reaction

In nuclear reactors this concept is expressed as the *effective multiplication constant* or K_{eff}. K_{eff} is defined as the ratio of the number of neutrons in the reactor in one generation to the number of neutrons in the previous generation. On the average, 2.5 neutrons are emitted per uranium fission. If K_{eff} has a value of greater than 1, the neutron flux is increasing, and conversely, if it has a value of less than 1, the flux is decreasing with time. Table 1 illustrates the reactor condition for various values of the multiplication constant.

Table 1 - The Effective Multiplication Constant

K_{eff}	=	Effective Multiplication Constant
$K_{eff} < 1$	=	Subcritical Condition
$K_{eff} = 1$	=	Critical Condition
$K_{eff} > 1$	=	Supercritical Condition

In a subcritical reactor, the neutron flux and power output will die off in time. When critical, the reactor operates at a steady neutron and power output. A reactor must be supercritical to increase the neutron flux and power level.

Therefore, the population of neutrons must be controlled in order to control the number of fissions that occur. Otherwise, the results could be devastating.

Fusion

Another reaction between nuclei which can be the source of power is *fusion.* Fusion is the act of combining or "fusing" two or more atomic nuclei. Fusion thus builds atoms. The process of fusing nuclei into a larger nucleus with an accompanying release of energy is called fusion.

Fusion occurs naturally in the sun and is the source of its energy. The reaction is initiated under the extremely high temperatures and pressure in the sun whereby H interacts with ${}^{12}_{6}\mathrm{C}$. Hydrogen is then converted to helium and energy is liberated in the form of heat.

$$\mathbf{4\left({}^{1}_{1}H\right) \longrightarrow {}^{4}_{2}He^{2+} + 2\left(e^{+}\right) + 24.7MeV}$$

What occurs in the above equation is the combination of 4 hydrogen atoms, giving a total of 4 protons and 4 electrons. 2 protons combine with 2 electrons to form 2 neutrons, which combined with the remaining 2 protons forms a helium nucleus, leaving 2 electrons and a release of energy.

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Course Title: **Radiological Control Technician**
Module Title: **Sources of Radiation**
Module Number: **1.05**

Objectives :

1.05.01 Identify the following four sources of natural background radiation including the origin, radionuclides, variables, and contribution to exposure.
a. Terrestrial
b. Cosmic
c. Internal Emitters
d. Radon

1.05.02 Identify the following four sources of artificially produced radiation and the magnitude of dose received from each.
a. Nuclear Fallout
b. Medical Exposures
c. Consumer Products
d. Nuclear Facilities

INTRODUCTION

Apart from the amount of radiation a worker may receive while performing work, they will also be exposed to radiation because of the very nature of our environment. All individuals are subject to some irradiation even though they may not work with radioactive substances. This natural source of exposure is often referred to as ***background radiation***.

Studies of the nature and origin of this source of exposure to man have revealed three main components: terrestrial radiation (which includes the radioactivities of the earth's surface, air and water), cosmic radiation, and the naturally occurring radionuclides of the human body. One might add that man-made sources influence the contribution from some of these sources. The amount which each of these factors contributes varies with the locale.

The study of these factors throughout the world is of value for a number of reasons. Foremost among these is that the use of such data provides a basis or standard from which allowable exposure limits for radiation workers may be developed. In areas where the levels are much higher because of larger concentrations of natural radioactive materials, knowledge may be gained about human hereditary effects at these increased levels. Such data are also needed in assessing the impact on, or contribution of a nuclear facility to the existing concentrations in a given area. In the design of buildings and/or shielding for low-level work, it is of value to know the radioactive contents of the substances used. Often the levels inside a building are higher than those outside of the building because this factor has been neglected.

Because of these needs, much data about background levels in many areas has been acquired. This section is devoted to the discussion of these background factors and the relative contribution of man-made radiation.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
2. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
3. NCRP Report No. 45 "Natural Background Radiation in the United States".
4. NCRP Report No. 56 "Radiation Exposure from Consumer Product Miscellaneous Sources".
5. NCRP Report No. 93 "Ionizing Radiation Exposure of the Population of the United States".

NATURAL BACKGROUND RADIATION SOURCES

1.05.01	*Identify the following four sources of natural background radiation including the origin, radionuclides, variables and contribution to exposure.* *a. Terrestrial*

Terrestrial Radiation

Radioactivity of the Earth

The presence of certain small amounts of radioactivity in the soil adds to the background levels to which man is exposed. The amount of radioactive materials found in soil and rocks varies widely with the locale. The main contribution to the background is the gamma ray dose from radioactive elements chiefly of the **uranium** and **thorium** series and lesser amounts from radioactive K-40 and Rb-87.

Due to the high concentration of monazite, a thorium mineral, some regions in the world have an extremely high background level. The majority of the population of the Kerala region in India receive an annual dose greater than 500 mrem. A small percentage of the inhabitants receive over 2,000 mrem per year and the highest recorded value has been 5,865 mrem in one year. It is interesting to note that this value is more than what is allowed for a DOE radiation worker. The Minas Garais state in Brazil has an average terrestrial background dose rate of 1,160 mrem per year. Their maximum recorded dose rate has been 12,000 mrem per year. In the United States on the average, a square mile of soil, one foot deep, contains one ton of K-40, three tons of U-238 and six tons of Th-232.

The amount of exposure one is subjected to depends upon the concentration in the soil and the type of soil. In the U.S., three broad areas have been found. These are: the coastal region along the Atlantic Ocean and the Gulf of Mexico, the Colorado Plateau region, and the remainder of the country. The yearly whole body dose equivalent rates in these areas range from 15-35 mrem, 75-140 mrem, and 35-75 mrem, respectively. When absorbed dose rate measurements are weighted by population, and averaged over the entire U.S., the yearly average is estimated at **28 mrem** (280 μSv) in NCRP Report No. 93.

Radioactivity of Water

Depending upon the type of water supply one is talking about, a number of products may turn up. For example, sea water contains a large amount of K-40. On the other hand, many natural springs show amounts of uranium, thorium, and radium. Almost all water should be expected to contain certain amounts of radioactivity. Since rain water will pick up radioactive substances from air, and

ground water will pick up activity present in rocks or soil, one would expect to find some radioactivity in water throughout the world.

The U.S. average of alpha emitters in water is <1 pCi/l. Some regions contain significantly higher levels of naturally occurring alpha emitters: 40-50 pCi/l may be found in Colorado; and 200 pCi/l may be found in bottled water from Brazil.

The chief source of dose rate from this background factor occurs as the result of uptake of these waters by ingestion. This leads to an internal exposure. Any estimate of the dose rate from this source is thus included in the estimate of the dose rate from radioactivity in the human body. The transfer of radioactive substances to the body seems to be mainly by food intake except in cases of very high water concentrations.

1.05.01	*Identify the following four sources of natural background radiation including the origin, radionuclides, variables and contribution to exposure.* *b. Cosmic*

Cosmic Radiation

Much work has been carried out in the study of cosmic radiation. This factor in background levels was discovered during attempts to reduce background. Though detection devices showed a response even in the absence of any known sources, it was assumed this background was due entirely to traces of radioactive substances in the air and ground. Thus, if a detector was elevated to a greater height above the earth's surface, the background should be greatly reduced. The use of balloons carrying ion chambers to great heights yielded data which showed the effect increased, rather than decreased. These and other data showed that radiation was really coming from outer space. The name *cosmic rays* was given to this high energy.

Further study has shown that cosmic radiation consists of two parts: **primary** and **secondary**. The primary component may be further divided into galactic, geomagnetically trapped radiation, and solar.

Primary

The **galactic cosmic rays** come from outside the solar system and are composed mostly of positively charged particles. Studies have shown that outside the earth's atmosphere, cosmic rays consist of 87% protons, of 11% alpha particles, and about 1% each of other heavier nuclei and electrons at latitudes above 55 degrees. These particles may have energies in the range of about 1 GeV and higher.

As a charged particle approaches the earth, it is acted upon by the earth's magnetic field. In order to pass on through to the earth, the particle must have a certain momentum. Otherwise, it may be trapped by the earth's magnetic field. This gives rise to the second type of primary cosmic rays, the **geomagnetically trapped radiation**.

Solar cosmic rays are produced following severe solar flares on the surface of the sun. These rays consist of protons. The events are classed as high energy or low energy. The high energy events can be observed by ground-level neutron devices. The low energy events are more frequent but must be detected at high altitude. Since these events produce radiation throughout the solar system, they are of great importance in shielding design for manned space missions.

Secondary

Secondary cosmic rays result from interactions which occur when the primary rays reach the earth's atmosphere. When the high energy particles collide with atoms of the atmosphere, many products are emitted: pions, muons, electrons, photons, protons, and neutrons. These, in turn, produce other secondaries as they collide with elements or decay on the way toward the earth's surface. Thus, a multiplication or shower occurs in which as many as 10^8 secondaries may result from a single primary.

Most of the primary rays are absorbed in the upper 1/10 of the atmosphere. At about 20 km and below, cosmic rays are almost wholly secondary in nature. The total intensity of cosmic rays shows an increase from the top of the atmosphere down to a height of 20 km. Although the primary intensity decreases, the total effect increases because of the rapid rise in the number of the secondaries. Below 20 km, the total intensity shows a decrease with height because of attenuation of the secondaries without further increase in their number due to primaries. At less than 6 km of altitude, the highly penetrating muons, and the electrons they produce, are the dominant components.

At the earth's surface, the secondary cosmic rays consist mainly of muons (hard component), electrons and photons (soft components), and neutrons and protons (nucleonic component). At sea level about 3/4 of the cosmic ray intensity is due to the hard component.

Because of the earth's magnetic field, cosmic ray intensity also varies with latitude. The energy which is needed for a charged particle to reach the earth's atmosphere at the geomagnetic equator is larger than that needed at other latitudes. The effect is greatest for latitudes between 15 and 50 degrees. Above 50 degrees, the intensity remains almost constant. Thus, the lowest value of the intensity occurs at the geomagnetic equator, and the effect is expressed as the percentage increase at 55 degrees over that at the equator. At sea level, the effect is small for the ionizing component (10%) but is larger for the neutron component.

The dose rate produced by this source of background may be divided into two parts. The portion caused by the ionizing component is estimated from ion chamber readings. The portion caused by the neutron component is hard to measure because the dose rate depends so much on the energy spectrum of the neutrons. For the neutron dose estimates one must rely on calculations.

At sea level and high latitudes, the ionization rate, is about 2.1×10^6 ion pairs per cubic meter. Using a neutron calculation, the sea level dose would be increased by about 5%. Taking into account the dose variation with altitude, and the population distribution with altitude, the average yearly dose equivalent rate to the U.S. population from **cosmic radiation** is estimated to be **27 mrem** (270 μSv). This dose equivalent rate would be expected to decrease slightly with latitude and increase with altitude. For example at Denver, the yearly dose would be about 50 mrem (500 μSv).

1.05.01 Identify the following four sources of natural background radiation including the origin, radionuclides, variables and contribution to exposure.

c. Internal Emitters

***Internal Emitters* (Radioactivity of the Human Body)**

Since small amounts of radioactive substances are found throughout the world in soil and water, some of this activity is transferred to man by way of the food chain cycle. A number of studies have been made to try to find a correlation between the amounts in soil and that in man. Results have not shown a clear-cut relationship as yet.

In the human body, K-40, Rb-87, Ra-226, U-238, Po-210, and C-14 are the main radionuclides of concern. Of these, **K-40** is the most abundant substance in man. The amount in food varies greatly, so that intake is quite dependent on diet. However, variations in diet seem to have little effect on the body content. The content of K-40 in body organs of man varies widely. Based on an average content of 0.2% by weight in soft tissue, 0.05% in bone, the yearly dose equivalent rate to the gonads is estimated to be 19 mrem (190 μSv); 15 mrem (150 μSv) to bone surfaces; and 15 mrem (150 μSv) to bone marrow. Rb-87 contributes only a few percent of these values.

Most of the **Ra-226** which is taken into the body will be found in the skeleton. Much data has been gathered on the concentration in humans, and the present assumed average skeletal concentration is taken as about 0.29 Bq/kg. The skeletal content of **Ra-228** is taken as 0.14 Bq/kg. The yearly dose rate produced by these components is estimated to be .5 mrem (5 μSv) to the gonads, 14.6 mrem (146 μSv) to bone surfaces and 2.2 mrem (22 μSv) to bone marrow.

Based upon an average concentration of **U-238** of 0.26 Bq/kg in bone, the estimated doses in man are 4.8 mrem (48 μSv) to bone surfaces and 0.9 mrem (9 μSv) to the marrow. From the estimated content in the gonads, the annual dose equivalent is estimated to be about 1 mrem (10 μSv).

Similarly, the **Po-210** decay chain contribution is taken as 2.22 Bq/kg, yielding annual dose equivalents of 24 mrem (240 μSv) to bone surfaces and 4.9 mrem (49 μSv) to bone marrow. The soft tissue concentration is taken as 0.111 Bq/kg, but is about twice that in the gonads. This gives an annual gonad dose equivalent of 6 mrem (60 μSv).

The average whole body content of carbon is taken as 23%. However, **C-14** is present in normal carbon only to a very small extent (C-14/C-12 ~10^{-12}), so that only a small amount of C-14 is present. The annual average dose equivalent turns out to be about 1 mrem (10 μSv) total body. In soft tissue, the annual dose is 0.7 mrem (7 μSv). The annual dose to the bone surfaces is 0.8 mrem (8 μSv), and to the bone marrow, 0.7 mrem (7 μSv).

The U.S. annual average dose equivalent for all **internal emitters** (food chain) in the body is **39 mrem** (390 μSv) as listed by the NCRP Report No. 93.

1.05.01 Identify the following four sources of natural background radiation including the origin, radionuclides, variables and contribution to exposure.

d. Radon

Inhaled Radionuclides **(Radioactivity of the Air)**

The background which is found in air is due mainly to the presence of radon and thoron gas, formed as daughter products of elements of the uranium and thorium series. The decay of U-238 proceeds to Ra-226. When Ra-226 emits an alpha as it decays, the gas Rn-222 is formed, which is called radon. In the thorium chain, the decay of Ra-224 results in the gaseous product Rn-220, which is called thoron.

Since uranium and thorium are present to some extent throughout the crust of the earth, these products are being formed all the time. Since they are gases, they tend to diffuse up through the earth's surface to become airborne. In turn, the decay products of these gases attach themselves to dust in the air.

The amount of these gases in the air depends upon the uranium and thorium content of a certain area. In any given area, the weather conditions will greatly affect the concentrations of these gases. It is also common to find that the levels indoors are higher than those outdoors. This is a function of the material of the building and the ventilation rate. In mines and other underground caverns, the concentrations have been found to be quite high.

Some homes in Grand Junction and Durango, Colorado, have been found to have high radon levels. This was traced to the use of uranium mill tailings, residues rich in radium, as backfill. This discovery has led to radon measurements in homes in other areas of the country. Some homes in Pennsylvania are situated on land with naturally elevated radium concentrations, giving rise to increased indoor radon levels. Investigations have been made of radon levels in homes in the Chicago area. Their results indicated that 6% of the homes studied had radon concentrations comparable to those found at Grand Junction. Because of the potential population dose from this source, much more work on defining this potential problem is being carried out.

The major source of exposure from radon in air occurs when the daughter products attach themselves to aerosols and are inhaled. This leads to an internal dose to the lungs. As for external exposure, the external gamma dose rate from Rn-222 and Rn-220 is estimated to be less than 5% of the total external terrestrial dose rate. The contribution of inhaled radon gas to the annual average effective dose equivalent is included as an **inhaled radionuclide**.

Among other radioactive products which are found in air in measurable amounts are C-14, H-3, Na-22, and Be-7. These are called **cosmogenic** radionuclides, since they are produced in the atmosphere by cosmic rays. None of these products add a significant amount to the background dose rate.

The U.S. annual average dose equivalent for various **inhaled radionuclides** (primarily radon) is estimated at **200 mrem** (2,000 μSv) by the NCRP Report No. 93.

MAN-MADE BACKGROUND RADIATION SOURCES

1.05.02 Identify the following four sources of artificially produced radiation and the magnitude of dose received from each.

a. Nuclear Fallout

Nuclear Fallout

The term *fallout* has been applied to debris which settles to the earth as the result of a nuclear blast. This debris is radioactive and thus a source of potential radiation exposure to man. Radioactive fallout is not considered naturally occurring but is definitely a contributor to background radiation sources.

Because of the intense heat produced in a nuclear explosion during a very short time, matter which is in the vicinity of the bomb is quickly vaporized. This includes fission products formed in the fission process, unused bomb fuel, the bomb casing and parts, and, in short, any and all substances which happen to be around. These are caught in the fireball which expands and rises very quickly. As the fireball cools and condensation occurs, a mushroom-shaped cloud is formed, containing small solid particles of debris as well as small drops of water. The cloud continues to rise to a height which is a function of the bomb yield and the meteorological factors of the area. For yields in the megaton

range (1 megaton equals an energy release equivalent to one million tons of TNT), the cloud top may reach a height of 25 miles.

The fallout which occurs may be described as local or world-wide. The portion of debris which becomes local fallout varies from none (in the case of a high-altitude air burst) to about half (in the case of a contact surface burst). The height at which the bomb goes off is thus quite important in the case of local fallout. If the fireball touches the surface of the earth, it will carry aloft large amounts of surface matter. Also, because of the vacuum effect created by the rapid rise of the fireball, other matter may be taken up into the rising fireball. This leads to the formation of larger particles in the cloud that tend to settle out quickly. If the width is not too great, the fallout pattern will be roughly a circle around ground zero. Ground zero is the point on the surface directly under, at, or above the burst.

Other bits of matter will fall out at various stages. the distance from ground zero at which they strike the surface and the time it takes depend upon the height from which they fall, their size, and the wind patterns at all altitudes. This results in a cigar-shaped pattern downwind of the burst point. Local fallout usually occurs within the first 24 hours after the blast.

If the height of the burst is such that the fireball does not touch the surface, then the debris is carried aloft and dispersed into the atmosphere. This matter then descends to earth at a later time and is called world-wide fallout.

The residence time of this debris is a function of the bomb yield. For yields in the kiloton range, the debris is not projected into the stratosphere. It is limited to a region called the troposphere, between about 9,000 and 17,000 meters. In this region, there is quite a bit of turbulence as well as precipitation. The debris is removed rather quickly; from about one day to one month.

If the burst is in the megaton range, the debris is carried into the stratosphere. In this region little mixing will occur, and the absence of rain or snow prevents this matter from being washed down. The time that it takes for this debris to return to the troposphere and be washed down varies. It is a function of both the height in the stratosphere to which the debris is lifted and the locale at which the burst occurs. It may take up to 5 years or more for this debris to return to earth. On the other hand, for bursts in the northern hemisphere in which the debris is confined to only the lower part of the stratosphere, the half-residence time is thought to be less than one year. Half-residence time is the time for one-half of the debris to be removed from the stratosphere.

In all, there are more than 200 fission products which result from a nuclear blast. The half-life of each of these products covers the range from a fraction of a second to millions of years. Local fallout will contain most of these products. Because of the time delay in the appearance of world-wide fallout, only a few of these products are important from that standpoint. Since local fallout is confined to a relatively small area, its effect on the human population can be negated by proper choice of test sites, weather conditions, and type of burst. The fallout of interest from the standpoint of possible effects on man due to testing is the world-wide fallout.

A number of factors must be considered when one attempts to assess the hazard from world-wide fallout. Because of the associated time delay before world-wide fallout shows up, many fission products and activation products decay out in transit. Others, because they are produced in such small amounts, are diluted so that they do not produce much of an effect. Also, once the fallout does arrive, to be of importance internally, there must be a transfer to the body and absorption into the body organs. All these factors combine to limit the number of fission products which may have an effect on man. The main contribution comes from Sr-90, Cs-137, I-131, C-14, H-3 with minor contributions from Kr-85, Fe-55, and Pu-239. Although the U.S. ceased atmospheric testing in 1962, the inventory of fission products from previous bursts has committed man to future doses. NCRP Report No. 93 lists the annual average effective dose equivalent from nuclear fallout exposure at less than 1 mrem (10 μSv). However the total dose commitment, to be delivered over many generations, is 140 mrem (1400 μSv).

1.05.02 Identify the following four sources of artificially produced radiation and the magnitude of dose received from each.

b. Medical Exposures

Medical Exposures

The exposure to the U.S. population from X-rays used in medical and dental procedures is the largest source of man-made radiation. It is estimated that more than 300,000 X-ray units are in use in the U.S., and that about 2/3 of the U.S. population is exposed. In 1970, the estimated annual average bone marrow dose equivalent from dental and medical X-rays to the U.S. population was about 78 mrem (780 μSv). In addition to the exposure from X-rays, nuclear medicine programs use radiopharmaceuticals for diagnostic purposes. Radiologists also use radionuclides for therapy treatment. It has been estimated that more than 10 million doses are administered each year. NCRP Report No. 160 gives the dose equivalent for medical radionuclides as ~ 300 mrem/yr

1) computed tomography (total average dose ~ 150 mrem/yr)
2) nuclear medicine (total average dose ~ 75 mrem/yr)
3) radiography/fluroscopy (total average dose ~ 75 mrem/yr)

Diagnostic X-Rays

There are many different types and styles of X-ray machines used in the medical field. An X-ray machine generally consists of the X-ray tube, an electrical source of high voltage, a type of filament, and radiation shielding to collimate the beam to some limited size and shape. A diagnostic X-ray machine is used to obtain an image of some part of the body on some type of storage material. There are three general types of diagnostic X-ray equipment: radiographic, fluoroscopic, and photofluorographic.

Radiography involves the use of an X-ray tube and a photographic plate. The patient is placed between the two and an image is produced on the film of the area exposed. A common "chest X-ray" is an example of a radiographic X-ray.

In a **fluoroscopic** X-ray machine the film cassette is substituted with an imaging device (image intensifier). This enables the radiologist to observe the part of the body exposed live on a video monitor. A blocking agent, such as barium, is often swallowed by the patient to allow the medical staff to observe internal processes in action. A fluoroscopic examination can be used to locate ulcers in a "GI series."

The **photofluorographic** process utilizes an X-ray tube, a fluorescent screen and a camera. This practice is similar to radiographic X-rays, with the substitution of a fluorescent screen for the film. The radiologist can take several pictures on one roll of film of the image on the fluorescent screen. Photofluorography is used for screening large numbers of individuals such as in the military or prison.

As science gradually became more aware of the potential hazards associated with radiation exposures, the doses received from diagnostic X-rays have been closely examined. Medical diagnostic exposures contribute more than 50% of the dose to the U.S. population from artificial sources. The U.S. Public Health Services has been tasked with tracking medical X-ray procedures at ten year intervals. Surveys were conducted in 1961, 1970, and 1980. Due to budget cut backs, the 1980 survey does not contain as much useful data as the one produced in 1970. The concept of "Genetically Significant Dose" (GSD) is used in most publications covering background radiation. The GSD includes only the fraction of the radiation which actually deposits energy in the gonads (ovaries and testes) of persons of childbearing potential. Dose rates that produce a small exposure over a years time cannot be expected to produce any acute somatic radiation injury. Late effects from this exposure are almost negligible at these low dose rates. Genetic mutations are transmitted on to our offspring who will then be exposed during their lifetimes. The cumulative effect on genetic mutations over several generations might show a very slight increase due to background radiation.

Medical Radionuclides

Radionuclides are used in medicine by two general classifications: Nuclear Medicine for diagnostic procedures and Radiation Oncology for radiation therapy. Because this science is utilized by a limited portion of the U.S. population, its contribution to the average U.S. dose is not significant.

Radionuclides are used to determine the extent of a medical problem in a patient. The radionuclide is "attached" to a pharmaceutical which is administered to the patient. The drug has the properties to deposit the radioisotope in the organ of concern. Then using external radiation detectors, the medical staff can determine abnormalities in the organ. A thyroid scan and lung function test are examples.

Since the radioisotope is internally deposited either by mouth or by injection, it should decay by emitting only photons. Isotopes emitting alpha or beta particles would be locally absorbed in the organ and would not contribute to the information signal. Another consideration in radionuclide selection would be the effective half-life. To maintain organ doses ALARA, isotopes with a few hour

half-life are optimum. Technetium-99m and Indium-113m are commonly used radiopharmaceuticals.

Radiation Oncology (study/treatment of tumors) uses radionuclides for tumor treatment. In the United States Cobalt-60 is generally used for the high activity sealed source. This consists of a mechanical device which moves the source to an opening in a collimator which projects a beam of photons used for treatment. A typical 6,000 curie Cobalt-60 source delivers about 100 rad/minute to a tumor.

1.05.02 Identify the following four sources of artificially produced radiation and the magnitude of dose received from each.

c. Consumer Products

Consumer Products

In NCRP Report 56, a number of consumer products and miscellaneous sources of radiation exposure to the U.S. population are discussed. In general, two groups of sources have been found:

1. Those in which the dose equivalent is relatively large and many people are exposed.

2. Those in which the dose equivalent is small but many people are exposed or the dose equivalent is large but only a few people are exposed.

Such products as television sets, luminous-dial watches, smoke detectors, static eliminators, tobacco products, airport luggage inspection systems, building materials and many other sources have been studied. The estimated annual average whole body dose equivalent to the U.S. population from consumer products is approximately **10 mrem** (100 μSv). The major portion of this exposure (approximately 70%) is due to radioactivity in building materials.

Television Receivers

Television receivers have the potential for three X-rays sources: the picture tube, the shunt regulator and the vacuum tube regulator. In 1960 the ICRP and the NCRP recommended limits be established such that receivers produce less than 0.5 mrem/hr at any access point 5 cm from the surface of the set. In May of 1967 a major manufacturer recalled 149 big screen sets. Of this group, two sets were found to produce exposures in excess of 100 mR/hr. Due to the ever increasing improvements in TV manufacturing, solid state, and the use of "hold down" circuits, the annual exposure is being reduced. X-ray emissions can be kept below 0.1 mR/hr with low voltage within manufacture specifications. Higher emissions can result if the voltage is increased by repairman in order to increase picture quality. It is estimated that the U.S. total average exposure from watching TV is between 0.5 and 1.5 mrem/yr.

Shoe-Fitting Fluoroscopes

In the 1950's the use of fluoroscopes was wide spread in shoe stores. It was estimated that 10,000 of these were in use in 1953. Exposures to the feet ranged from 7 to 14 Roentgens per 20 second exposure. The concurrent exposure to the pelvis ranged between 30 and 170 mR per exposure. Shoe-fitting fluoroscopes have been banned or restricted in most states.

Radioluminous Watches

Radium-226 was used widely in the earlier part of this century for it's luminescence in watches, clocks and dials. No radium-226 watches have been sold in the U.S. since 1970. It is estimated that 10 million of these watches are still in use. Individual dose can reach 310 mrem/yr for the wearer of a watch containing 4.5 uCi of radium-226. The average dose to radium watch wearers is approximately 3 mrem/yr.

The majority of luminescent watches on the market today contain either tritium (H-3) or promethium-147. It's estimated that the 16 million who wear tritium watches receive 0.6 mrem/yr, and the 2 million who wear promethium watches receive 0.25 mrem/yr.

Miscellaneous

There are many additional consumer products that may be included as a source of radiation. Polonium and lead isotopes have been found in tobacco products and contribute a dose-equivalent to small areas of the bronchial epithelium of up to 8 rem/yr to smokers. Building materials, smoke detectors, lantern mantles, and ceramic glazes are all known sources. Another source of radiation exposure to the public arises from the wide use of coal. Coal contains C-14, K-40, uranium and thorium and when burned, the resulting flyash released to the atmosphere carries some of this radioactivity with it. This leads to inhalation of airborne flyash producing lung exposure. The dose equivalent rate in the vicinity of one of these plants has been estimated to be in the range of 0.25-4 mrem/y (2.5-40 μSv/y).

1.05.02 Identify the following four sources of artificially produced radiation and the magnitude of dose received from each.

d. Nuclear Facilities

Nuclear Facilities

By 1988, 90 nuclear power plants had been licensed in the U.S. In addition, over 300 other reactors, classed as non-power reactors, are being operated. In order to provide fuel for these reactors, mining and milling of uranium ore is carried out and fuel fabrication plants are operating. There are several hundred mines, 20 uranium mills and 21 fuel fabrication facilities.

Sources of radiation from nuclear reactors consist of prompt neutrons, gamma rays and possible exposures from contamination or environmental releases. The NRC has been tasked by the federal government to calculate doses for populations living within 50 miles of a nuclear facility. Three radionuclides released during routine operations, which contribute to the population dose, are H-3, C-14, and Kr-85. Current estimates of the yearly average dose equivalent in the U.S. from environmental releases is <1 mrem (10 μSv).

Total Background Radiation

The average annual total effective dose to the general population (non-smokers) from naturally occurring and manmade sources is about 620 mrem.

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Course Title: **Radiological Control Technician**
Module Title: **Radioactivity & Radioactive Decay**
Module Number: **1.06**

Objectives :

1.06.01 Identify how the neutron to proton ratio is related to nuclear stability.

1.06.02 Identify the definition for the following terms:
a. radioactivity
b. radioactive decay

1.06.03 Identify the characteristics of alpha, beta, and gamma radiations.

1.06.04 Given simple equations identify the following radioactive decay modes:
a. alpha decay
b. beta decay
c. positron decay
d. electron capture

1.06.05 Identify two aspects associated with the decay of a radioactive nuclide.

1.06.06 Identify differences between natural and artificial radioactivity.

1.06.07 Identify why fission products are unstable.

1.06.08 Identify the three naturally-occurring radioactive families and end product of each.

1.06.09 Given a nuclide, locate its block on the Chart of the Nuclides and identify the following for that nuclide:
a. atomic number
b. atomic mass
c. natural percent abundance
d. stability
e. half-life
f. types and energies of radioactive emissions

1.06.10 Given the Chart of Nuclides, trace the decay of a radioactive nuclide and identify the stable end-product.

1.06.11 Identify the definition of the following units:
a. curie
b. becquerel

1.06.12 Identify the definition of specific activity.

1.06.13 Identify the definition of half-life.

1.06.14 Calculate activity, time of decay, and radiological half life using the formula for radioactive decay.

1.06.15 Identify the definition of the following:
- a. exposure
- b. absorbed dose
- c. equivalent dose
- d. radiation weighting factor

1.06.16 Identify the definition of the following units:
- a. roentgen
- b. rad/gray
- c. rem/sievert

INTRODUCTION

As discussed in previous lessons, there are many different kinds of elements. The atoms of these elements are comprised of a nucleus surrounded by orbital electrons. The nucleus consists of protons and neutrons. Each element has a specific number of protons, while the number of neutrons may vary, resulting in various isotopes of the same element.

Additionally, it has been shown that a slight difference in mass-energy exists between a nucleus and its constituent parts, which is the energy that binds the nucleus together. This requires that each nucleon give up a certain amount of mass in order for the nucleus to be held together. Since only certain combinations of protons and neutrons (isotopes) exist in nature, this must mean that a specific combination of neutrons and protons is required in order to have a nucleus that will remain intact indefinitely. A variation from this specific combination may be possible, but the nucleus may not be completely stable; that is to say, there may be more energy present in the nucleus than is required to hold it together. If a nucleus has excess energy, it will not be stable, and will most likely try to get rid of that excess energy in order to become stable.

Stable nuclei have no excess energy and will remain unchanged forever as long as there is no external influence causing them to change. Unstable nuclei, however, because of their excess energy, will spontaneously give up their excess energy in transforming themselves into more stable nuclei, even when there is no external influence. These transformations are independent of extra-nuclear considerations such as temperature or chemical status of the atom. The emission of excess energy by unstable nuclei in order to achieve stability is the phenomenon of *radioactivity*.

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1.06.01 Identify how the neutron to proton ratio is related to nuclear stability.

NUCLEAR STABILITY

Forces in the Nucleus

Nuclear stability is governed by the particular combination and arrangement of neutrons to protons in a given nucleus. The stability of the nucleus is affected by three forces acting in the nucleus (see Table 1):

TABLE 1. Forces Acting in the Nucleus

Force	Interaction	Range
Gravitational	Very weak *attractive* force between all nucleons	Relatively long
Electrostatic	Strong *repulsive* force between like charged particles (protons)	Relatively long
Nuclear Force	Strong *attractive* force between all nucleons	Extremely short

The gravitational and electrostatic forces can be calculated using principles from classical physics. In doing so it is found that the gravitational force is so small that it can be neglected. The repulsive electrostatic force between protons is found to be quite significant and occurs over a relatively long range. If only these two forces existed in the nucleus, then it would be impossible to have stable nuclei with more than one proton. The gravitational forces are much too small to hold the nucleons together compared to the electrostatic forces repelling the protons. Since stable atoms do exist, there must be another attractive force acting within the nucleus.

The nuclear force is independent of charge. It acts equally only between pairs of neutrons, pairs of protons, or a neutron and a proton. Since the range of the nuclear force is much shorter than the range of the electrical force, neutrons can only interact with those nucleons to which they are immediately adjacent, whereas protons interact with each other even though remotely located within the nucleus. Since the repulsive forces associated with protons will be significant regardless of their location in the nucleus, the repulsive forces will have a large impact on the nuclear stability. For this reason, the number of neutrons must increase more rapidly than the number of protons in order to maintain stability.

Neutron/Proton Ratio

In stable atoms there is a balance between the attractive (nuclear) and repulsive (electrostatic) forces in the nucleus. If the forces do not balance, the atom cannot be stable. This means that only certain combinations or ratios of neutrons and protons are stable such that the repulsive force is balanced by the attractive forces. The coulombic (electrostatic) forces become increasingly significant as the atomic number increases above 20. Consequently, with increasing atomic number a neutron excess is required for a stable nuclide.

Thus, for elements in the Periodic Table with low atomic numbers, greater nuclear stability is found when the number of neutrons is about equal to the number of protons. As elements increase in Z number (number of protons) above 20, the neutron to proton ratio (n:p ratio) gradually increases until Z=83 (bismuth), where the n : p ratio required for stability exceeds 1.5 to 1. Finally, at the high atomic number part of the Periodic Table, above ^{2}Bi, there are no completely stable nuclei.

The stable range can be graphed and is usually called the *line of stability*. The graph shows a dashed line representing a 1:1 ratio of neutrons to protons for any Z number (see Figure 1). The actual "line" of stability is represented by the ratio of neutrons to protons for naturally-occurring stable isotopes. The line of stability graph can be thought of as a simplified representation of the Chart of the Nuclides. The number of neutrons (N) is the "x-axis" and number of protons (Z) is the "y-axis".

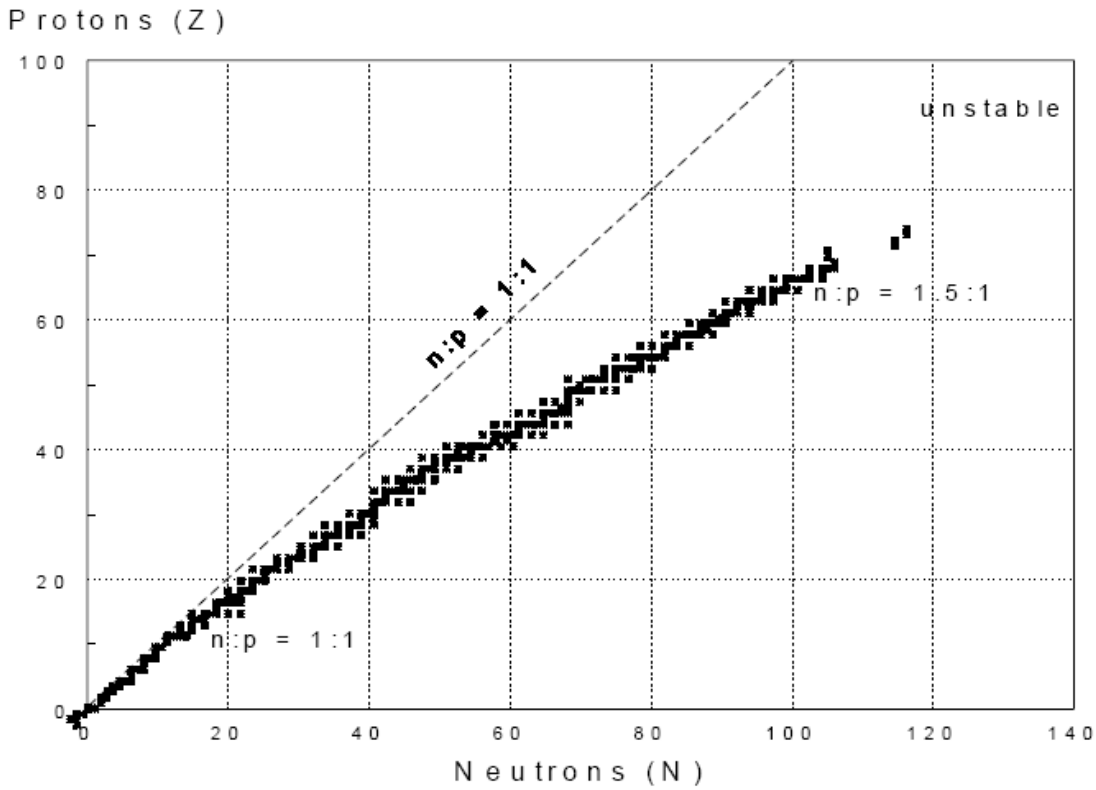


FIGURE 1. Neutron:Proton Ratios for Stable Nuclides

The stability conditions based on n:p ratios are not very critical, and a stable range of n:p ratios exists for any given element. For a given atomic number, conditions may vary widely, such that numerous stable isotopes (same atomic number, different mass numbers) can occur for a particular element as many as 10 stable isotopes for some elements. For a given mass number, there may be several stable arrangements of protons and neutrons resulting in several stable *isobars* (same mass number, different atomic numbers).

Stability Ranges

In summary, nuclear stability is governed by the particular combination and arrangement of neutrons and protons in a given nucleus. If the combination and arrangement of neutrons and protons does not fall within a stable "range," the nucleus is unstable. An unstable nucleus attempts to achieve stability by changing its nuclear configuration. This will be accomplished by nuclear transformations which eliminate surplus nucleons so as to balance nuclear forces. When a proton or neutron is eliminated from the nucleus the ratio of neutrons and protons is thereby changed. As to whether a proton or a neutron is eliminated depends on which force is greater: the electrostatic force (protons), or the nuclear force (neutrons).

1.06.02	*Identify the definition of the following terms:* *a. radioactivity* *b. radioactive decay*

RADIOACTIVITY

When a atom is radioactive it will change its nuclear configuration by eliminating surplus nucleons through transformations. This is done by changing neutrons to protons, or vice versa, and then ejecting the surplus mass or energy from the nucleus. This emission of particles or energy from the nucleus is called *radiation*. Radiation can be in the form of particles or electromagnetic energy waves. These emissions occur randomly as each atom tries to achieve a more stable nuclear configuration.

The property of certain nuclides to spontaneously emit radiation is called *radioactivity*. In other words, if a nuclide has this property it is said to be radioactive. (The term *radionuclide* has been coined to refer to these radioactive nuclides.) The emission of a particle or electromagnetic radiation in order to reach a more stable configuration produces a change or *transformation*. Following a transformation the nucleus is usually more stable than it was, but it may not be completely stable. So, another transformation will take place in which the nucleus will again emit radiation. The amount of energy given off and the type of emission that occurs will depend on the configuration of the nucleus immediately before a specific transformation occurs. Each step in the series of transformations will mean a distinct reduction in total mass-energy of the nucleus. As the energy of the nucleus is reduced, the nucleus is said to *disintegrate* or decay. The **process by which a nucleus spontaneously disintegrates (or is transformed) by one or more discrete energy steps until a stable state is reached** is called *radioactive decay*.

The nucleus before the decay (or transformation) is called the *parent* and the nucleus after the decay is called the *daughter*. When there are a series of transformations before a stable state is reached, the daughter of one decay may also be radioactive and thus be the parent to another daughter. As the various steps from parent to daughter are traced to stability, a series of transmutations is seen, called a *decay chain*. The complete chain includes the original parent, all of its daughters and the final, stable end-product. Examples of various decay chains will be shown throughout the remainder of this lesson.

Nature of Radioactivity

Certain nuclides are unstable as they occur in nature and are therefore referred to as being *naturally* radioactive, while others are *artificially* radioactive because they have become radioactive as a result of some man-made reaction. Evidence of natural radioactivity was first reported by Henri Becquerel in 1896. Becquerel demonstrated that uranium ore would darken a photographic plate shielded with opaque paper in much the same manner as X-rays. He postulated that the uranium emitted very penetrating rays, similar to X-rays. The phenomenon

ultimately was called radioactivity. In time, it was determined that there were many elements beyond the atomic number of lead (*Z*=82) which showed similar radiating characteristics.

After a long and complicated series of investigations, to which many outstanding physicists contributed, a better understanding of natural radioactivity was available. The understanding culminated with the experiments of Ernest Rutherford. In 1903, he clearly showed there were three kinds of radioactive emissions, which he named *alpha*, *beta*, and *gamma*, after the first three letters of the Greek alphabet.

1.06.03		*Identify the characteristics of alpha, beta, and gamma radiations.*
1.06.04		*Given simple equations identify the following radioactive decay modes:*
	a.	*alpha decay*
	b.	*beta decay*
	c.	*positron decay*
	d.	*electron capture*

MODES OF DECAY AND TYPES OF RADIOACTIVE EMISSIONS

As mentioned above, Rutherford was initially able to identify three types of radiation resulting from radioactive decay: alpha, beta and gamma. Initially, all three radiations were commonly referred to as *rays*. With time, the characteristics of each of these radiations was determined. It was found that alpha and beta are actually *particulate* radiations, not rays. Since then, other radiations have been discovered through numerous experiments and tests.

When a radioactive nuclide decays, a transmutation occurs. The decay product, or daughter has become an atom of a new element with chemical properties entirely unlike the original parent atom. With each transmutation an emission from the nucleus occurs. There are several modes of decay and emissions associated with each mode.

Alpha Decay

With a few exceptions, only relatively heavy radioactive nuclides decay by alpha emission. An alpha particle is essentially a helium nucleus. It consists of two protons and two neutrons, giving it a mass of 4 amu. Because of the two protons it has an electric charge of +2. The symbol α is used to designate alpha particles.

A nucleus emitting an alpha particle decays to a daughter element, reduced in atomic number (*Z*) by 2 and reduced in mass number (*A*) by 4. The standard notation for alpha decay is:

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

For example, Radium-226 decays by **alpha emission** to produce Radon-222 as follows:

$$^{226}_{88}\mathbf{Ra} \longrightarrow {}^{222}_{86}\mathbf{Rn} + {}^{4}_{2}\boldsymbol{\alpha}$$

Alpha particles are the least penetrating of the three types of radiation. They can be absorbed or stopped by a few centimeters of air or a sheet of paper.

Beta Decay

A nuclide that has an excess number of neutrons (i.e. the n:p ratio is high) will usually decay by beta emission. The intranuclear effect would be the changing of a neutron into a proton, thereby decreasing the n:p ratio, resulting in the emission of a beta particle. Beta particles are negatively charged particles. They have the same mass as an electron (1/1836 of proton or 5.49E-4 amu) as well as the same charge (-1) and can be considered high speed electrons. Because of the negative charge of the beta particle, beta emission is often more explicitly referred to as "beta-minus" emission (the particle sometimes being referred to as a *negatron*). Beta particles originate in the nucleus, in contrast with ordinary electrons, which exist in orbits around the nucleus. The symbol β^- is used to designate beta particles.

In beta-minus emitters, the nucleus of the parent gives off a negatively charged particle, resulting in a daughter more positive by one unit of charge. Because a neutron has been replaced by a proton, the atomic number increases by one, but the mass number is unchanged. There is also the emission of an *antineutrino*, symbolized by the Greek letter nu with a bar above it $(\bar{v})$.

The standard notation for beta decay is:

$$^{A}_{Z}\mathbf{X} \longrightarrow {}^{A}_{Z+1}\mathbf{Y} + \boldsymbol{\beta} + \bar{\mathbf{v}}$$

For example, Lead-210 decays by **beta-minus emission** to produce Bismuth-210 as follows:

$$^{210}_{82}\mathbf{Pb} \longrightarrow {}^{210}_{83}\mathbf{Bi} + \boldsymbol{\beta} + \bar{\mathbf{v}}$$

Beta particles are emitted with kinetic energies ranging up to the maximum value of the decay energy, E_{max}. The average energy of beta particles is about $1/3E_{max}$. They travel several hundred times the distance of alpha particles in air and require a few millimeters of aluminum to stop them.

Neutrinos (v) and *anti-neutrinos* $(\bar{v})$.are neutral (uncharged) particles with negligible rest mass, travel at the speed of light and are very non-interacting. They account for the energy distribution among positrons and beta particles from given radionuclides in the positron- and beta-decay processes respectively.

Positron Decay

A nuclide that has a low n : p ratio (too many protons) will tend to decay by positron emission. A positron is often mistakenly thought of as a positive electron. If positive electrons existed, then

when they encountered an ordinary negative electron, the Coulomb force would cause the two particles to accelerate toward each other. They would collide and then the two equal but opposite charges would mutually cancel. This would leave two neutral electrons. Actually, a positron is the anti-particle of an electron. This means that it has the opposite charge (+1) of an electron (or beta particle). Thus, the positron is a positively charged, high-speed particle which originates in the nucleus. Because of its positive charge and a rest mass equal to that of a beta particle, a positron is sometimes referred to as "beta-plus." The symbol β^+ is used to designate positrons.

With **positron emitters**, the parent nucleus changes a proton into a neutron and gives off a positively charged particle. This results in a daughter *less* positive by one unit of charge. Because a proton has been replaced by a neutron, the atomic number decreases by one and the mass number remains unchanged. The emission of a *neutrino* (symbolized by (v)) also occurs in conjunction with the positron emission.

Positron decay is illustrated by the following notation:

$$^{A}_{Z}\mathbf{X} \longrightarrow {}^{A}_{Z-1}\mathbf{Y} + \beta^{+} + \mathbf{v}$$

For example, Nickel-57 decays by positron emission:

$$^{57}_{28}\mathbf{Ni} \longrightarrow {}^{57}_{27}\mathbf{Co} + \beta^{+} + \mathbf{v}$$

Electron Capture

For radionuclides having a low n:p ratio, another mode of decay can occur known as orbital *electron capture* (EC). In this radioactive decay process the nucleus captures an electron from an orbital shell of the atom, usually the K shell, since the electrons in that shell are closest to the nucleus. The nucleus might conceivably capture an L-shell electron, but K-electron capture is much more probable. This mode of decay is frequently referred to as *K-capture*. The transmutation resembles that of positron emission, as follows:

$$^{A}_{Z}\mathbf{X} + \mathbf{e}^{-} \longrightarrow {}^{A}_{Z-1}\mathbf{Y} + \mathbf{v}$$

The electron combines with a proton to form a neutron, followed by the emission of a neutrino. Electrons from higher energy levels immediately move in to fill the vacancies left in the inner, lower-energy shells. The excess energy emitted in these moves results in a cascade of *characteristic X-ray* photons.

Either positron emission or electron capture can be expected in nuclides with a low n : p ratio. The intranuclear effect of either mode of decay would be to change a proton into a neutron, thus increasing the n : p ratio.

Note that ^{57}Ni has two modes of decay. This is an example of *branching* which is explained in the section **DECAY PHENOMENA**.

$$^{57}_{28}\mathbf{Ni} + \mathbf{e}^{-} \longrightarrow {}^{57}_{27}\mathbf{Co} + \mathbf{v}$$

Gamma Emission

Gamma emission is another type of radioactive decay. Nuclear decay reactions resulting in a transmutation generally leave the resultant nucleus in an excited state. Nuclei, thus excited, may reach an unexcited or *ground state* by emission of a gamma ray.

Gamma rays are a type of electromagnetic radiation. They behave as small bundles or packets of energy, called *photons*, and travel at the speed of light. For all intents and purposes, gamma radiation is the same as X-rays. Gamma rays are usually of higher energy (MeV), whereas X-rays are usually in the keV range. The basic difference between gamma rays and X-rays is their origin; gamma rays are emitted from the nucleus of unstable atoms, while X-rays originate in the electron shells. The basic difference between gamma rays and visible light is their frequency. The symbol γ is used to designate gamma radiation.

Since the gamma decay doesn't involve the gain or loss or protons of neutrons, the general equation is slightly different from the other decay equations.

$$^{A}_{Z}\mathbf{X}^{*} \longrightarrow {}^{A}_{Z}\mathbf{X} + \mathbf{y}$$

All of the transmutation examples given could be accompanied by gamma emission. Although most nuclear decay reactions do have gamma emissions associated with them, there are some radionuclide species which decay by particulate emission with no gamma emission.

Table 2 provides a summary of the characteristics of the various types of radioactive emissions that have been discussed. Table 3 summarizes the various modes of radioactive decay.

TABLE 2. Types of Radioactive Emissions

Radiation	Symbol	Form	Origin	Essential Parts	Mass (amu)	Charge	Energy Spectrum	Miscellaneous information
Alpha	α	Charged particle	nucleus	2p,2n	4	+2	MeV	mono-energetic; from heavy radionuclides
Beta[-minus] (Negatron)	β^-	Charged particle	nucleus	$1e^-$	«1	-1	0 to max.	fission products
Gamma	γ	Electromagnetic Radiation	nucleus	photon	none	none	MeV	usually follows particle emission
X-ray	X	Electromagnetic Radiation	electron orbitals	photon	none	none	keV	cascade following EC; Bremsstrahlung
Positron (Beta plus)	β^+	Charged particle	nucleus	antimatter equivalent of $1e^-$	«1	+1	0 to max.	will annihilate with e^-
Neutron	n	Uncharged particle	nucleus	1n	1	0	eV to MeV	born "fast"
Proton	p	Charged particle	nucleus	1p	1	+1	keV to MeV	scattered in neutron interactions
Ion/Fission Fragment	FF	Charged particle	nucleus	light and heavy nuclei	varies	»1	MeV	result from fission
Neutrino ν	ν	Uncharged particle	nucleus	--	. 0	0	MeV	from β^+ decay
Antineutrino	$\bar{\nu}$	Uncharged particle	nucleus	--	. 0	0	MeV	from β^- decay

TABLE 3. Modes of Decay

DECAY MODE	EQUATION	NUCLEAR TRANSFORMATION	EXAMPLE
Alpha	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$	$2P+2N \longrightarrow \alpha$	${}^{210}_{84}Po \longrightarrow {}^{206}_{82}Pb + {}^{4}_{2}\alpha$
Beta	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + \beta + \bar{v}$	$N \longrightarrow P^{+} + e^{-} \longrightarrow \beta$	${}^{32}_{15}P \longrightarrow {}^{32}_{10}S + \beta$
Positron	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + \beta^{+} + v$	$P \longrightarrow N + \beta^{+} \longrightarrow \beta^{+}$	${}^{123}_{56}Ba \longrightarrow {}^{123}_{55}Cs + \beta^{+}$
Electron Capture (EC) or K-capture	${}^{A}_{Z}X + e^{-} \longrightarrow {}^{A}_{Z-1}Y + \beta^{+} + v$	$P + e^{-} \longrightarrow N$	${}^{136}_{62}Sm + e^{-} \longrightarrow {}^{136}_{61}Pm$
Gamma	${}^{A}_{Z}X + e^{-} \longrightarrow {}^{A}_{Z-1}Y + v$	$E \longrightarrow y$	${}^{198}_{79}Au^{*} \longrightarrow {}^{198}_{79}Au + y$

Other Types of Transformations

Internal conversion

This phenomena occurs when a gamma photon does not escape the electron cloud surrounding the nucleus, but transfers to one of the orbital electrons enough energy to eject it from the atom. The photon is said to have undergone *internal conversion*. The conversion electron is ejected from the atom with kinetic energy equal to the gamma energy minus the binding energy of the orbital electron. This process usually takes place in the K-shell. There will then follow emission of characteristic X-rays as with electron capture. In principle, it is similar to the photoelectric effect (to be discussed in Lesson 1.07).

Isomeric transition

Isomeric transition commonly occurs immediately after particle emission; however, the nucleus may remain in an excited state for a measurable period of time before dropping to the ground state at its own characteristic rate. A nucleus that remains in such an excited state is known as an *isomer* because it is in a metastable state; that is, it differs in energy and behavior from other nuclei with the same atomic number and mass number. Generally, the isomer achieves ground state by emitting delayed (usually greater than 10^{-9} seconds) gamma radiation.

The metastable or excited state, is usually represented by a small m following the mass number, A, in the standard nuclide notation. For example, Technetium-99m and Technetium-99 are isomers. $^{99m}_{43}\mathbf{Tc}$ will decay to $^{99}_{43}\mathbf{Tc}$ with the emission of a 140.5 keV gamma. Further radioactive decay can still occur from the ground state. In this case, ^{99}Tc decays to ^{99}Ru, which is stable.

1.06.05	*Identify two aspects associated with the decay of a radioactive nuclide.*

DECAY PHENOMENA

Each radionuclide, artificial and natural, has its own characteristic *pattern* of decay. There are several aspects associated with this pattern:

- Modes of decay
- Types of emissions
- Energies of the emissions involved
- Rate of decay

All nuclei of a given radionuclide seeking stability by radioactive decay do so in a specific manner. As indicated previously, ^{226}Ra decays by alpha emission which is accompanied by a gamma photon. This represents the only mode of decay open to ^{226}Ra.

There are some radioactive nuclides which may decay with *branching*, whereby a choice of decay modes exists. In such case, a definite branching ratio exists. A case in point is the decay of ^{57}Ni, mentioned previously. This isotope of nickel decays 50% by K-capture and 50% by $\exists^{+}$ emission. The branching ratio would be:

$$\frac{\beta^{+}}{EC} = 1$$

Not only do various radionuclides disintegrate in a constant manner insofar as the *types* of emissions are concerned, but the emissions from each nuclide exhibit a *distinct energy* picture. The energies associated with radiations are given in terms of "million electron volts" (MeV). Beta emissions may occur with energies to about 5 MeV; alphas to about 10 MeV; and gamma photons to about 3 MeV. The energy of the particulate radiations is manifested as kinetic energy--the higher the energy the greater the velocity of the particle. However, the velocity of photons is constant (c = speed of light) and energy differences are manifested by varying wavelengths and frequencies.

The other characteristic aspect associated with decay patterns is the rate of decay, or activity. The disintegrations of radionuclides occur with a regularity characteristic for each particular species. Such disintegrations are spontaneous and random. A single radium nucleus, for instance, may disintegrate at once or wait thousands of years before emitting an alpha particle. All that can be predicted with any certainty is that half of all the ^{226}Ra nuclei present will disintegrate in 1,622 years. This period is called the half-life of ^{226}Ra. Half-lives vary greatly for natural occurring radioisotopes; e.g. ^{212}Po, with a half life of 0.298 microseconds and ^{232}Th, with a half-life of over 1.42E10 years.

<u>Singly-occurring Natural Radionuclides</u>

Careful measurements show that almost all materials contain traces of radioactivity. One might suspect that these traces might be due to some of the heavy radionuclides belonging to one of the radioactive series described. However, some of the lighter elements are themselves radioactive.

TABLE 4. Naturally-occurring Radionuclides

Radionuclide	**Half-life**	Alpha*	Beta*	Gamma*
$^{40}_{19}K$	1.26E9 yrs.	----	1.314	1.460
$^{87}_{37}Rb$	5.0 E10 yrs.	----	0.274	----
$^{147}_{62}Sm$	1.05E11 yrs.	2.23	----	----
$^{176}_{71}Lu$	3.0 E10 yrs.	----	0.43	0.88 0.202 0.306
$^{182}_{75}Re$	4.0 E10 yrs.	----	0.003	0.134

* Emission energies in MeV

It may have been noted that Carbon-14 was not included as a natural radionuclide in Table 4, even though it has received considerable popular attention in recent years, as naturally-occurring radiocarbon has been found in definite, though small, proportions. The ^{14}C existing in the atmosphere is being formed continually as a result of nuclear reactions between atmospheric nitrogen and neutrons from cosmic rays. This is shown in the following reaction:

$$^{14}_{7}\mathbf{N} + ^{1}_{0}\mathbf{n} \longrightarrow ^{14}_{6}\mathbf{C} + ^{1}_{1}\mathbf{H}$$

1.06.06 Identify differences between natural and artificial radioactivity.

Artificial Radioactivity

As discussed earlier, there are radionuclides which occur as a result of various **man-made** reactions. These are called *artificial* radionuclides. The vast majority of radionuclides are produced in this manner.

As implied in the nomenclature, natural and artificial radioactivity differ in origin. There are other distinctions between the two types which will be discussed. Nevertheless, the nuclei of artificial radionuclides are unstable in much the same manner as their natural counterparts. The intranuclear factors governing decay are also similar for both groups. A brief account of the discovery of artificial radioactivity will be given before further discussing its similarities and dissimilarities to natural radioactivity.

Induced Transmutations

In 1919, Lord Rutherford demonstrated that it was possible to produce artificially a *transmutation* of elements. The manner in which naturally-occurring radioactive atoms are changed or transmuted by emitting radiation has been discussed. Lord Rutherford set up and observed a nuclear reaction in reverse, one might say, whereby high-speed charged particles (projectiles) bombarded stable atomic nuclei (target), resulting in a reaction at the nuclear level and *inducing a transmutation*. The first observed nuclear reaction used alpha particles from ^{214}Bi (Radium C) as the charged particles. These were made to impinge upon nitrogen nuclei, acting as the target. The reaction is written as follows:

$$^{14}_{7}\mathbf{N} + ^{4}_{2}\boldsymbol{\alpha} \longrightarrow ^{17}_{8}\mathbf{O} + ^{1}_{1}\mathbf{H}$$

Induced Radioactivity

During the first 15 years of experimental work with nuclear reactions, the transmutation products (insofar as could be observed) were NOT radioactive. However, the reactions generally were accompanied by the emission of a charged particle and a gamma ray. These emissions are not construed as imparting the property of radioactivity to the target element, since they occur practically instantaneously.

It was determined in 1934 that induced transmutations could produce nuclei which were residually unstable in somewhat the same manner as naturally occurring radionuclides. Irene Curie and Frederic Joliot reported that certain light elements (boron, magnesium, aluminum), when bombarded with alpha particles, continued to emit radiation for a finite time after bombardment had stopped. The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of induced or artificial radioactivity:

$$^{27}_{13}\mathbf{Al} + ^{4}_{2}\boldsymbol{\alpha} \longrightarrow ^{30}_{15}\mathbf{P} + ^{1}_{0}\mathbf{n}$$

The resultant nucleus $^{30}_{15}$P was observed to be radioactive, emitting a small charged particle and reaching stability within minutes.

The work of Curie and Joliot stimulated similar experiments throughout the world. As a result, radioactive isotopes of nearly every element in the Periodic Table were produced by bombarding a stable isotope with charged particles, neutrons, or in certain instances photons. Over 1,000 unstable nuclear species are listed in the Chart of the Nuclides.

Natural vs. Artificial

Heavy radionuclides (natural, and artificial) generally decay by a long series of alpha and beta emissions. Lighter, artificial radionuclides, such as activation and fission products, usually decay by beta or positron emission or by orbital electron capture. In contrast to natural radioactivity, lighter artificially-produced radionuclides generally revert to stability in only a few decay steps.

1.06.07	*Identify why fission products are unstable.*

Fission Products

Another source of radionuclides is nuclear fission. The nuclear fragments directly resulting from fission invariably have **too large a proportion of neutrons to protons for stability**, and consequently tend to achieve stability by beta minus emission. For example, take a thermal fission of ^{235}U:

$$^{235}_{92}\mathbf{U} + ^{1}_{0}\mathbf{n} \longrightarrow ^{141}_{55}\mathbf{Cs} + ^{92}_{37}\mathbf{Rb} + 2\left(^{1}_{0}\mathbf{n}\right)$$

The n:p ratio for stable Cesium (^{133}Cs) is 1.4:1, whereas the above fission product has a ratio of about 1.6:1. The stable ratio for Rubidium (^{85}Rb) is 1.3:1, while the product above has a ratio of about 1.5:1. As can be seen, the fission products in the above equation have too many neutrons. Each fission fragment initiates a radioactive series, called a *fission decay chain*, involving several successive beta decay transformations. Fission product beta emission, as with other beta emitters, generally is accompanied by gamma emission.

Predicting Mode of Decay

Radioactive nuclides tend to decay in a way that results in a daughter nuclide that lies closer to the line of stability. Generally speaking, nuclides below the line of stability will usually undergo beta-minus decay. Nuclides above the line of stability will usually undergo positron decay or electron capture. Nuclides at the upper end of the line of stability will usually undergo alpha decay. These are general rules that have many exceptions, especially in the region of heavy nuclides. Figure 2 illustrates the type of decay nuclides in different regions will typically undergo.

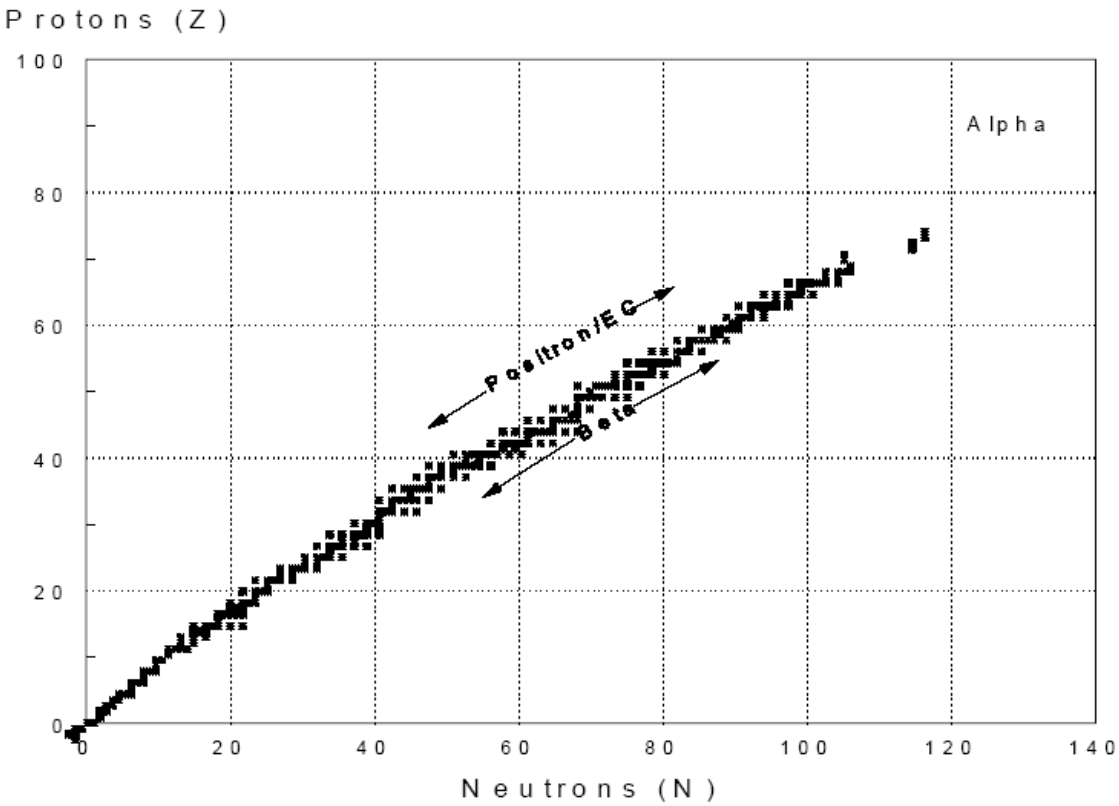


FIGURE 2. Types of Decay Relative to Line of Stability

1.06.08	*Identify the three naturally-occurring radioactive families and the end product of each.*

RADIOACTIVE FAMILIES

The transmutations associated with naturally-occurring radionuclides frequently yield a daughter which is also radioactive. To date, about 70 different naturally occurring radionuclides have been identified, each with its own characteristic pattern of radioactivity. Most of these yield radioactive daughters and are now known to be intimately interrelated in radioactive *series* or *families*

Three Natural Decay Series

It has been established that most isolated radioactive species with Z > 82 belong to one of three independent groups or families (see Figure 3). Each family starts with a parent radionuclide, decaying or transmuting into a radioactive daughter nuclide, which would again transmute into a daughter nuclide, also radioactive, and so on until stability is attained. One family starts with Uranium-238 (${}^{238}_{92}\mathrm{U}$) and is called the **Uranium series**. Another starts with Thorium-232 (${}^{232}_{90}\mathrm{Th}$) and is called the **Thorium series**. A third starts with Uranium-235 (${}^{235}_{92}\mathrm{U}$) and is called the **Actinium series**.

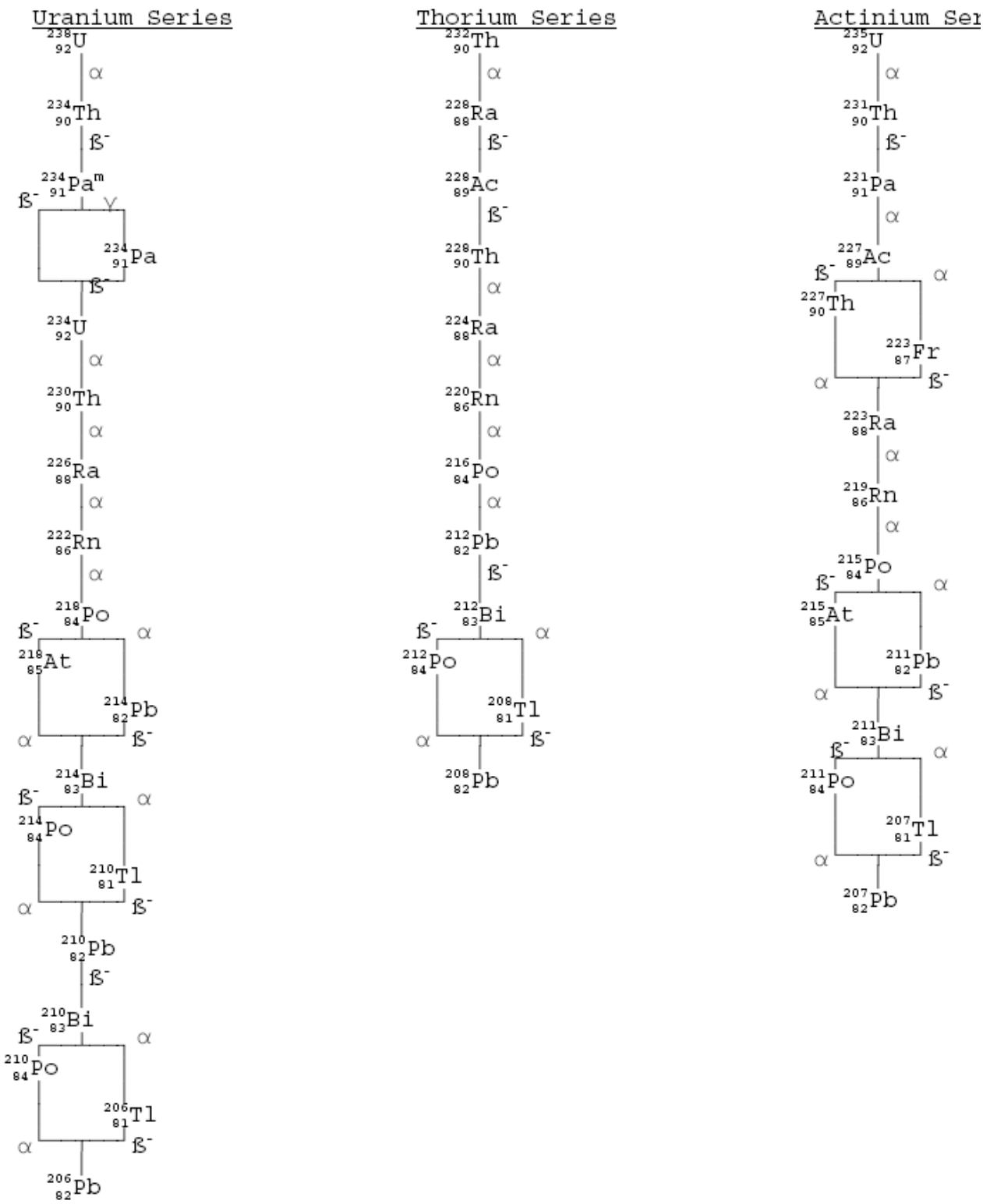
In each series, there is a "seesawing" in the transmutation chain between decreasing the atomic number by two with $\forall$ emission and increasing it by one with $\exists^{-}$ emission. Each series has an isotope of Radon [historically known as *Radon* (${}^{222}_{86}\mathrm{Rn}$), *Thoron* (${}^{220}_{86}\mathrm{Rn}$), and *Actinon* (${}^{219}_{86}\mathrm{Rn}$) respectively] as a member of the series. All isotopes of Radon are radioactive and are gases at standard temperature and pressure. Each series ends in a different stable isotope of Lead (${}^{206}_{82}\mathrm{Pb}$, ${}^{208}_{82}\mathrm{Pb}$, and ${}^{207}_{82}\mathrm{Pb}$ respectively).

Figure 3 shows the three natural decay series.

Artificial Series

There is also a fourth series, the **Neptunium series**, named after its longest-lived member. Actually, the neptunium series has been artificially produced and no longer occurs in nature, but it is assumed that it did occur in nature at one time and has become extinct because of the relatively short half-lives involved. The longest-lived radionuclide in the series is ${}^{237}_{93}\mathrm{Np}$ with a half-life of 2.2E06 years. Assuming the age of the earth is 2.2E09 years, this would indicate that, from the time of creation, ${}^{237}\mathrm{Np}$ has undergone 1,000 half-lives decay. The fraction of a radionuclide remaining after 1,000 half-lives would be astronomically small, in the order of 10^{-300}. It is obvious, therefore, why it would be difficult to find traces of neptunium and its descendants in nature.

FIGURE 3. Natural Decay Series



1.06.09	*Given a nuclide, locate its block on the Chart of the Nuclides and identify the following:* *a. atomic number* *b. atomic mass* *c. natural percent abundance* *d. stability* *e. half-life* *f. types and energies of radioactive emissions*
1.06.10	*Given the Chart of Nuclides, trace the decay of a radioactive nuclide and identify the stable end-product.*

CHART OF THE NUCLIDES

General Arrangement

In arranging the nuclides in chart form, the number of neutrons (N) is plotted horizontally on the x-axis against the number of protons (atomic number, Z) on the y-axis. Such a plot at once reveals the continuity in composition in progressing from the lighter to the heavier elements. The full-size **Chart of the Nuclides** (poster) is much easier to follow than the **Nuclides and Isotopes** volume which contains all of the material from the chart in book form. A guide for using the chart is found in the lower right-hand corner of the chart or on pages 18 and 19 of the book.

Specific Nuclide Representation

Each specific nuclide is represented in the Chart of the Nuclides by a block. The coloring and labeling of each block specifies certain information concerning the properties of the nuclide. Values for atomic number (Z) are given along the left side of the grid, and values for number of neutrons (N) are found along the bottom.

A **grey block** denotes a *stable nuclide*. A typical example is stable sodium (Na). A key to the listed data within the block is shown below.

Na23 100 σ_γ (.40+.13),.32 22.989767	Nuclide: Sodium-23 Grey color: stable Percent Abundance: 100% Neutron activation cross section in barns-- (n, γ) interaction Atomic mass: 22.989767 amu

Unlike sodium, most elements have more than one stable isotope. For example, magnesium (Mg) has three stable isotopes as shown below.

	Mg 24	**Mg 25**	**Mg 26**
Percent abundance	78.99	10.00	11.01
Atomic mass (amu)	23.985042	24.985837	25.982594

A **white** block denotes an *artificially produced radioactive* nuclide. A typical example is $^{59}_{26}\mathrm{Fe}$. A key to data listed within the block is shown below:

Fe 59	- nuclide
45.51 d	- half-life (yellow color: 10 to 100 days)
β^- .466, .271	- beta energies in MeV
γ 1099.2,1291.6,	- gamma energies in keV
E 1.56	- disintegration energy in MeV

A white block with a **black triangle in the lower right hand corner** denotes an artificially produced radionuclide resulting from slow neutron fission (*fission product*).) An example follows.

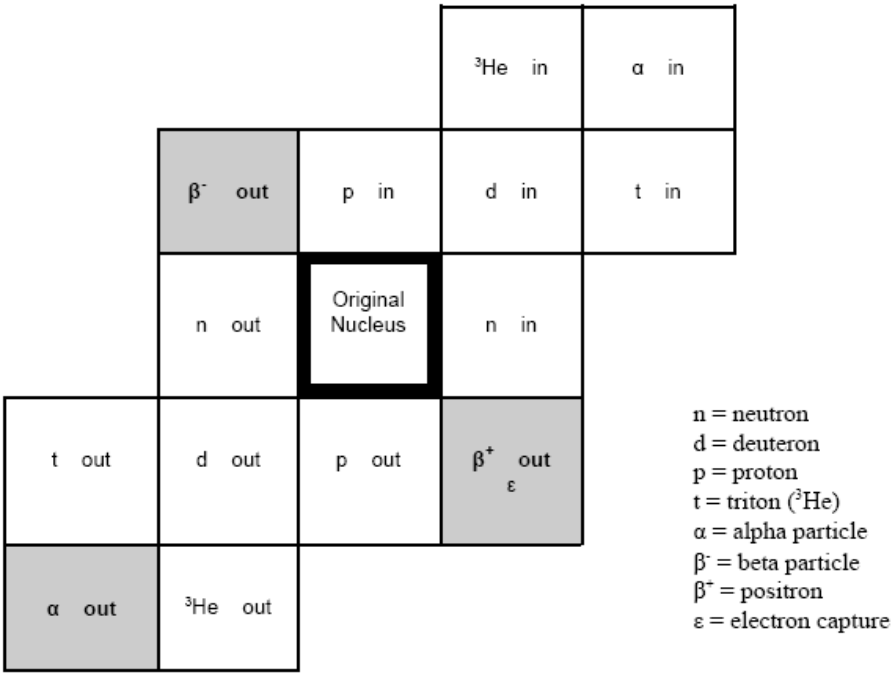
Sr 90	- nuclide
29.1 a	- half-life
β^- .546	- beta energy in MeV
no γ	- no associate gamma emission
E .546	- beta decay energy in MeV

A **grey block with a black bar across the top** denotes a long-lived, *naturally- occurring radioactive* isotope. ^{238}U is a good example.

U 238	- nuclide
99.2745	- percent abundance
4.47E9 a	- half-life
α 4.197, 4.147	- mode of decay, radiation and energy in MeV
γ 49.6	- gamma energy in keV
238.050785	- isotopic mass in amu

Depicting Nuclear Processes

As a result of decay, radionuclides shift from block to block within the *Chart of the Nuclides*. The diagram below (taken from the Guide for using the Chart of the Nuclides) shows the relative locations of the products of various nuclear processes.



As can be seen, the relative locations (displacements) of the primary modes of decay are:

Alpha (α)	down 2, left 2
Beta (B^-)	up 1, left 1
Positron (B^+)/EC	down 1, right 1

Displacements can also occur as a result of nuclear reactions brought about through bombarding given nuclides with various nuclear particles or gamma photons. These changes are depicted in the "Guide for using the Chart of the Nuclides."

<u>Chart of the Nuclides Summary</u>

The *Chart of the Nuclides* provides considerable information about the behavior of nuclides. There is continuity in composition of the nuclides. For example, a line drawn through the stable nuclides forms a rather smooth curve extending from the lower left to the upper right corner of the Chart of the Nuclides.

Nuclides below this line are characterized by having an excess of neutrons and will, in general, be beta particle emitters.

Nuclides above this line are characterized by having an excess of protons and will, in general, decay by positron emission or electron capture.

Nuclides lying beyond the line of stability will, in general, demonstrate a tendency to seesaw between alpha decay and beta decay. All nuclides, if followed through their various decay schemes will eventually end in a grey box (stable isotope).

The Chart presents in compact style much valuable information concerning the properties of the nuclides. These data include for:

1. Stable nuclides

   a. Relative abundance
   b. Cross section for activation

2. Radioactive nuclides

   a. Types of emissions
   b. Energy of emissions
   c. Half-life.

1.06.11	*Identify the definition of the following units:* *a. curie* *b. becquerel*

UNITS OF ACTIVITY

The rate of decay of a radioactive substance constitutes the quantity of radioactivity, or *activity*, in that substance. The definition of activity refers to the number of transformations (disintegrations) per unit time. Since the fundamental unit of time is the second, the quantity activity is measured in disintegrations per second, or dps. Since the second is a very short time period in which to make a measurement, activity is measured in units of disintegrations per minutes, or dpm. The SI unit of activity is the becquerel, while the historical unit is the curie. Each will be discussed below.

The Curie

Before the large-scale production of artificial radioisotopes, radium had become a standard of comparison for radioactivity measurements. Originally, the unit *curie* applied only to radium. Named for Marie Curie, it was based on the disintegrations per second (dps) occurring in the quantity of radon gas in equilibrium with one gram of radium. If permitted to attain this equilibrium, one gram of radium will produce about 0.66 mm^3 of radon. In this quantity of radon, about 37 billion atoms disintegrate each second.

In 1930, the International Radium Standard Commission extended the definition to include that quantity of any radioactive decay product of radium which underwent the same number of dps as one gram of radium. It avoided specifying the figure exactly, so for some years the exact value of the curie varied with each successive refinement in the measurement of the decay constant or the atomic weight of radium.

In 1950, the International Joint Commission on Standards, Units, and Constants of Radioactivity redefined the *curie* by accepting 37 billion dps as a curie of radioactivity regardless of its source or characteristics. Current regulations define the curie (Ci) as 3.7E10 disintegrations per second (2.22E12 dpm).

Since the curie represents a very large amount of activity, often smaller, and more convenient subunits are used:

TABLE 5. Curie Subunits

Unit	Abbr.	dps	dpm
curie	Ci	3.7E10	2.22E12
millicurie	mCi	3.7E7	2.22E9
microcurie	µCi	3.7E4	2.22E6
nanocurie	nCi	3.7E1	2.22E3
picocurie	pCi	3.7E-2	2.22

The Becquerel

The SI derived unit of activity is the *becquerel* (Bq) and is that quantity of radioactive material in which one atom is transformed per second or undergoes one disintegration per second (1 dps). Since the becquerel is a rather small unit, metric prefixes are often applied to aid in designating larger amounts of activity:

TABLE 6. Becquerel Superunits

Unit	Abbr.	dps	dpm
becquerel	Bq	1	60
kilobecquerel	kBq	1E3	6E4
megabecquerel	MBq	1E6	6E7

The relationship between the becquerel and curie is:

1Bq = 1 dps = 2.7E-11 Ci 1 Ci = 3.7E10 dps = 3.7E10 Bq

Using unit analysis and conversion, activity measurements given in dps, dpm or curies can be converted to becquerels.

1.06.12 Identify the definition of specific activity.

SPECIFIC ACTIVITY

Specific activity is defined as the **activity per unit mass** of a radioactive substance and is reported in units such as curies per gram (Ci/g) or becquerels per kilogram (Bq/kg). Recall that the curie originated from the number of emanations from one gram of radium every second. Thus, the activity of one gram of radium is equivalent to one curie. This means that the specific activity of radium would be 1 Ci/g.

It is important, however, to note that when applied to radionuclides other than radium, the unit curie does not make apparent what mass of the material is required. Since one curie of activity is 37 billion dps, the mass of the material required to produce this number of dps will be a function of the decay rate of the atoms of the material (i.e., the disintegration constant) and of the number of atoms of the material per gram (i.e., *gram atomic mass [weight]*). For example, a curie of pure ^{60}Co ($T_{½}$ = 5.27 years) would have a mass less than 0.9 milligrams, whereas a curie of natural ^{238}U ($T_{½}$ = 4.5E9 years) would require over two metric tons of the metal. Obviously, the shorter the half-life of a radionuclide, the greater its specific activity.

1.06.13 Identify the definition of half-life.

THE RADIOACTIVE DECAY LAW

The activity of any sample of radioactive material decreases or decays at a fixed rate which is a characteristic of that particular radionuclide. No known physical or chemical agents (such as temperature, pressure, dissolution, or combination) may be made to influence this rate. The rate may be characterized by observing the fraction of activity that remains after successive time intervals.

For convenience we choose a fraction that is easy to work with, one-half (½). In using this fraction we can observe the decay of a radionuclide with the passing of time. We can observe how long it takes for the activity to be reduced to one half of the activity. This time that is required for the activity present to be reduced to one-half we call the *half-life*. If successive half-lives are observed, we can see a reduction each time by a fraction of one-half, and the effect will be cumulative. In other words, one half-life reduces to $(½)^1$; two half-lives reduces to ½ × ½ = $(½)^2$ or ¼; three half-lives will reduce to ½ × ½ × ½ = $(½)^3$ or 1/8, etc. In the general case the fraction of activity remaining after any number of half lives will be $(½)^n$, where n is the number of half-lives that have elapsed. To put it still another way, the reduction in activity occurs at an exponential rate, which we have expressed as the power of ½.

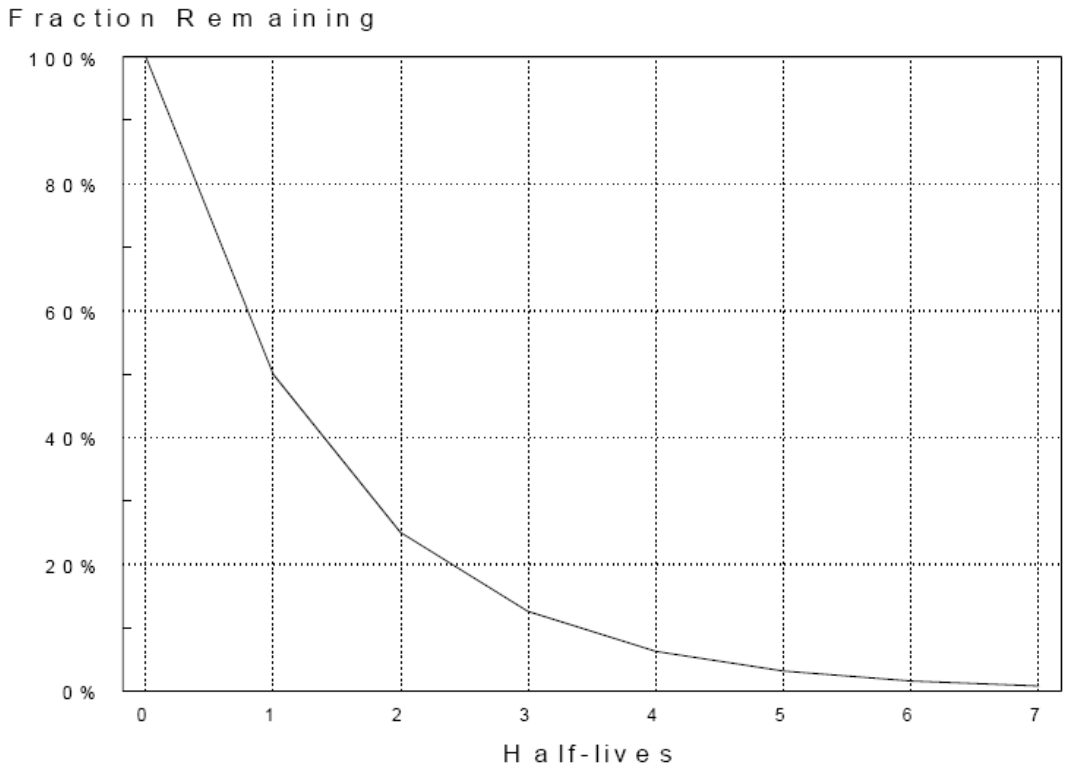


FIGURE 4. Radioactive Decay (Linear Scale)

In Figure 4 it can be seen that as time passes, radioactive decay occurs at an exponential rate. In using the half-life for our time value, we express this exponential function as $(½)^n$. Beginning at the instant chosen as the starting point we have 100% of the activity, since no time has elapsed, and the number of half-lives is zero ($n = 0$). If we use t to represent time, at this point, then, $t = 0$.

If we let $T_{½}$ represent the half-life, then, after one half-life, $t = T_{½}$, and $n = 1$. This demonstrates that n represents the ratio of time versus the half-life. Mathematically, this is expressed as:

$$n = \frac{t}{T_{½}}$$

where: ***n*** = number of half-lives
t = time elapsed
$\boldsymbol{T_{½}}$ = half-life

Obviously, the units of t must be the same as the time units of $T_{½}$ in order to determine the value of n. For example, if the half-life of a certain radionuclide is 10 hours, and we allow 4 hours to elapse, the number of half-lives would be 4/10 = 0.4, or 0.4 half-lives. The fraction remaining at that instant where t = 4 hours would be:

$$\left(\frac{1}{2}\right)^{\frac{1}{10}} = \left(\frac{1}{2}\right)^{0.4} = 0.7578$$

The activity at the instant where t = 0 is the initial or original activity, represented as A_0. The activity at any time t after 0 we will denote as A_t. The value of A_t at any time t will be the fraction remaining times A_0. The fraction remaining is determined from the number of half-lives that have passed. A useful "rule of thumb" to remember is that seven half-lives will reduce any activity to less than 1 percent of its original value. Using a proportion we can see the relationship between the two activities:

$$\frac{A_0}{A_t} = \frac{1}{\left(1/2\right)^n}$$

By cross-multiplying we obtain the equation for determining the remaining activity:

$$A_t = A_0\left(1/2\right)^n$$

For example, if the initial activity of the radionuclide mentioned above was 52 μCi, then the activity after 4 hours would be:

$$A_t = 52\mu Ci\left(\frac{1}{2}\right)^{\frac{4}{10}}$$
$$A_t = 52\left(0.7578\right)$$
$$A_t = 39.4\mu Ci$$

Remember that we stated earlier that radioactive decay is an exponential process. Recall also that a logarithm is, by definition, an exponent. If we were to plot the activity on a logarithmic scale against the time on a linear scale, the resulting curve should be a straight line. Figure 5 illustrates that this is the case.

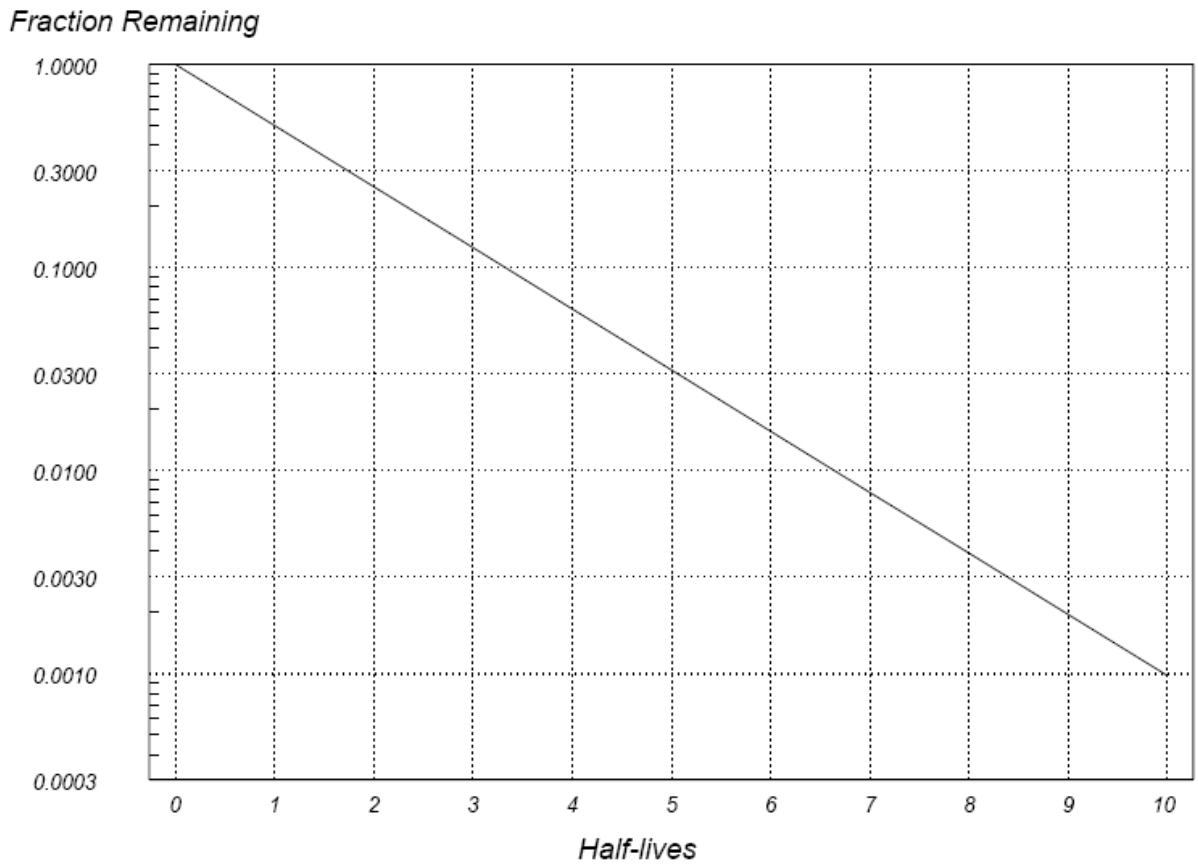


FIGURE 5. Radioactive Decay (Semi-log Scale)

This graph shows us that the rate of decay does in fact occur <u>at a constant rate</u>. As time elapses from the starting instant, the activity is reduced thereafter at the constant rate of disintegration for the particular radionuclide involved, which we represent by the Greek letter 8 (pronounced "lambda"). In the graph above, the reduction of activity is now a logarithmic (exponential) function of $(½)^n$. Since n is the ratio of t versus $T_{½}$, the fraction remaining after time t will be less than 1, resulting in a negative natural-logarithmic value (ln ½ = -ln 2 = -0.693). (Using calculus, the natural logarithm (ln) resulted from the integration of the first equation devised by Rutherford.) The fraction remaining will be a function of the decay constant (8) and the time (t). If we then relate the decay constant to the half-life, 8 will be a composite of the natural log of 2 and the half-life. Since the process leads to a decrease in activity, the exponent will be represented by -8t. Therefore, the decay constant itself will represent:

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

Thus, the decay constant is the fraction that disintegrates per unit time (reciprocal time). If, for example, the half-life is in seconds, 8 will be in sec^{-1}.

1.06.14	*Calculate activity, time of decay, and radiological half life using the formula for radioactive decay.*

The equation for activity using the decay constant will be:

$$A_t = A_0 e^{-\lambda t}$$

Note that in this equation the base of the natural log is raised to a power which includes the -ln 2. The result of this equation is exactly the same at that which results from the equation using $(½)^n$. It is simply a different way of expressing the decrease in activity with the passage of time as a result of radioactive decay.

Using the data in the prior example, the equation would be:

$$A_t = 52e^{\left(\frac{-\ln 2}{10}\right)4}$$
$$A_t = 52e^{-0.277}$$
$$A_t = 52(0.7578)$$
$$A_t = 39.4\mu Ci$$

<u>Example</u>: Given 10 mCi of ^{32}P, which has a half-life of 14.2 days, find the quantity remaining after 60 days.

$$A_t = 10e^{\left(\frac{-\ln 2}{14.2}\right)60}$$
$$A_t = 10e^{-2.93}$$
$$A_t = 10(0.0534)$$
$$A_t = 0.534mCi$$

By algebraic manipulation other variables in this equation can be solved for if the other values are known. One example would be calculating the original activity based on the current activity, decay constant and elapsed time.

Practice Problems

1. A Phosphorous-32 source has a half-life of 14.28 days and had an activity of 75,000 dpm as of 12/2/92. What was the activity as of 12/28/92?

2. A 55 nCi ^{90}Sr source was assayed on 6/1/88. What would the activity be on 6/1/93? (The half-life of ^{90}Sr is 29.1 years)

3. An 60 mCi iodine solution of ^{131}I was created and then left on a laboratory shelf for two weeks before it was used. What was the activity of the solution at the time it was used? (Iodine-131 has a half-life of 8.04 days)

4. A radon air sample was collected and then counted 4 hours later. If the sample count showed an activity of 5E4 pCi, what was the activity on the sample at the time it was collected? (Radon-222 has a half-life of 3.8235 days)

5. A 10.5 Ci ^{60}Co radiography source was prepared 3 years ago, having a half-life of 5.271 years. What is the activity today?

6. A pure alpha source reads 244,000 dpm today. It is a ^{210}Po source which has a half-life of 138.38 days. If the source was manufactured a year ago, what the activity at the time it was manufactured?

7. A ^{137}Cs source has an activity of 750 mCi, with a half-life of 30.17 years. How long will it take for the source to be read less than 100 mCi?

8. An air sample was collected in a thorium storage building and was counted immediately, yielding 2.5E3 pCi/l. The sample was recounted 5 minutes later giving an activity of only 59.4 pCi/l. What is the half-life and the most likely isotope on the sample?

SERIES DECAY

The subject, "Series Decay" concerns the mathematical relationship of quantities of activity present when two or more radionuclides exist in a decay chain. Examples of a decay chain are the natural decay series, or a two-step fission product decay series such as:

$$\mathbf{Sr^{90}} \longrightarrow \boldsymbol{\beta} + \mathbf{Y^{90}} \longrightarrow \boldsymbol{\beta} + \mathbf{Zr^{90}} \text{ (stable)}$$

The relationship between three or more radionuclides is described by H. Bateman. The solution, while straight forward, is quite involved. A two-step relationship (parent-daughter) can be readily derived and is reasonably easy to work with.

PARENT-DAUGHTER RELATIONSHIPS

In a radioactive decay series, the decay of the parent nuclide produces a daughter product and radiation is emitted. The daughter nuclide also produces radioactivity when it decays, as does each successive daughter in the chain until stability is reached, resulting in total collective activity. The activity contributed from the parent versus the daughters will vary depending on the half-life of the parent and the half-lives of the daughters. When the amount of activity being produced is the same as the amount that is decaying, a state of *equilibrium* is said to exist. There are several types of equilibrium, depending on how the half-life of the daughter compares to the half-life of the parent.

Secular Equilibrium

In secular equilibrium the half-life of the parent is very much longer than the half-life of the daughter. When in equilibrium, the activity of the daughter is equal to the activity of the parent. Initially, the majority of the activity will be contributed by the parent. As more and more of the parent nuclide decays, the amount of activity contributed by the daughter will increase.

Transient Equilibrium

In transient equilibrium the half-life of the parent is longer than that of the daughter, but not very long. In a freshly purified parent fraction, the daughter activity builds up, then decays with the same rate of decay as the parent.

No Equilibrium

When the half-life of the parent is shorter than that of the daughter, the two never reach a state of equilibrium. Figure 6 illustrates this.

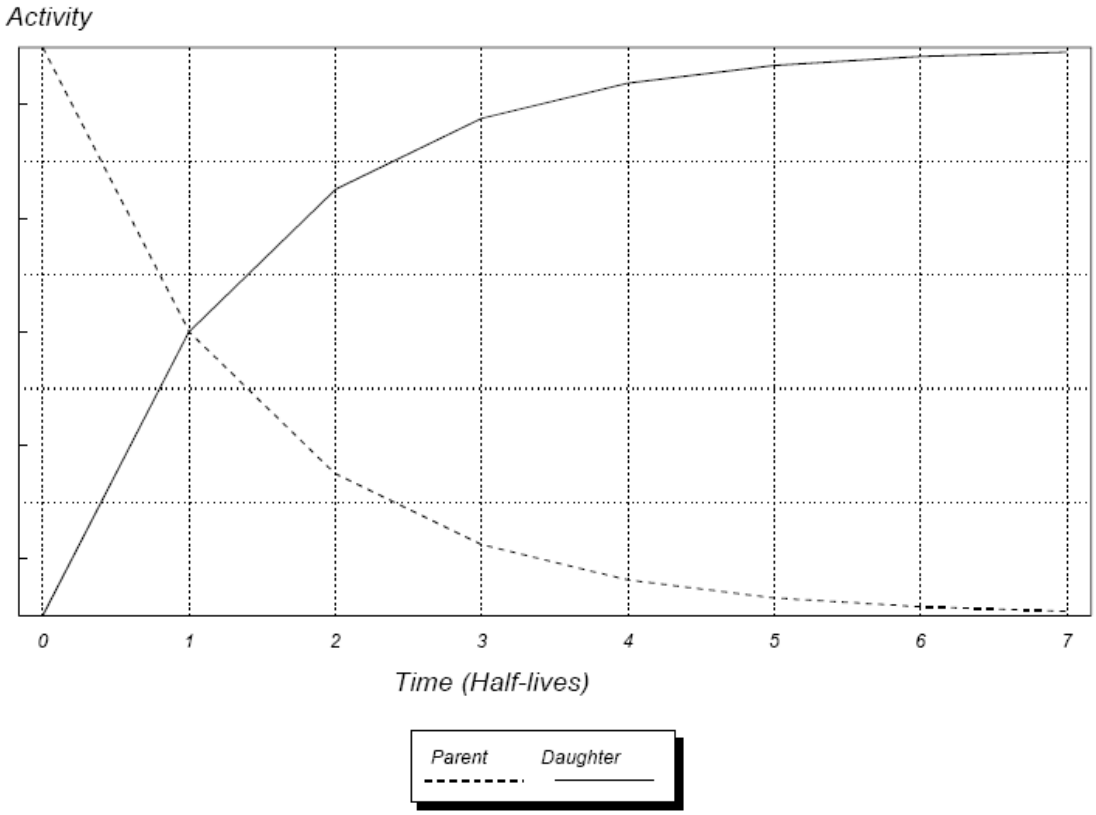


FIGURE 6. No Equilibrium

1.06.15 Identify the definition of the following:

a. exposure
b. absorbed dose
c. equivalent dose
d. quality factor

1.06.16 Identify the definition of the following units:

a. roentgen
b. rad/gray
c. rem/sievert

RADIATION DOSIMETRY TERMINOLOGY

During the early days of radiological experience there was no precise unit of radiation dose that was suitable either for radiation protection or for radiation therapy. For example, one early unit devised was the "skin erythema unit," where allowable dose was the amount required to produce skin reddening. Because of the great energy dependence of these various units, as well as other inherent defects, none of these was useful for radiobiological studies or for radiation protection. Furthermore, since the fraction of the energy in a radiation field that is absorbed by the body is energy dependent, it is necessary to distinguish between radiation *exposure* and *absorbed dose*.

Exposure (X)

Exposure is a measure of the ability of photons (X and gamma) to produce ionization in air. Traditionally, the unit of exposure is the **roentgen** (R). The unit is defined as the sum of charge per unit mass of air; that is:

1 roentgen = 2.58E-4 coulombs/kg of air

Note: The roentgen was originally defined as the quantity of X or gamma radiation that will produce ions carrying 1.0 electrostatic unit (esu) of electrical charge in 1 cubic centimeter of dry air under standard conditions.

There is no SI unit defined for exposure. This was done intentionally to discourage further use of the quantity. The definition of the roentgen places severe limitations on the interpretation of radiation measurements since it describes only the amount of ionization caused by x-ray or gamma radiation (E < 3 MeV) in air. Another unit must be used to describe the amount of ionization caused by any radiation in any material.

Absorbed Dose (D)

Units of dose measure the amount of radiation energy absorbed or deposited per unit of mass. The "energy deposited" by radiation is an expression for the "amount of ionization caused" and both expressions mean the same thing. For example, as a charged particle passes through air, it creates ion pairs. The creation of each of these pairs requires about 33.9 eV. The radiation, therefore, gives up this amount of energy to the air each time it creates an ion pair; in other words, it deposits energy in the air.

The Rad

The old (CGS) unit of absorbed dose is the **rad**, which is an acronym for **R**adiation **A**bsorbed **D**ose. The unit rad can be applied to all types of radiation and is defined as the deposition by any radiation of **100 ergs of energy in one gram of any material**.

Note: For simplicity purposes, 1 rad of photons is usually considered to be equivalent to 1 R. The actual physical relationship is such that an exposure of 1 R would produce an absorbed dose of 0.87 air rads. This means that 1 R = 87 ergs/g.

The Gray

The SI Derived unit of absorbed dose is the **gray** (Gy), equivalent to the deposition of one joule of energy per kilogram (1 J/kg). The relationship between the gray and the rad is that 1 Gy = 100 rad:

$$1Gy = \frac{1J}{kg} \times \frac{1E7ergs}{1J} \times \frac{1kg}{1E3g} \times \frac{1rad}{100ergsl\,\mathrm{g}} = 100rad$$

Although the rad and gray are measures of ionization produced, they do not give any information about the biological effects of the radiation that is absorbed. It is meaningful to emphasize that the energy deposited by the radiation (as a result of the ionization) is the quantity which is actually measured in rad units. Thus, the amount of ionization produced in the detector of a radiation detection instrument can be related to the energy absorbed and expressed by the instrument meter in the unit rad or rad/hr.

Radiation Weighting Factor (W_R)

In 2007 DOE updated most of the dosimetric terms used in 10 CFR part 835 to reflect the recommendations for assessing dose and associated terminology from ICRP Publications 60, *1990 Recommendations of the ICRP on Radiological Protection*, and 68, *Dose Coefficients for Intakes of Radionuclides by Workers*. DOE made these changes mainly because these recommendations are based on updated scientific models and more accurately reflect the occupational doses to workers than the models previously used by DOE.

Table 7 lists the comparison of the different terms. Sites have 3 years to implement these changes. Refer to the previous training handbook for previous terms to use until the newer terms are implemented at the site level.

DOE recognized that, for activities involving both activities under 10 CFR 835 and excluded activities, e.g., activities involving NRC licensed activities, it was not clear as to how the rule would be applied when using different dose coefficients and weighting factors to calculate the overall cumulative total effective dose for the worker. Accordingly, DOE stated that, for the purpose of compliance with determining cumulative total effective dose, DOE considers the following terms to be equivalent.

TABLE 7. Comparison of Dosimetric Terms

Previous Dosimetric Term (and Term as Defined by Excluded Activity Cognizant Regulator)	DOE Amended Dosimetric Term
Committed effective dose equivalent	Committed effective dose
Committed dose equivalent	Committed equivalent dose
Cumulative total effective dose equivalent	Cumulative total effective dose
Deep dose equivalent	Equivalent dose to the whole body
Dose equivalent	Equivalent dose
Effective dose equivalent	Effective dose
Lens of the eye dose equivalent	Equivalent dose to the lens of the eye
Quality factor	Radiation weighting factor
Shallow dose equivalent	Equivalent dose to the skin or Equivalent dose to any extremity
Weighting factor	Tissue weighting factor
Total effective dose equivalent	Total effective dose

A radiation weighting factor is used to relate the absorbed dose of various kinds of radiation to the biological damage caused to the exposed tissue. A radiation weighting factor is necessary to relate the effects of radiation because the same amounts absorbed (energy per kilogram of tissue) of different kinds of radiation cause different degrees of damage. The radiation weighting factor converts the absorbed dose to a unit of *equivalent dose* (discussed below) to a common scale that can be added with and compared to damage caused by any kind of radiation. The radiation weighting factor is a conversion factor used to derive the equivalent dose from the absorbed dose, expressed as:

$$\boldsymbol{H_T = D}\ W_R$$

where: H = equivalent dose
D = absorbed dose averaged over the tissue or organ
W_R = radiation weighting factor

There is a radiation weighting factor associated with each specific type and energy of radiation. By knowing what type and energy of radiation is present, we can determine the radiation weighting factor and relate the absorbed dose to the equivalent dose. A high radiation weighting factor indicates that type of radiation has a greater biological risk or greater effect than radiation with a lower radiation weighting factor for the same absorbed dose.

TABLE 8. Radiation Weighting Factors

Radiation Type	W_R
X-Rays, Gamma Rays, positrons, electrons (including beta particles)	1
Neutrons < 10 keV	5
Neutrons 10 keV to 100 keV	10
Neutrons > 100 keV to 2 MeV	20
Neutrons > 2 MeV to 20 MeV	10
Neutrons > 20 MeV	5
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles , fission fragments, heavy nuclei	20

For example an absorbed dose of 100 millirad thermal neutron would be converted to equivalent dose as follows:

$$100 \text{ mrad } (n_t) \times 5 = 500 \text{ mrem}$$

The radiation weighting factor can also be applied to an absorbed-dose rate (rad/hr) in order to obtain equivalent dose rate (rem/hr).

Equivalent Dose (H_T)

A measurement of the equivalent dose is calculated as the absorbed dose multiplied by the radiation weighting factor, which relates the relative risk from the type of radiation absorbed to the risk from the same dose of X or gamma radiation.

The Rem

A unit of equivalent dose is the **rem**, which is an acronym for **R**oentgen **E**quivalent **M**an. The rem was the quantity of ionizing radiation whose biological effect (in man) is equal to that produced by 1 roentgen of x-rays or gamma radiation. The equivalent dose in rem is numerically equal to the absorbed dose in rad multiplied by the radiation weighting factor:

$$\text{rem} = \text{rad} \times W_R$$

The Sievert

The SI Derived unit of equivalent dose is the **sievert** (Sv). The equivalent dose in sieverts is equal to the absorbed dose in grays multiplied by the radiation weighting factor:

$$\text{sievert} = \text{gray} \times W_R$$

Since, one gray is equal to 100 rad, it follows that:

$$1 \text{ Sv} = 100 \text{ rem}$$

It should be emphasized that the relative risk from one rem equivalent dose from neutrons is the same as the risk from one rem equivalent dose from gamma or any other radiation. Use of equivalent dose units for recording personnel radiation exposure permits us to add exposures from various types of radiation and get a total equivalent dose which is proportional to the risk.

Table 8 provides a summary of these dosimetry units and their associated values.

TABLE 8. Dosimetry Terminology Summary

Term	Unit	Abbr.	Value(s)	Medium	Radiation(s)
Exposure	roentgen	R	1 ESU/cc 87 ergs/g	dry air at STP	X, γ
	--	X	2.58E-4 C/kg	air	
CGS ***Absorbed Dose (D)***	**R**adiation **A**bsorbed **D**ose	rad	100 ergs/g	any	all
SI	gray	Gy	1 J/kg 100 rad		
CGS ***Equivalent Dose(H_T)***	**R**oentgen **E**quivalent **M**an	rem	equivalent biological damage as 1 Roentgen	tissue	all
SI	Sievert	Sv	100 rem		

ANSWERS TO ACTIVITY PRACTICE PROBLEMS

1. 21,230.9 dpm
2. 48.8 nCi
3. 17.95 mCi
4. 51534 pCi
5. 7.1 Ci
6. 1.52E6 dpm
7. 87.7 years
8. 55.6 seconds - Radon-220 (Thoron)

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Course Title: **Radiological Control Technician**
Module Title: **Interaction of Radiation with Matter**
Module Number: **1.07**

Objectives:

1.07.01 Identify the definitions of the following terms:
a. ionization
b. excitation
c. bremsstrahlung

1.07.02 Identify the definitions of the following terms:
a. specific ionization
b. linear energy transfer (LET)
c. stopping power
d. range
e. W-value

1.07.03 Identify the two major mechanisms of energy transfer for alpha particulate radiation.

1.07.04 Identify the three major mechanisms of energy transfer for beta particulate radiation.

1.07.05 Identify the three major mechanisms by which gamma photon radiation interacts with matter.

1.07.06 Identify the four main categories of neutrons as they are classified by kinetic energy for interaction in tissue.

1.07.07 Identify three possible results of neutron capture for slow neutrons.

1.07.08 Identify elastic and inelastic scattering interactions for fast neutrons.

1.07.09 Identify the characteristics of materials best suited to shield:
a. alpha
b. beta
c. gamma
d. neutron radiations

INTRODUCTION

All radiation possesses energy, either inherently (electromagnetic radiation) or as kinetic energy of motion (particulate radiations). The interaction of radiation with matter transfers some or all of this energy to atoms of the medium through which the radiation is passing. To say that radiation interacts with matter is to say that it is either scattered or absorbed. The mechanisms of energy transfer for radiation are of fundamental interest in the field of radiological health for the following reasons:

- Deposition of energy in body tissues may result in physiological injury.
- The products of interactions are used in radiation detection systems.
- The degree of absorption or type of interaction is a primary factor in determining shielding requirements.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
2. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
3. "Health Physics and Radiological Health Handbook"; Shleien; 1992.

TRANSFER OF ENERGY MECHANISMS

1.07.01	*Identify the definitions of the following terms:* *a. ionization* *b. excitation* *c. bremsstrahlung*

The transfer of energy from the emitted particle or photon to atoms of the absorbing material may occur by several mechanisms but, of the radiations commonly encountered, the following three are the most important:

Ionization

Ionization is any process which results in the removal of a bound electron (negative charge) from an electrically neutral atom or molecule by adding enough energy to the electron to overcome its binding energy. This leaves the atom or molecule with a net positive charge. The result is the creation of an ion pair made up of the negatively charged electron and the positively charged atom or molecule. A molecule may remain intact or break-up, depending on whether an electron that is crucial to molecular bonds is affected by the event.

Figure 1 below schematically shows an ionizing particle freeing an L shell electron.

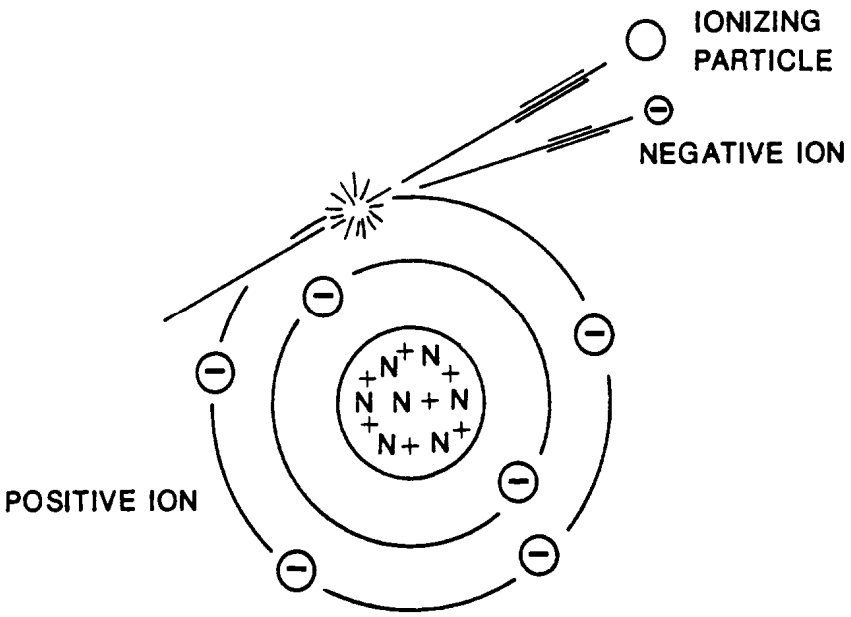

Figure 1 - Ionization

Excitation

Electron excitation is any process that adds enough energy to an electron of an atom or molecule so that it occupies a higher energy state (smaller binding energy) than its lowest bound energy state (ground state). The electron remains bound to the atom or molecule, but depending on its role in the bonds of the molecule, molecular break-up may occur. No ions are produced and the atom remains electrically neutral. Figure 2 below schematically shows an alpha particle (2 protons and 2 neutrons) exciting an electron from the K shell to the L shell because of the attractive electric force (assuming there was a vacant position available in the L shell).

Nuclear Excitation is any process that adds energy to a nucleon in the nucleus of an atom so that it occupies a higher energy state (smaller binding energy). The nucleus continues to have the same number of nucleons and can continue in its same chemical environment

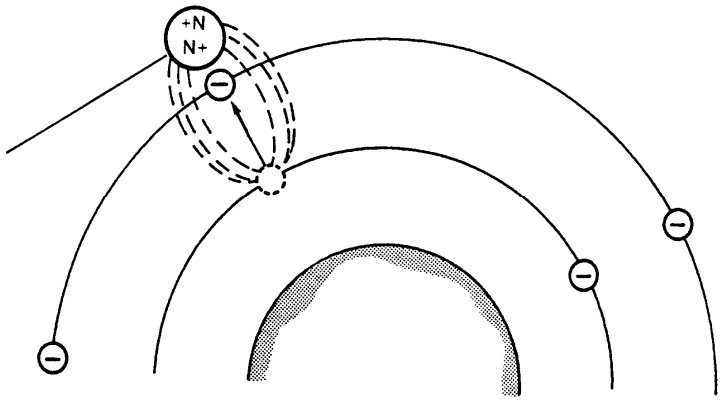

Figure 2 - Electron Excitation

Bremsstrahlung

Bremsstrahlung is the radiative energy loss of moving charged particles as they interact with the matter through which they are moving. Significant bremsstrahlung results from the interaction of a high speed charged particle with the nucleus of an atom (positive charge) via the electric force field. In the case of a negatively charged electron, the attractive force slows down the electron, deflecting it from its original path. The kinetic energy that the particle loses is emitted as a photon (called an x-ray because it is created outside the nucleus). Bremsstralung has also been referred to as "braking radiation", "white radiation", and "general radiation". Bremsstrahlung production is enhanced with high Z materials (larger coulomb forces) and high energy electrons (more interactions occur before all energy is lost).

Ordinarily, the atoms in a material are electrically neutral, i.e., they have exactly as many negative electrons in orbits as there are positive protons in the nucleus. Thus, the difference, or net electrical charge, is zero. Radiations have the ability to either free one or more of the electrons from their bound orbits (ionization) or raise the orbital electrons to a higher energy level (excitation). After ionization, an atom with an excess of positive charge and a free electron are created. After excitation, the excited atom will eventually lose its excess energy when an electron in a higher energy shell falls into the lower energy vacancy created in the excitation process. When this occurs, the excess energy is liberated as a photon of electromagnetic radiation (x-ray) which may escape from the material but usually undergoes other absorptive processes locally.

Nuclei also have various possible energy states of the nucleons above the ground or lowest bound energy state. The nucleus can be excited but nuclear excitation occurs only for neutrons or other radiations of relatively high energies. Following nuclear excitation analogous to atomic electron excitation above, the nucleus will eventually return to the ground state and release the excess energy in photons of electromagnetic radiation (gamma rays).

DIRECTLY IONIZING RADIATION

Charged particles do not require physical contact with atoms to interact with them. The "Coulomb force" (force from the electrical charge) will act over a distance to cause ionization and excitation in the absorber medium. Particles with charge (such as alpha and beta) that lose energy in this way are called directly ionizing radiation. The strength of this force depends on:

- Energy (speed) of the particle
- Charge of the particle
- Density and atomic number (number of protons) of the absorber.

The "Coulomb force" for even a singly charged particle (an electron) is significant over distances greater than atomic dimensions (remember this is the same force that holds the electrons in bound energy states about the nucleus). Therefore, for all but very low physical density materials, the loss of kinetic energy for even an electron is continuous because the "Coulomb force" is constantly "pushing" on electrons of at least one atom and possibly many atoms at the same time.

1.07.02 *Identify the definitions of the following terms:*

a. *specific ionization*
b. *linear energy transfer (LET)*
c. *stopping power*
d. *range*
e. *W-value*

Specific Ionization

As a charged particle passes through an absorber, the energy loss can be measured several ways. One method used is specific ionization. Specific ionization is the number of ion pairs formed by the particle per unit path length and is often used when the energy loss is continuous and constant such as with beta particles (electrons) or alpha particles. The number of ion pairs produced is dependent on the type of ionizing particle and the material being ionized. For example, an alpha particle traveling through air has a specific ionization of 80,000 ion pairs per cm of travel. A beta particle has a specific ionization of about 5,000 ion pairs per cm of travel in air. Specific ionization is a macroscopic quantity that accounts for all energy losses that occur before an ion pair is produced.

Linear Energy Transfer

Another measure of energy deposited in an absorber by a charged particle is the Linear Energy Transfer (LET). The LET is the average energy locally deposited in an absorber resulting from a charged particle per unit distance of travel (keV/cm). The LET is therefore a measure of the local concentration of energy per path length resulting from ionization effects. Biological damage from radiation results from ionization.

Stopping Power

Stopping power of an absorber is its ability to remove energy from a beam of charged particles. Stopping power is measured as the average energy lost by a charged particle per unit distanced travelled (keV/cm). Stopping power and LET may have the same units but are not equal because, although ionization may occur and removes energy from the beam, not all of that energy gets deposited locally and so does not contribute to LET. In other words, LET ≤ stopping power because some electron ions may interact via Bremsstrahlung or excitation and the resulting photons escape the local area. Materials having higher stopping power values cause the particle to lose its energy over shorter distances.

Range

Inversely related to the stopping power of the absorber is the range of the charged particle. The concept of range only has meaning for charged particles whose energy is kinetic energy which is lost continuously along their path. The range of a charged particle in an absorber is the average depth of penetration of the charged particle into the absorber before it loses all its kinetic energy and stops. If a particle has a high range, the absorber has a low stopping power. If the particle has a short range, the absorber has a high stopping power.

W-Value

Specific Ionization, Linear Energy Transfer, Stopping Power, and Range can all be related to each other if one knows the average amount of energy needed to ionize a material. The average amount of energy needed to create an ion pair in a given medium is called the W-Value for the medium. Table 1 below summarizes the terms used in describing the energy losses from radiations in matter.

Table 1. Summary of Energy Loss Terms and Units

Term	Abbr.	Definition	Units
W-value	W	the average amount of energy needed to produce an ion pair in a given medium	eV/ion pair
Specific ionization	S.I.	(average number of) ion pairs produced (by a charged particle) per unit distance traveled in an absorbing medium	ion pairs/cm
Linear Energy Transfer	LET	(average value of) energy locally deposited (by a charged particle) in an absorbing medium per unit distance	keV/cm
Range	R	average distance traveled by a radiation in an absorbing medium	cm
Stopping Power	S	for a given absorber, the average energy lost by a charged particle per unit distance traveled	keV/cm

ALPHA ABSORPTION

An alpha particle is made up of two protons (positively charged) and two neutrons, all strongly bound together by nuclear forces. If such a particle approaches an electron (negatively charged), it experiences a strong electrostatic attraction, whereas if it approaches an atomic nucleus (also positively charged) it will tend to be repelled. Alpha particles have a mass about 8,000 times that of an electron. They are ejected from the nuclei of radioactive atoms with velocities of the order of 1/20 the speed of light. All of these properties--its large mass, its charge, and its high velocity tend to make the alpha particle an efficient projectile when it encounters atoms of an absorbing material. In other words, it would have a high probability of interacting, or colliding, with orbital electrons, and also atomic nuclei.

When speaking of "collisions" between subatomic particles, it should be understood that the particles (for example an alpha and an electron) need approach each other only sufficiently close for Coulomb forces to interact. Such an interaction may then be referred to as a collision.

Figure 3 below schematically shows such a collision, resulting in ionization. In this case, the kinetic energy of the alpha particle is decreased and shows up as a free electron with kinetic energy. The free electron's kinetic energy is less than the alpha energy loss by the amount of energy necessary to free the electron (its binding energy). Because the alpha particle is so much more massive than the electron, the alpha particle typically only loses a small fraction of its energy in any collision and travels in a relatively straight path through the material.

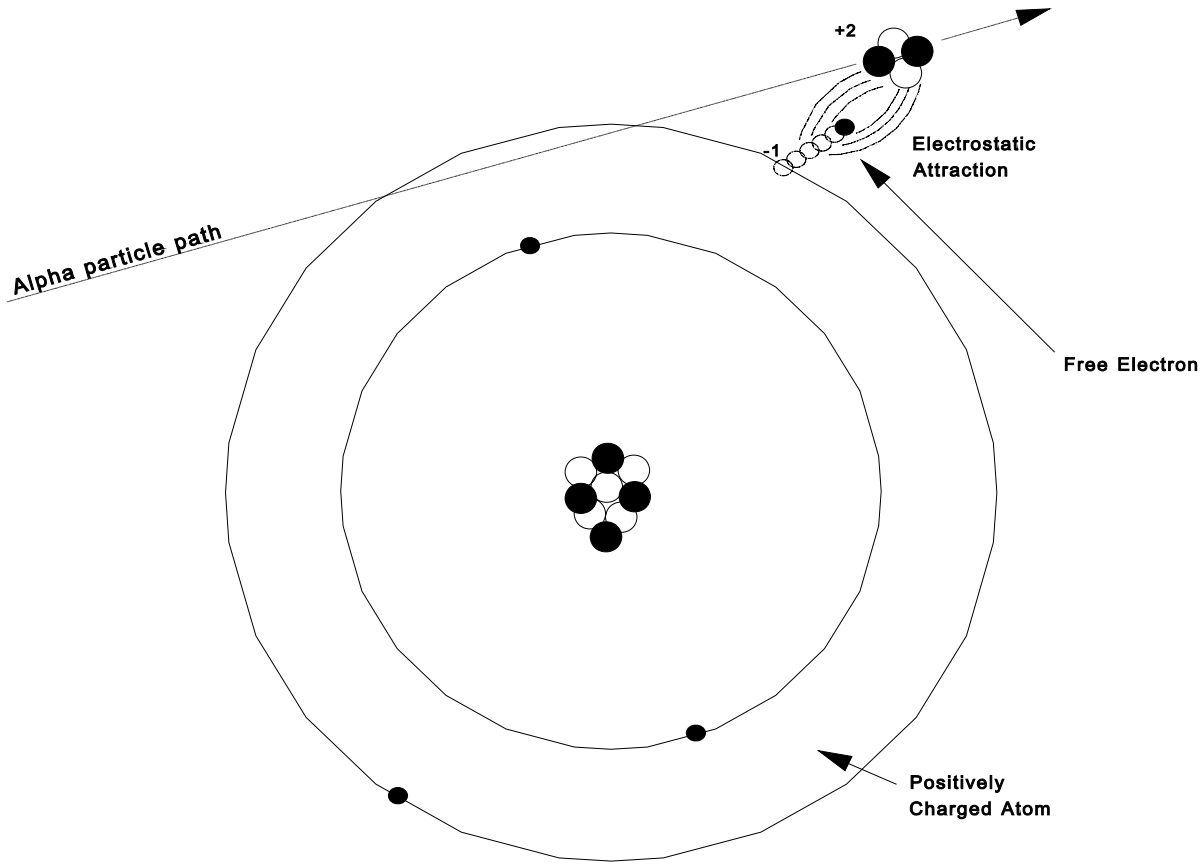

Figure 3 - Ionization by an Alpha Particle

1.07.03	*Identify the two major mechanisms of energy transfer for alpha particulate radiation.*

Alpha collisions may result in energy transfer by 1) ionization and/or 2) excitation. And since a finite amount of energy is required to ionize or excite an atom, the kinetic energy of the alpha particle is gradually dissipated by such interactions until it captures two electrons and settles down to a quiet existence as a helium atom. Since the average amount of energy to ionize most materials is much less than the initial energy of most alpha particles, many ionizations will occur before the alpha particle is stopped.

Due to the high probability of interaction between an alpha particle and the orbital electrons of the absorbing medium and because of the +2 charge, a large number of ion pairs are formed per unit path length. Therefore, this type of radiation loses its energy over a relatively short distance. For these reasons, the range of alpha particles is much less than the range of other forms of radiation. It is, in summary, a highly ionizing, weakly penetrating radiation.

Alpha particles from a given radionuclide are all emitted with the same energy, consequently those emitted from a given source will have approximately the same range in a given material. Alpha particle range is usually expressed in centimeters of air. The relationship between range and energy has been expressed empirically as follows:

$$\mathbf{R_a = 0.318\ E^{3/2}}$$

where:

$\mathbf{R_a}$ = Range in cm of air at 1 atmosphere and 15 °C
$\mathbf{E}$ = Energy in MeV.

As stated above, the number of ion pairs formed per centimeter of path in any given medium is called the specific ionization for that particular ionizing radiation.

$$\text{Specific ionization} = \frac{\text{number of ion pairs formed}}{\text{Centimeter of path length}}$$

On average, approximately 34 electron volts of energy is lost for each primary ion pair formed in air. Only about half to two-thirds of this energy is actually required to remove the orbital electron, the balance being lost in electronic excitation processes. Depending on the energy of the alpha particle, the number of ion pairs formed per centimeter of path in air will range from 5,000 to 80,000.

BETA ABSORPTION

A beta particle is a free (unbound) electron with kinetic energy (e.g. a moving electron). Therefore, the rest mass and charge of a beta particle are the same as that of an orbital electron. The negatively charged electron has an anti-particle which has the same mass but a positive charge called a positron. Their masses are very much smaller than the mass of the nuclei of the atoms making up the absorbing medium. An interaction between a positively charged beta particle or a negatively charged beta particle and an orbital electron is therefore an interaction between two charged particles of similar mass. Negatively charged beta particles and orbital electrons have like charges; therefore, they experience an electrostatic repulsion when in the vicinity of one another. Positively charged beta particles and orbital electrons have unlike charges, so they experience an electrostatic attraction when in the vicinity of one another.

Because the rest masses are equal, the interaction between either of these two beta particles and an orbital electron is similar to the collision between billiard balls. Therefore, a beta particle may lose all of its energy in a single collision. In such an interaction, the target electron acquires such high kinetic energy it becomes a particle similar to the beta particle.

Normally, however, a beta particle of either charge loses its energy in a large number of ionization and excitation events in a manner analogous to the alpha particle. Due to the

smaller size and charge of the electron, however, there is a lower probability of beta radiation interacting in a given medium; consequently, the range of a beta particle is considerably greater than an alpha particle of comparable energy.

A negatively charged beta particle has a charge opposite to that of the atomic nucleus, therefore an electrostatic attraction will be experienced as the beta approaches the nucleus. A positively charged beta particle has a charge the same as that of the atomic nucleus, therefore an electrostatic repulsion will be experienced as the beta approaches the nucleus. Since the mass of either particle is small compared with that of a nucleus, large deflections of the beta can occur in such collisions, particularly when electrons of low energies are scattered by high atomic number elements (high positive charge on the nucleus). As a result, a beta particle usually travels a tortuous, winding path in an absorbing medium.

1.07.04 Identify the three major mechanisms of energy transfer for beta particulate radiation.

Like an alpha particle, a beta particle may transfer energy through ionization and excitation. In addition, a beta may have a Bremsstrahlung interaction with an atom which results in the production of X-rays. Figure 4, following, schematically shows a Bremsstrahlung interaction. In this case, a high energy beta penetrates the electron cloud surrounding the nucleus of the atom, and experiences the strong electrostatic attractive force of the positively charged nucleus. This results in a change in velocity/kinetic energy of the particle and the emission of a Bremsstrahlung X-ray.

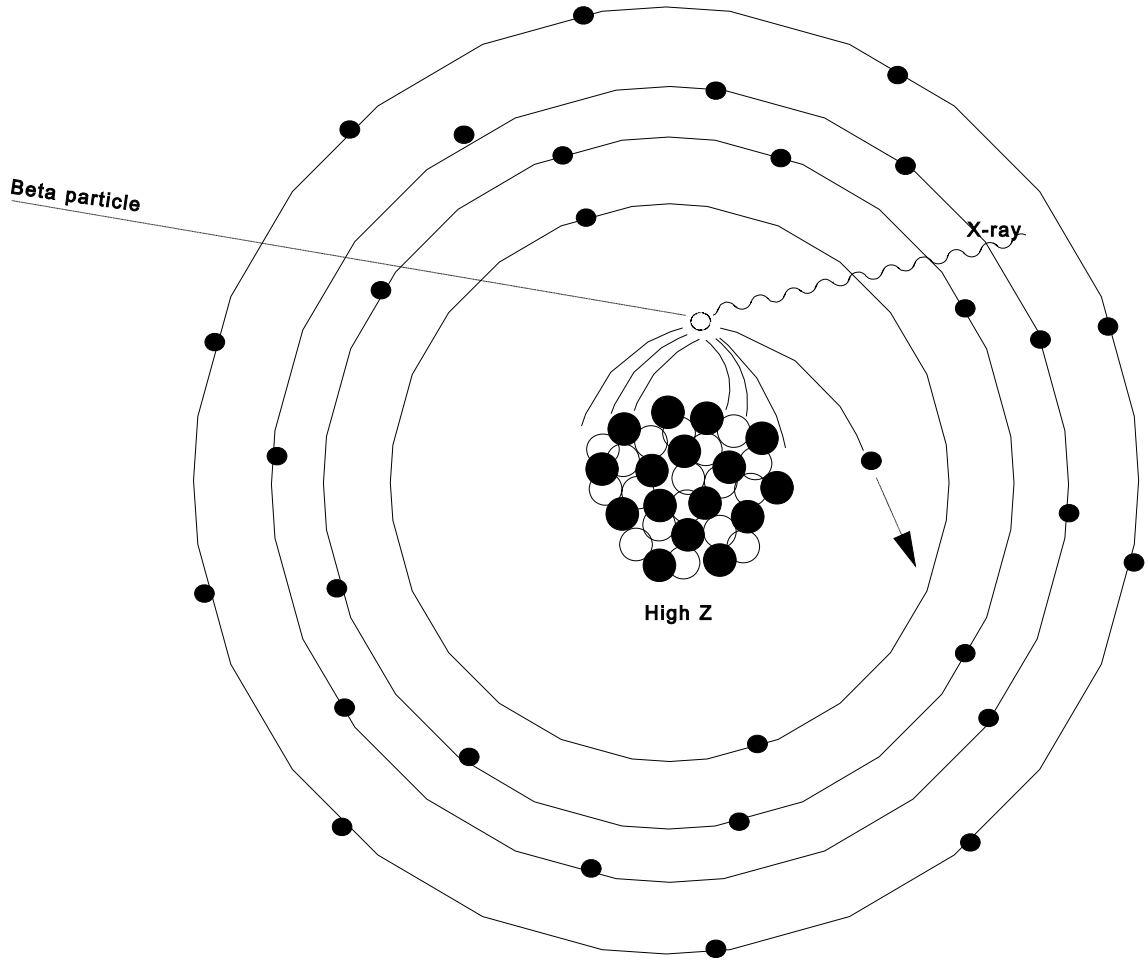

Figure 4 - Bremsstrahlung Radiation

The energy of the X-ray emitted depends on how much deflection of the beta particle occurred, which in turn, depends on how close the electron came to the nucleus. Therefore, a spectrum of different energy X-rays are observed from the many different Bremsstrahlung encounters an electron will have before it loses all of its energy. Because it is much less likely for a close encounter with the nucleus than a distant encounter, there are more low energy X-rays than high energy X-rays (maximum energy is the energy of the beta particle). Bremsstrahlung becomes an increasingly important mechanism of energy loss as the initial energy of the beta increases, and the atomic number of the absorbing medium increases.

Beta particles resulting from radioactive decay may be emitted with an energy varying from practically zero up to a maximum energy. Each beta particle will have a range in an absorber based on its energy. After entering a medium, there will be beta particles with different energies. Therefore, determining the number of beta particles found at a given depth in an absorber and the number of X-rays produced is complex and a function of the energy distribution of the beta particles.

INDIRECTLY IONIZING RADIATION

The types of radiation that have no charge (electromagnetic radiation and neutrons) have no coulomb force field extending beyond their physical dimensions to interact with the fundamental particles of matter. They must come sufficiently close and their physical dimensions contact these particles in order to interact. Radiation and neutrons have physical dimensions much smaller than atomic dimensions. They, therefore, move freely through the largely empty space of matter and have a small probability of interacting with matter. In contrast to directly ionizing radiation described above, uncharged radiation does not continuously lose energy by constantly interacting with the absorber. Instead, it may penetrate material and move "through" many atoms or molecules before its physical dimension contacts that of an electron or nucleus. Indeed, in a chest X-ray, the image is the distribution of X-rays that made it to the film without interacting in the patient's chest. This type of radiation is called <u>indirectly ionizing radiation</u>. The probability of interaction is dependent upon the energy of the radiation and the density and atomic number of the absorber. When indirectly ionization particles do interact, they produce directly ionizing particles (charged particles) that cause secondary ionizations.

GAMMA ABSORPTION

X- and gamma rays differ only in their origin, and an individual X-ray could not be distinguished from an individual gamma ray. Both are electromagnetic waves, and differ from radio waves and visible light waves only in having much shorter wavelengths. The difference in name is used to indicate a different source: gamma rays are of nuclear origin, while X-rays are of extra-nuclear origin (i.e., they originate in the electron cloud surrounding the nucleus). Both X-rays and gamma rays have zero rest mass, no net electrical charge, and travel at the speed of light. They are basically only distortions in the electromagnetic field of space, and can be viewed as packets of energy (quanta) that interact with atoms to produce ionization even though they themselves possess no net electrical charge. As previously pointed out, gamma rays will be discussed as the prototype of this type of radiation.

1.07.05	*Identify the three major mechanisms by which gamma photon radiation interacts with matter.*

There are three major mechanisms by which gamma rays lose energy by interacting with matter.

The Photoelectric Effect

The photoelectric effect (first mechanism) is an all-or-none energy loss. The photon imparts all of its energy to an orbital electron of some atom. The photon, since it consisted only of energy in the first place, simply vanishes. The photoelectric effect is only significant for initial photon energies less than 1 MeV. Figure 5, following, schematically shows a photoelectric interaction. The energy is imparted to the orbital electron in the form of kinetic energy of motion, overcoming the attractive force of the nucleus for the electron (the binding energy) and usually causing the electron to leave its orbit with considerable velocity. Thus, an ion-pair results.

The high velocity electron, which is called a photoelectron, is a directly ionizing particle and typically has sufficient energy to knock other electrons from the orbits of other atoms, and it goes on its way producing secondary ion-pairs until all of its energy is expended. The probability of photoelectric effect is maximum when the energy of the photon (gamma) is equal to the binding energy of the electron. The tighter an electron is bound to the nucleus, the higher the probability of photoelectric effect so most photoelectrons are inner-shell electrons. The photoelectric effect is seen primarily as an effect of low energy photons with energies near the electron binding energies of materials and high Z materials whose inner-shell electrons have high binding energies.

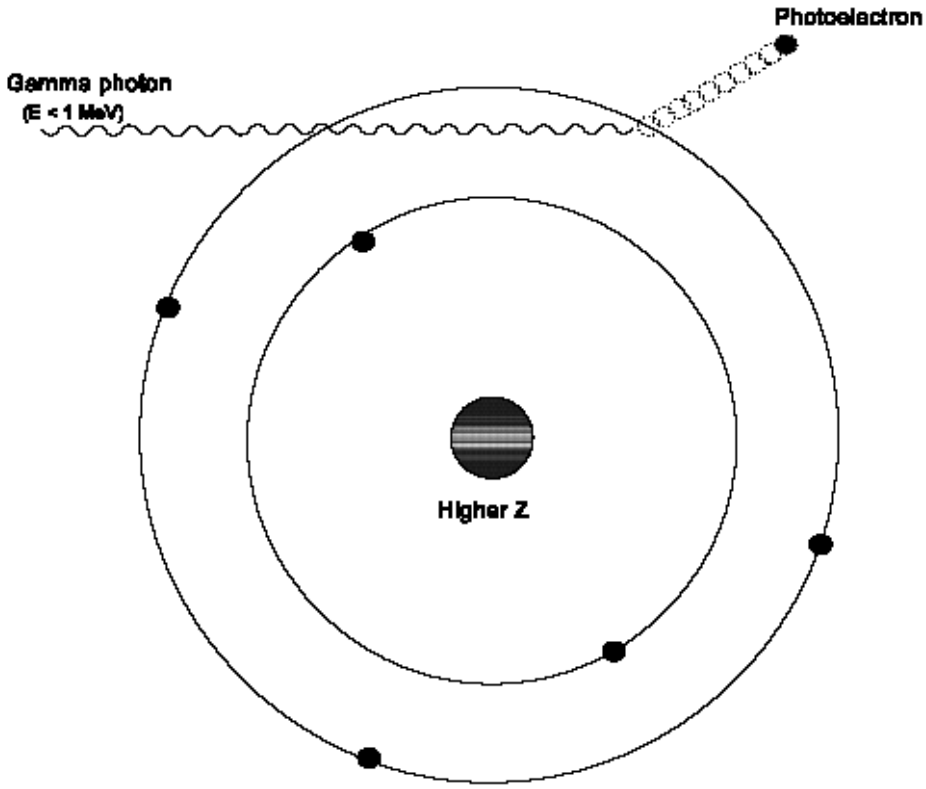

Figure 5 - Photoelectric Effect

Compton Scattering

In Compton scattering (the second mechanism) there is a partial energy loss for the incoming photon. The photon interacts with an orbital electron of some atom and only part of the energy is transferred to the electron. Compton scattering is the dominant interaction for most materials for photon energies between 200 keV and 5 MeV. Figure 6, following, schematically shows a Compton interaction also called Compton scattering.

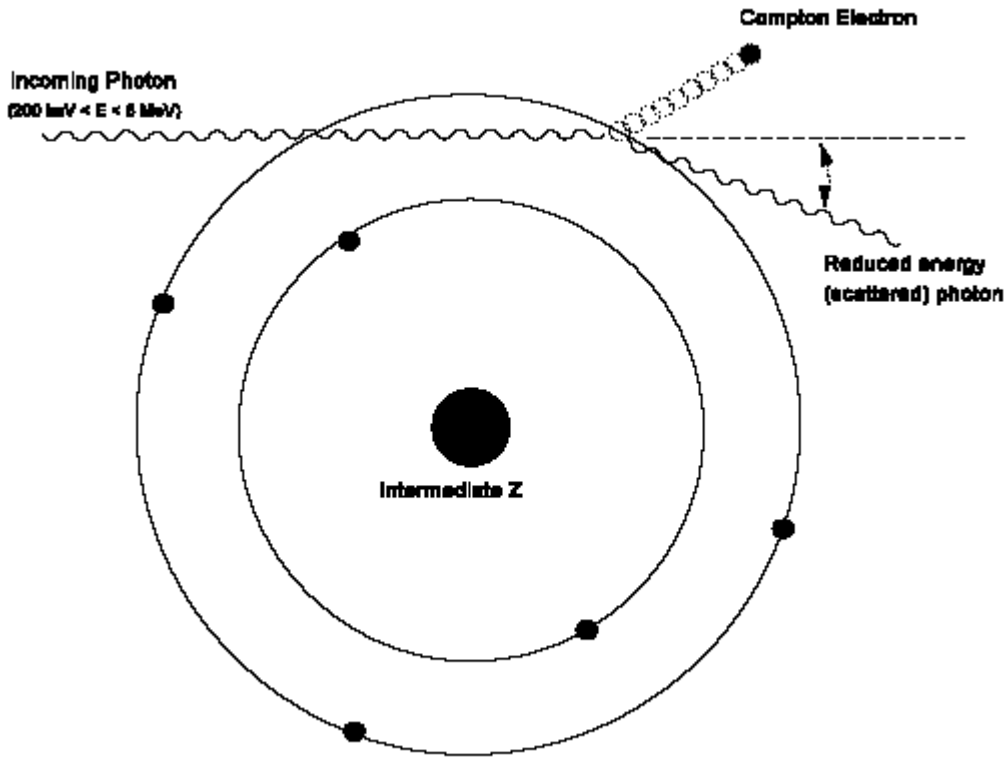

Figure 6 - Compton Scattering

A photon continues on with less energy and in a different direction to conserve momentum in the collision. The high velocity electron, now referred to as a Compton electron, produces secondary ionization in the same manner as does the photoelectron, and the "scattered" photon continues on until it loses more energy in another photon interaction. By this mechanism of interaction, photons in a beam may be randomized in direction and energy, so that scattered radiation may appear around corners and behind shields where there is no direct line of sight to the source. The probability of a Compton interaction increases for loosely bound electrons. Therefore, most Compton electrons are valence electrons. Compton scattering is primarily seen as an effect of medium energy photons.

Pair Production

Pair production (the third mechanism) occurs when all of energy of the photon is converted to mass. This conversion of energy to mass only occurs in the presence of a strong electric field, which can be viewed as a catalyst. Such strong electric fields are found near the nucleus of atoms and is stronger for high Z materials. Figure 7, following, schematically shows pair production and the fate of the positron when it combines with an electron (its anti-particle) at the end of its path. In pair production a gamma photon simply disappears in the vicinity of a nucleus, and in its place appears a pair of electrons: one negatively charged and one

positively charged. These anti-particles are also called an electron and a positron respectively. The mass of these electrons has been created from the pure energy of the photon, according to the familiar Einstein equation $E = mc^2$, where (E) is energy in joules, (m) is mass in kilograms, and (c) is the velocity of light in m/sec. **Pair production is impossible unless the gamma ray possesses greater than 1.022 MeV of energy to make up the rest mass of the particles.** Practically speaking, it does not become important until 2 MeV or more of energy is possessed by the incident photon.

Any excess energy in the photon above the 1.022 MeV required to create the two electron masses, is simply shared between the two electrons as kinetic energy of motion, and they fly out of the atom with great velocity. The probability of pair production is lower than photoelectric and Compton interactions because the photon must be close to the nucleus. The probability increases for high Z materials and high energies.

The negative electron behaves in the same way as any electron with kinetic energy, producing secondary ion-pairs until it loses all of its energy of motion. The positive electron (positron) also produces secondary ionization as long as it is in motion, but when it has lost its energy and slowed almost to a stop, it encounters a free (negative) electron somewhere in the material. The two are attracted by their opposite charges, and upon contact, because they are antiparticles, they annihilate each other, converting the mass of each back into pure energy. Thus, two gamma rays of 0.511 MeV each arise at the site of the annihilation (accounting for the rest mass of the particles). The ultimate fate of the "annihilation gammas" is either photoelectric absorption or Compton scattering followed by photoelectric absorption.

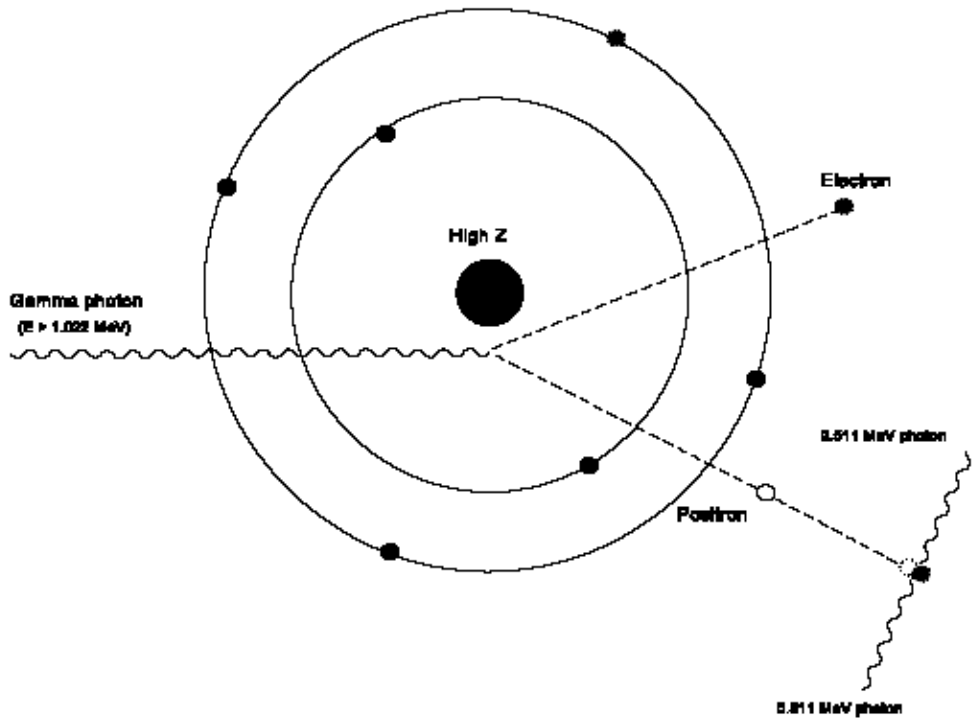

Figure 7 - Pair Production and Annihilation

NEUTRON INTERACTIONS

The neutron has a mass number of 1 and no charge. Because it has no charge the neutron can penetrate relatively easily into a nucleus. Free unbound neutrons are unstable (radioactive) and disintegrate by beta emission with a half-life of approximately 10.6 minutes. The resultant decay product is a proton which eventually combines with a free electron (not necessarily the beta particle) to become a hydrogen atom.

During the time when free neutrons exist, they can interact with the material they are in (primarily with nuclei) and lose energy. Neutron interactions with the nucleus are very energy dependent so neutrons are classified on the basis of their kinetic energies. When a neutron is in "thermal equilibrium" with a material, it has kinetic energies appropriate for the kinetic energies of the atoms of the material. The most probable velocity of free neutrons in various substances at room temperature is approximately 2,200 meters per second. Their kinetic energy may be calculated from the equation:

$$E = 1/2mv^2$$

where:

E = kinetic energy
m = Neutron mass in grams
v = Neutron velocity in cm/sec.

substituting:

$$E=\frac{1}{2}\times 1.66E\text{-}24gm\times\left(\frac{2.2E5cm}{sec}\right)^2$$

$$E=4.02E\text{-}14gm\text{-}cm^2/sec^2 \longrightarrow ergs$$

Since: 1 erg = 6.24E11 eV

$$E=\left[4.02E\text{-}14ergs\right]\left[\frac{6.24E11eV}{1erg}\right]$$

$$E=0.025eV$$

Neutrons with this average kinetic energy at 20 °C are called thermal neutrons.

1.07.06	*Identify the four main categories of neutrons as they are classified by kinetic energy for interaction in tissue.*

When neutrons are classified by their kinetic energies into various categories, frequently the energy ranges and names given to each neutron energy range is determined by the materials being used or research being conducted. For example, reactor physics, weapons physics, accelerator physics, and radiobiology each have generated a classification system that serves their needs. Typically the only category common to them all is thermal. The classification used for neutron interaction in tissue is important in radiation dosimetry and is shown in Table 2.

Table 2. Neutron Energy Categories

Category	Energy Range
Thermal	– 0.025 eV (≤ 0.5 eV)
Intermediate	0.5 eV - 100 keV
Fast	100 keV - 20 MeV
Relativistic	> 20 MeV

One should be familiar with the classification of neutrons by energy that applies to the area where they are working so no confusion arises when using terminology. For the remainder of this discussion, neutrons ≤ 2 keV will be called "slow neutrons" and neutrons ≥ 2 keV will be called "fast neutrons." These are intended to be general references and do not correspond to specific energy ranges that are used in any specific discipline.

Classification of neutrons according to kinetic energy is important from two standpoints: (a) the interaction of neutrons with the nuclei of atoms differs with the neutron energy, and (b) the methods of producing, detecting and shielding against the various classes of neutrons are different.

Detection of neutrons is relatively difficult, due to the lack of ionization along their paths; negligible response to externally applied electric, magnetic or gravitational fields; and the fact that they interact primarily with atomic nuclei, which are exceedingly small.

Neutron Reactions

When describing neutron reactions with a nucleus, the standard notation is (n,Y) where n is the initial neutron and Y is the resulting emissions following the interaction with the nucleus.

1.07.07	*Identify three possible results of neutron capture for slow neutrons.*

Radiative capture with gamma emission is the most common type of reaction for slow neutrons. This (n,γ) reaction often results in product nuclei which are radioactive. For example:

$$^{59}_{27}\text{Co} + ^{1}_{0}\text{n} \longrightarrow ^{60}_{27}\text{Co} + \text{y}$$

This process of converting a stable nucleus to its radioactive counterpart by neutron bombardment is called "neutron activation." Many radionuclides used in nuclear medicine are produced by this process.

A second type of general reaction for slow neutrons is that giving rise to charged particle emission. Typical examples include (n,p), (n,d), and (n,α) reactions, i.e., reactions in which a proton, a deuteron, or an alpha particle is ejected from the target nucleus.

A third type of neutron-induced nuclear reaction is fission. Typically, fission occurs following the absorption of a slow neutron by several of the very heavy elements. When ^{235}U nuclei undergo fission by neutrons, an average of 2 to 3 neutrons are expelled along with associated gamma radiation. The nucleus splits into two smaller nuclei which are called primary fission products or fission fragments. These products usually undergo radioactive decay to form secondary fission product nuclei. As an example, if one neutron fissions a ^{235}U nucleus, it could yield yttrium-95, iodine-139, two neutrons and fission energy. There are some 30 different ways that fission may take place with the production of about 60 primary fission fragments. These fragments and the atoms which result from their decay are referred to as fission products, and they number between 400 and 600, according to the type and number of nucleons their nuclei possess.

Many fission products have found application in medicine, industry, and research. A well known example is ^{131}I which is used extensively in medicine as both a diagnostic and therapeutic agent.

The fission process is the source of energy for nuclear reactors and some types of nuclear weapons. Also, neutrons generated from the fissioning of the fuel in a reactor are used to activate stable materials to a radioactive form as previously discussed. Many radioisotopes used in medicine are produced by neutron activation in this manner.

Elastic and Inelastic Scattering

Neutron scattering is a fourth type of interaction with the nucleus. This description is generally used when the original free neutron continues to be a free neutron following the interaction. Scattering is the dominant process for fast neutrons when the neutron is moving too fast to become absorbed by a nucleus. Multiple scattering by a neutron is the mechanism of slowing down or "moderating" fast neutrons to thermal energies. This process is sometimes called "thermalizing" fast neutrons.

1.07.08	*Identify elastic and inelastic scattering interactions for fast neutrons.*

Elastic scattering occurs when a neutron strikes a nucleus (typically of approximately the same mass as that of the neutron) as schematically shown in Figure 8. Depending on the size of the nucleus, the neutron can transfer much of its kinetic energy to that nucleus which recoils off with the energy lost by the neutron. Hydrogen causes the greatest energy loss to the neutron because the single proton in the nucleus is approximately the same mass as the neutron. The process is analogous to the rapid dissipation of the energy of a cue ball when it hits another ball of equal mass on a billiard table. During elastic scattering reactions, it is worth noting, no gamma radiation is given off by the nucleus. The recoil nucleus can be knocked away from its electrons and, being positively charged, can cause ionization and excitation.

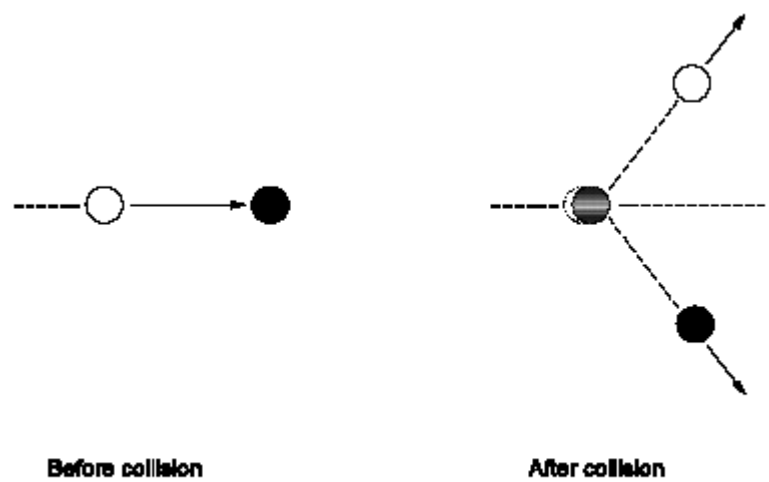

Figure 8 - Elastic Scattering

Inelastic scattering occurs when a neutron strikes a large nucleus as schematically shown in Figure 9 below. The neutron penetrates the nucleus for a short period of time, transfers energy to a nucleon inside, and then exits with a small decrease in energy. The nucleus is left in an excited state, emitting gamma radiation which can cause ionization and/or excitation.

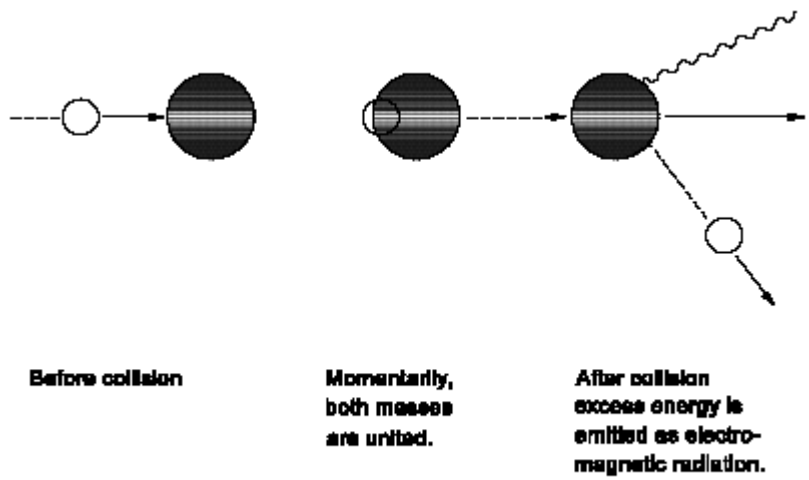

Figure 9 - Inelastic Scattering

Reactions in Biological Systems:

Fast neutrons lose energy in soft tissue mainly by repeated scattering interactions with hydrogen nuclei. The hydrogen nuclei are themselves scattered in the process. The scattered hydrogen nuclei have been "knocked" free of their electron and are thus moving protons (called recoil protons) which cause ionization.

Slow neutrons are captured in soft tissue and release energy by two principal mechanisms:

$$ {}^{1}_{0}n + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + y\left(2.2\text{MeV}\right) $$

and

$$ {}^{1}_{0}n + {}^{14}_{7}N \longrightarrow {}^{14}_{6}C + {}^{1}_{1}p\left(0.66\text{MeV}\right) $$

The gamma and proton energies may be absorbed in the tissue and cause damage that can result in deleterious effects. This will be discussed in lesson 1.08.

Whenever charged particles, neutrons or photons are able to penetrate the nucleus and have sufficient energy, transmutations may be caused which often result in radioactivity. The bombarding projectile can be a neutron, proton, deuteron, alpha particle, electron, or gamma photon. Such bombarding particles may originate from other transmutations, radioactive decay, fission, fusion, or particle accelerators. As a result of the interaction of the projectile and target, a compound nucleus is formed, exists for an instant, (10E-12 sec), and then separates into a product particle or particles and product nucleus. Three laws govern these reactions: (1) conservation of mass number; (2) conservation of atomic number; and (3) conservation of total energy.

RADIATION SHIELDING

Introduction. Shielding is an important principle for radiological control. In this section, the basic principles for protection of personnel from the three major types of penetrating ionizing radiation ((γ, β, neutron) are discussed. These principles are applicable regardless of types or energy of the radiation. However, the applications of the principles will vary quantitatively, depending on type, intensity and energy of the radiation source, e.g., beta particles from radioactive materials will require a different amount of shielding than high speed electrons from a high energy particle accelerator. For directly ionizing particles, the application of these principles would reduce personnel exposure to zero, for indirectly ionizing radiation, the exposure can be minimized consistent with the ALARA philosophy (to be discussed in Lesson 1.10).

Shielding of photons. When shielding against X-rays and gamma rays, it is important to realize that photons are removed from the incoming beam on the basis of the probability of an interaction such as photoelectric effect, Compton scatter, or pair production. This process is called attenuation and can be described using the "linear attenuation coefficient", μ, which is the probability of an interaction per path length x through a material (typical units are $\frac{1}{cm}$ or cm^{-1}). The linear attenuation coefficient varies with photon energy, type of material, and physical density of material. Mathematically the attenuation of photons is given by:

$$I(x) = I_o e^{-\mu x}$$

where:

$I(x)$	=	Radiation intensity exiting x thickness of material
I_o	=	Radiation intensity entering material
e	=	Base of natural logarithms (2.714.....)
μ	=	Linear attenuation coefficient
x	=	Thickness of material.

This equation shows that the intensity is reduced exponentially with thickness and only approaches zero for large thicknesses. I(x) never actually equals zero. This is consistent with the notion that because X-rays and gamma rays interact based on probability, there is a finite (albeit small) probability that a gamma could penetrate through a thick shield without interacting. Shielding for X-rays and gamma rays then becomes an ALARA issue and not an issue of shielding to zero intensities.

The formula above is used to calculate the radiation intensity from a narrow beam behind a shield of thickness x, or to calculate the thickness of absorber necessary to reduce radiation intensity to a desired level. Tables and graphs are available which give values of μ determined experimentally for all radiation energies and many absorbing materials. The larger the value of μ the greater the reduction in intensity for a given thickness of material. The fact that lead has a high μ for X- and gamma radiation is partially why it is widely used as a shielding material.

Although attenuation of the initial beam of photons occurs by photoelectric, Compton, and pair production interactions, additional photons can be produced by subsequent interactions (immediately in the case of Compton). If the beam is narrow, these additional photons are "randomized" and are no longer part of the narrow beam of radiation. If the beam is broad, photons can be "randomized" and scattered <u>into</u> the area one is trying to shield. The secondary photons are accounted for by a build up factor, B, in the attenuation equation as follows:

$$I = BI_0 e^{-ux}$$

where B is the buildup factor. Tables of dose build-up factors (indicating that the increased radiation intensity is to be measured in terms of dose units) can be found in the Radiological Health Handbook.

The buildup is mostly due to scatter. Scattered radiation is present to some extent whenever an absorbing medium is in the path of radiation. The absorber then acts as a new source of radiation. Frequently, room walls, the floor, and other solid objects are near enough to a source of radiation to make scatter appreciable. When a point source is used under these conditions, the inverse square law is no longer completely valid for computing radiation intensity at a distance. Measurement of the radiation is then necessary to determine the potential exposure at any point.

In summarizing shielding of photons the important considerations are:

- That persons in the area behind a shield where there is no direct line of sight to the source are not necessarily adequately protected.

- That a wall or partition is not necessarily a "safe" shield for persons on the other side.

- That in effect, radiation can be deflected around corners"; i.e., it can be scattered.

Shielding will also attenuate beta radiation, and it takes relatively little shielding to absorb it completely (i.e. the particle's range is less than the thickness of the material). Therefore, the general practice is to use enough shielding for complete absorption. For low energy beta emitters in solution, the glass container generally gives complete absorption. In many cases plastic shielding is effective and convenient.

The absorption of great intensities of beta radiation results in the production of Bremsstrahlung radiation. Since Bremsstrahlung production is enhanced by high Z materials, for effective shielding of beta particles one would use a low Z material, such as plastic. This would allow the Beta particle to lose its energy with minimal Bremsstrahlung production. A material suitable to shield the Bremsstrahlung X-rays (such as lead) would then be placed on the "downstream" side of the plastic. If low density and low Z number material (i.e., aluminum, rubber, plastic, etc.) is used for shielding beta particles most Bremsstrahlung can be avoided.

Tables and graphs are available which give the maximum range of beta particles of various energies in different absorbing media. These can be used for calculation of the shielding necessary for protection against beta radiation.

Fast neutrons are poorly absorbed by most materials and the neutrons merely scatter through the material. For efficient shielding of fast neutrons, one needs to slow them down and then provide a material that readily absorbs slow neutrons.

Since the greatest transfer of energy takes place in collisions between particles of equal mass, hydrogenous materials are most effective for slowing down fast neutrons. Water, paraffin, and concrete are all rich in hydrogen, and thus important in neutron shielding. Once the neutrons have been reduced in energy, typically either boron or cadmium are used to absorb the slow neutrons.

Borated polyethylene is commonly available for shielding of fast neutrons. Polyethylene is rich in hydrogen and boron is distributed, more or less, uniformly throughout the material to absorb the slowed neutrons that are available. When a boron atom captures a neutron, it emits an alpha particle, but because of the extremely short range of alpha particles, there is no additional hazard.

A shield using cadmium to absorb the slowed neutrons is usually built in a layered fashion because cadmium is a malleable metal that can be fashioned into thin sheets. Neutron capture by cadmium results in the emission of gamma radiation. Lead or a similar gamma absorber must be used as a shield against these gammas. A complete shield for a capsule type neutron source may consist of, first, a thick layer of paraffin to slow down the neutrons, then a surrounding layer of cadmium to absorb the slow neutrons, and finally, an outer layer of lead to absorb both the gammas produced in the cadmium and those emanating from the capsule.

Due to the relatively large mass and charge of alpha particles, they have very little penetrating power and are easily shielded by thin materials. Paper, unbroken dead layer of skin cells, or even a few centimeters of air will effectively shield alpha particles. The fact that alpha particles will not penetrate the unbroken dead layer of skin cells makes them primarily an external contamination problem and not an external dose problem. If alpha particles are allowed to be deposited internally, they become a very serious health hazard.

1.07.09 Identify the characteristics of materials best suited to shield:

a. alpha
b. beta
c. gamma
d. neutron radiations

Table 3. Shielding Material

Radiation	Typical Shielding Characteristics
alpha	thin amounts of most any material (paper, unbroken dead cell layer of skin, few cm of air)
beta	low Z and low density material (rubber, aluminum, plastic)
gamma	high Z and high density material (lead, depleted uranium)
neutron	hydrogenous material for moderation (oil, plastic, water) and capture material for absorption (boron, cadmium)

Course Title: **Radiological Control Technician**
Module Title: **Biological Effects of Radiation**
Module Number: **1.08**

Objectives:

1.08.01 Identify the function of the following cell structures:
a. Cell membrane
b. Cytoplasm
c. Mitochondria
d. Lysosome
e. Nucleus
f. DNA
g. Chromosomes

1.08.02 Identify effects of radiation on cell structures.

1.08.03 Define the law of Bergonie and Tribondeau.

1.08.04 Identify factors which affect the radiosensitivity of cells.

1.08.05 Given a list of types of cells, identify which are most or least radiosensitive.

1.08.06 Identify primary and secondary reactions on cells produced by ionizing radiation.

1.08.07 Identify the following definitions and give examples of each:
a. Stochastic effect
b. Deterministic effect

1.08.08 Identify the LD 50/30 value for humans.

1.08.09 Identify the possible somatic effects of chronic exposure to radiation.

1.08.10 Distinguish between the three types of the acute radiation syndrome, and identify the exposure levels and the symptoms associated with each.

1.08.11 Identify risks of radiation exposure to the developing embryo and fetus.

1.08.12 Distinguish between the terms "somatic" and "heritable" as they apply to biological effects.

INTRODUCTION

Within a year after Roentgen's discovery of X-rays in 1895, it was learned that exposure to ionizing radiation could lead to biological damage. Since that time, a tremendous amount of research has been done attempting to interpret the reactions which take place from the moment that radiation enters a living cell until some permanent damage is produced. From beginning to end, these initial reactions are probably completed in a millionth of a second, making them very difficult to study. For this reason, it is still not known which of the many chemical or biochemical reactions brought about by ionizing radiation are responsible for initiating biological damage.

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1.08.01 Identify the function of the following cell structures:

a. Cell membrane
b. Cytoplasm
c. Mitochondria
d. Lysosome
e. Nucleus
f. DNA
g. Chromosomes

CELL STRUCTURE

Since the primary site of radiation damage is in the cell, the logical place to start a study of the biological effects of radiation is with the structure of this basic unit of all living material.

Cells are the building blocks of which man and his living environment are composed; they are the fundamental unit of which all living organisms are made. Although there is no such thing as a typical cell, all cells have several features in common.

Most cells are composed of protoplasm: a mixture of carbohydrates, lipids, proteins, nucleic acids, inorganic salts, gases and between 70 and 80% water. The cell may be subdivided into three major parts: (1) the cell membrane; (2) the cytoplasm; and (3) the nucleus. *(See Figure 1)*

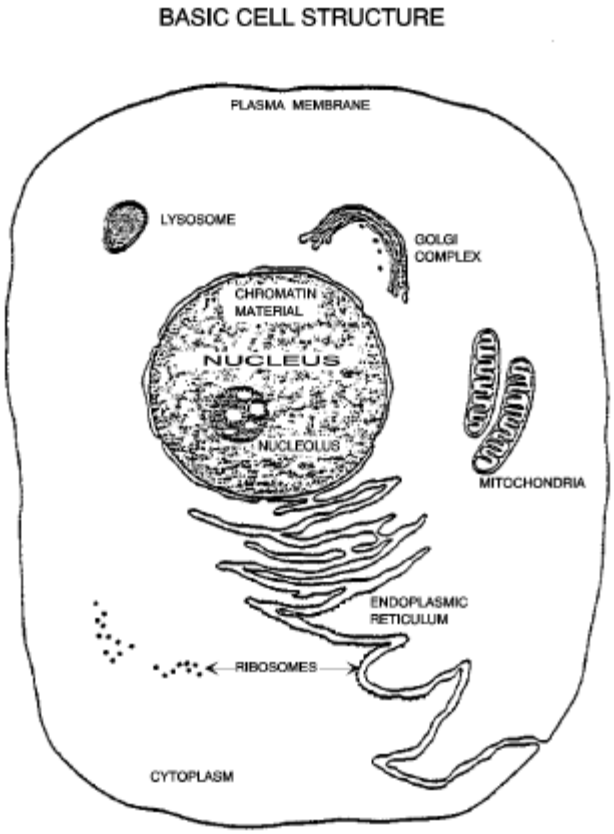

Figure 1

Cell Membrane. The cell membrane is only 100 angstrom units (a millionth of a centimeter) thick, and is a living functional part of the cell. It helps to regulate the concentration of water, salts, and organic matter which form the interior environment of the cell. In red blood cells, and nerve cells, the membrane distinguishes between sodium and potassium ions even though these ions are alike in size and electrical charge. The membrane actively transports potassium ions into the cell and opposes the entrance of sodium ions. The membrane is thus capable of "active transport." In addition, all food entering the cell and all waste products or secretions leaving it must pass through this membrane.

Cytoplasm. The cytoplasm is a jelly like substance in which the nucleus is suspended; it is encased within the cell membrane. This material is an aqueous solution of soluble proteins and salts which constitutes the interior environment of the cell.

Mitochondria. Many small functional units called organelles are contained in the cytoplasm. Principal among these are the mitochondria, which are the "power plants" of both plant and animal cells. It is here that oxygen is used for the

oxidation of essential foodstuffs and the formation of carbon dioxide. The metabolic energy so released is captured in the chemical bonds of a special energy storing molecule known as ATP (adenosine triphosphate). This molecule supplies the energy for all the activities of the cell, including reproduction and repair.

Lysosomes. The lysosomes contain the digestive enzymes that break down large molecules, such as those of fats, proteins, and nucleic acids, into smaller constituents that can be oxidized by the oxidative enzymes of the mitochondria. The lysosomal membrane isolates the digestive enzymes from the rest of the cytoplasm. Rupture of the membrane and release of the enzymes leads to the dissolution of the cell.

Nucleus. Each cell contains a small, usually oval, body known as the nucleus. In some cells this has a relatively fixed position and is found near the center; in others it may move around freely and be found almost anywhere in the cell. The nucleus is an important center of control of the cell, directing cellular activity and containing the hereditary factors (genes) responsible for the traits of the animal or plant.

The membrane surrounding the nucleus and separating it from the adjacent cytoplasm is called the nuclear membrane. It is a double membrane with annuli, or holes, in the outer layer, open to the cytoplasm. This suggests that the cytoplasm of the cell is in direct communication with the protoplasm of the cell nucleus (the nucleoplasm). The function of this nuclear membrane is to regulate the constant flow of materials into and out of the nucleus.

The nucleoli are spherical bodies which are found within the cell nucleus. These cell constituents are packed with tiny granules similar to the ribosomes of the cytoplasm. The nucleoli are rich in ribonucleic acid (RNA) and appear to be active centers of protein and RNA synthesis.

Figure 2.
Double Helix

DNA (DeoxyriboNucleic Acid) is the most important material making up the chromosomes and serves as the master blueprint for the cell. The nucleic acids, DNA and RNA, function together to produce the cell's proteins. DNA determines what types of RNA are produced which, in turn, determine the types of protein that are produced. It is generally assumed to take the form of a twisted ladder or double helix. *(See Figure 2)* The sides of the ladder are strands of alternating sugar and phosphate groups. Branching off from each sugar group is one of four nitrogenous bases: cytosine, thymine, adenine and guanine. *(See Figure 3)* The rungs of the ladder consist of two nitrogenous bases, one from each strand, linked by hydrogen bonds. Cytosine is always paired with guanine and thymine is always paired with adenine. A section of DNA that codes for one protein is referred to a gene although the "message" from several genes can be carried by single piece of RNA.

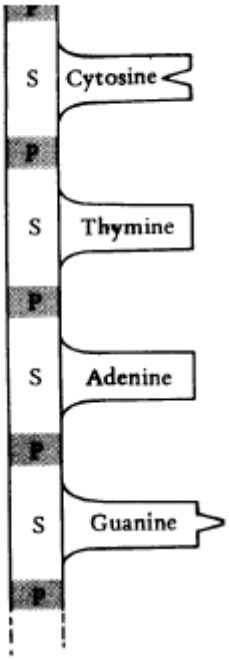

Figure 3.
DNA Base Pairs

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Chromosomes consist of highly convoluted supercoils of DNA and associated protein.

To ensure its survival, each new cell must possess all the required DNA (a complete chromosome complement).

1.08.02 Identify effects of radiation on cell structures

RADIATION EFFECTS ON CELL CONSTITUENTS

A great deal of work has been performed on examining the effects of radiation on various organelles. The following dose rates apply to human cells.

It has been established it takes about 3,000 to 5,000 rads (30-50 gray) of absorbed dose to rupture the **cell membrane**. This major injury to the cell allows the extracellular fluids to enter into the cell. Inversely, it also allows leakage out of ions and nutrients which the cell brought inside. Membrane rupture may result in the death of a cell, in this case death would be compared to drowning. Large

doses below 3,000 rads (30 gray) increase the permeability of the cell membrane and some leakage occurs.

Radiation effects on cytoplasm are negligible compared to observed effects on structures which are suspended within it. The first involve the **mitochondria**. It requires a few thousand rad to disrupt their function. This results in the immediate interruption of the cells food supply (ATP). If the cell has a large reserve of ATP it can repair the damage to the mitochondria and then continue to produce ATP. The greater the dose received, the longer the repair time will be. If the stored food supply is not adequate to nourish the cell during repair, then the cell will die from starvation.

Another organelle within the cytoplasm that is effected by radiation is the lysosome. The **lysosome** will be ruptured at dose levels between 500 and 1,000 rads (5-10 gray). When this occurs, the enzymes are released within the cell and begin digesting structures of the cell. This cell death can be compared with suicide. At much larger doses the digestive enzymes are rendered inactive.

The most radiologically sensitive part of the cell is the **nucleus**. Because there is a wide band of sensitivity for cell nuclei, quantifying a dose range is difficult. The major effect of radiation on the cell nucleus is the inhibition of **DNA** replication. This means that the cell is unable to prepare for division. Before a cell divides it produces a complete duplicate set of **chromosomes** which carry all the information needed to reproduce the organism. With damaged DNA, duplicate chromosomes cannot be manufactured. If this process is delayed long enough, the cell dies and the death of the cell can be compared to death in childbirth. At lower doses DNA production is delayed only a short time. As the dose is increased, the delay period gets longer until death occurs.

1.08.03 Define the law of Bergonie and Tribondeau.

RADIOSENSITIVITY AND THE LAW OF BERGONIE AND TRIBONDEAU

As early as 1906 an attempt was made to correlate the differences in sensitivity of various cells with differences in cellular physiology. These differences in sensitivity are stated in the Law of Bergonie and Tribondeau: "*The radiosensitivity of a tissue is directly proportional to its reproductive capacity and inversely proportional to its degree of differentiation*." In other words, cells most active in reproducing themselves and cells not fully mature will be most harmed by radiation. This law is considered to be a rule-of-thumb, with some cells and tissues showing exceptions.

1.08.04 Identify factors which affect the radiosensitivity of cells.

Since the time that the Law of Bergonie and Tribondeau was formulated, it is generally accepted that cells tend to radiosensitive if they are:

1. Cells that have a *high division rate*.
2. Cells that have a *high metabolic rate*.
3. Cells that are of a *non-specialized type*.
4. Cells that are well *nourished*.

1.08.05 Given a list of types of cells, identify which are most or least radiosensitive.

The law can be used to classify the following tissues as **radiosensitive**:

1. Germinal (reproductive) cells of the ovary and testis i.e., spermatogonia
2. Hematopoietic (bloodforming) tissues: red bone marrow, spleen, lymph nodes, thymus
3. Basal cells of the skin
4. Epithelium of the gastrointestinal tract (interstitial crypt cells)

The law can be used to classify the following tissues as **radioresistant**:

1. Bone
2. Liver
3. Kidney
4. Cartilage
5. Muscle
6. Nervous tissue.

1.08.06 Identify primary and secondary reactions on cells produced by ionizing radiation.

PRIMARY AND SECONDARY EFFECTS

A great many agents can cause injuries to the human cell. When such injury occurs, the effects are the same regardless of the agent which caused the damage. Ionizing radiation produces damage to cells, but in a mostly nonspecific way; that is, other physical and chemical substances cause the same effects because the body responds the same to certain cell damage regardless of the cause.

Radiation passing through living cells will directly ionize or excite atoms and molecules in the cell structure. These changes affect the forces which bind the atoms together into molecules. If the molecule breaks up (dissociates), the fragments are called free radicals and ions, and are not chemically stable. Free radicals are electrically neutral structures with one unpaired electron. Because the cell has a higher water content, the most important free radicals are those formed from water molecules. For example, an excited H_2O^* molecule may dissociate into

$$H_2O^* \rightarrow H^\circ + OH^\circ$$

in which the hydrogen radical H° has an unpaired e^- and the OH° radical will have nine e^-, one of which will be unpaired. The free radicals are very reactive chemically, and when combining can produce hydrogen peroxide (H_2O_2), which is a chemical poison and is the most harmful free radical product. Further effects are produced when the radicals and ions interact with other cell material. In this way, damage is caused in a direct and indirect manner. The role that each type of action plays in the total damage to the cell is still an unsolved problem. Of the damage which is done, the effects are greatest in the nucleus of the cell, but injury to the cytoplasm can also cause serious effects in the cell.

The total effect on cell processes is a function of the dose of radiation. The cell processes will be affected in varying degrees up to the ultimate result - cell death. Some damage to the cell may be repaired. This can be accomplished by action of the cell itself, or by replacement of badly injured cells in a given tissue through mitosis of healthy cells. On the other hand, if the extent of the damage to an organ is quite large, the organ may not be able to repair itself, That is, damaged cells may show confused growth but eventually be unable to divide. Or the cells may begin to exhibit uncontrolled growth. Although many factors are important in assessing the total damage, it seems likely that most cell functions and structures can be impaired by radiation.

1.08.07 *Identify the following definitions and give examples of each:*

a. Stochastic effect
b. Deterministic effect

STOCHASTIC EFFECTS

Stochastic effects are those in which the probability within a population of the effect occurring increases with dose, without threshold. Any dose, therefore, has a certain probability, however low, of causing the effect. Stochastic effects may result from injury to a single cell or a small number of cells. Carcinogenic (cancer) and heritable effects are examples of stochastic effects. In these, once the effect is induced, the severity is already determined by the nature of the effect.

Stochastic effects are assumed to have some chance of occurring no matter how low the dose. DOE dose limits intend to limit the probability of stochastic effects occurring to an acceptable level. That is, any exposure to radiation involves a risk, and no risk should be undertaken without the expectation of a net benefit.

DETERMINISTIC EFFECTS

Deterministic, or (as previously labeled) non-stochastic, effects are those in which the severity of the effect varies with the dose. For these types of effects, a threshold dose exists. That is, if the dose is kept below the threshold dose, the effect will not be observed. Deterministic effects are considered to result from the collective injury of a substantial number of cells in the tissue. Examples of such effects are cataracts, skin ulcerations or burns, depletion of blood-forming cells in bone marrow, and impairment of fertility.

1.08.08 Identify the LD 50/30 value for humans

LETHAL DOSE

Not only do various organisms vary in their sensitivity to radiation, but individuals of the same species also react differently. Because of this biological variability, the dose which is lethal to 50% of the individuals exposed is used. The concept used is LD 50/30. LD 50/30 is defined as the dose of radiation expected to cause death (Lethal Dose) within 30 days to 50% of those exposed, without medical treatment. The best estimate for the LD 50/30 for humans is between 300 and 500 rads (3-5 gray), and is usually stated as 450 rad (4.5 gray).

1.08.09 Identify the possible somatic effects of chronic exposure to radiation.

EFFECTS OF CHRONIC EXPOSURES TO IONIZING RADIATION

Chronic radiation exposure effects involve a low dose over a relatively long period of time (weeks to years). The effects, if any occur, do not manifest themselves until many years after the exposure. Other than radiation sickness associated with acute exposure, there is no unique disease from radiation, but only a statistical increase in existing conditions. The following section discusses possible chronic effects from exposure to ionizing radiation. One possible effect from acute and chronic exposure that has received much attention is genetically based. These effects are addressed in the next section.

Cancer. With proper selection of animal species, strains, and dose, ionizing radiation may be shown to exert an almost universal carcinogenic action resulting in tumors in a great variety of organs and tissues. There is human evidence as well that radiation may contribute to the induction of various kinds of neoplastic diseases. Human evidence of this includes radium dial painters, radiologists early in the century, uranium miners, and atomic bomb survivors. The main sites of solid tumors are the breast in women, thyroid, lung and some digestive organs. These tumors have long latent periods (approximately 10 to greater than 30 years) and occur in larger numbers than leukemia. Leukemia (abnormal increase in white blood cells) has a much shorter latent period. The incidence peaks within a few years of exposure and returns to normal levels after about 25 years.

Cataracts. The lens of the eye is highly susceptible to irreversible damage by radiation. When the cells of the lens become damaged, they lose their transparency and a cataract is thus formed. Exposures as small as 600 to 900 R may produce a cataract, although the symptoms and signs may not be apparent for years after the exposure. The damaging effects of penetrating radiation to the lens of the eye may be cumulative, and repeated small doses may result in cataract formation.

Radiation induced effects are produced primarily by neutron and gamma radiation. Experiments with animals and human case histories indicated that neutron radiation constitutes the greatest danger, with gamma radiation of slightly less importance. Susceptibility to radiation induced cataract formation seems to be somewhat dependent on age. Radiation is more likely to produce cataracts in younger persons because of continuous growth of the lens (growing tissues are more radiosensitive).

Extensive irradiation of the eye may result in inflammation of the cornea or in an increase in tension within, and hardening of, the eyeball. These conditions usually

become manifest several weeks after the exposure and may terminate in loss of vision.

Life Span. In a number of animal experiments, radiation has been demonstrated to shorten life span. The aging process is complex and largely obscure and the exact mechanisms involved in it are, as yet, uncertain. Irradiated animals in these investigations appear to die of the same diseases as non-irradiated controls, but they do so at an earlier age. How much of the total effect is due to premature aging and how much to an increased incident of radiation induced diseases is still unresolved.

The study of small amounts of exposure to radiation for beneficial purposes is termed radiation hormesis. One pioneer in the field, Dr. Luckey of the University of Missouri, Columbia, stated in a 1982 article, "Extensive literature indicates that minute doses of ionizing radiation benefit animal growth and development, fecundity (ability to produce offspring), health and longevity. Specific improvements appear in neurological function, growth rate and survival of young, wound healing, immune competence, and resistance to infection, radiation morbidity (radiation sickness), and tumor induction and growth."

An extension of life and a lower incidence of cancer has been seen in rodents exposed to lower doses, (100 to 400 rads [1-4 gray]), over a lifetime.

1.08.10 Distinguish between the three types of the acute radiation syndrome, and identify the exposure levels and the symptoms associated with each.

ACUTE EFFECTS

Acute effects are classified as effects that occur within 1-2 months of the exposure. This definition is somewhat arbitrary in view of the various factors that can affect the length of time between the exposure and the effect. Normally, acute effects are only observed if the dose is greater than 10 rads (0.1 gray) and delivered over a short time (acutely).

Generally, the larger the dose, the shorter the time to produce an acute effect. For example, in the absence of medical treatment, the time between an acute dose and death is typically 1-2 months for 500 rad, compared with 1-2 days for 5000 rad.

At high dose rates the body repair mechanisms become less effective an the differences in the biological damage from low LET radiation disappear. As such, the concept of the equivalent dose does not apply to acute exposures greater that 15 rem (0.15 sievert). Above this, the exposure should only be expressed as a dose in rads. For example, the dose from gammas that would kill 50% of an exposed human population is estimated to be from 350 to 450 rads (3.5-4.5 gray),

one to two times the required neutron dose. At low doses however, the dose from gammas typically needs to be 5 to 10 times the neutron dose to produce comparable effects.

RADIATION SYNDROMES AND STAGES IN MAN

A syndrome is a combination of symptoms resulting from a single cause and occurring together so as to constitute a single clinical picture.

Large acute whole-body exposures in man may result in one of three radiation syndromes. At the lowest doses sufficient to produce one of these syndromes (200 - 1,000 rads [2-10 gray]) the primary affected tissue is the hematopoietic system. At higher doses (1,000 - 5,000 rads [10-50 gray]) the gastrointestinal tract is the critical tissue, although the hematopoietic system is also greatly affected. Above 5,000 rads (50 gray) we say that the dominant effects involve the central nervous system even though the hematopoietic system and gastrointestinal tract have been effectively destroyed by such a dose.

Each syndrome can be considered to progress through the following four stages: the prodromal (initial) stage; the latent phase; a period of illness; and recovery or death.

Prodromal Stage. This is the first set of symptoms that occurs following a sufficiently large acute dose. The symptoms may include nausea, vomiting and diarrhea (NVD) as well as anorexia (loss of appetite) and fatigue. The actual causes of the prodromal symptoms are unknown. To some degree, the time of onset of these symptoms is indicative of the magnitude of the dose, however, the appearance of these symptoms, especially nausea and vomiting, can also be induced psychologically.

Latent Phase. This is an asymptomatic period between the prodromal stage and the onset of symptoms of later stages. The higher the dose the shorter the latent phase. At sufficiently high doses the latent phase effectively disappears.

Illness. Many of the characteristics of the prodromal stage reoccur along with a variety of additional symptoms, i.e., ulcerations about the mouth, fever, etc.

Recovery or Death. With an acute dose above 1,000 rads (10 gray), death is almost certain, even with the best of medical care. It is generally believed that without medical attention death is certain above 600 rads (6 gray).

HEMATOPOIETIC SYNDROME

The hematopoietic system syndrome is produced by acute whole body doses of 200 to 1,000 rads (10 gray). Death, if it occurs, will primarily be a result of damage to the hematopoietic (blood forming) organs: red bone marrow, lymph nodes, spleen and thymus. Damage to other systems, notably the gastrointestinal tract, will also play a role.

Effects of Radiation on Blood Cells.

Lymphocytes. These are a type of leukocyte (white blood cell) responsible for antibody production. Lymphocytes are formed in the lymph nodes, the thymus and parts of the spleen.

Although mature lymphocytes do not divide, they are very radiosensitive and can be killed directly by radiation. Within 15 minutes of a dose as low as 10 rads (0.1 gray), the lymphocyte population can be seen to decrease. In fact, this decrease in the number of lymphocytes can be used to estimate the dose. Recovery of the lymphocyte population is slow.

Granulocytes. This type of leukocyte is produced in the red bone marrow and fights infection by engulfing foreign particles in the body. The granulocytes themselves are radioresistant but their lifespan is short (less than one day). This means that damage to their radiosensitive precursors results in a measurable decrease in the number of granulocytes within a few days of the exposure. Recovery of the granulocyte population is faster than that for lymphocytes.

Platelets. These cytoplasmic fragments are produced in red bone marrow. They are not true cells but nevertheless play an important role in promoting the coagulation of blood. Following acute whole body doses above 50 rads (0.5 gray), a decrease in the platelet population will occur in 2 - 5 days. Like granulocytes, they are radioresistant and any decrease in their number is due to damage to their precursor cells, the magakaryocytes. Their longer lifespan, approximately 4 days, means they disappear more slowly than granulocytes.

Erythrocytes. Erythrocytes are responsible for carrying oxygen from the lungs to the various tissues of the body. Comparatively long-lived, they have an average life-span of 4 months. Approximately one week after the exposure, a drop in the number of red blood cells will occur. This decrease is a result of damage to their radiosensitive precursors, the stem cells of the red bone marrow. The latter either stop dividing or die when they attempt to divide. For the victim to have any chance at recovery, some of these stem cells must survive the exposure.

Progress of the Hematopoietic System Syndrome.

Prodromal Stage. Following doses of 200 - 1,000 rads (2-10 gray) the prodromal stage with its associated NVD will occur within 1 to 5 days of the exposure.

Latent Phase. This asymptomatic period will last 1 to 3 weeks after the prodromal stage.

Illness. Following the latent phase a period of extreme illness begins. Characteristic symptoms of this period include NVD, fatigue, anemia (brought about by the decrease in the red blood cell population), fever, epilation (loss of hair), anorexia and petechial (pinpoint) hemorrhaging on the skin caused by damage to the lining of capillaries.

Death. Death, if it occurs, will be within 2 to 6 weeks of the exposure. The most probable causes of death will be *hemorrhaging* and *infection*. The hemorrhaging is caused by damage to the radiosensitive cells lining the fine blood vessels and is compounded by the reduced population of platelets. Infection occurs because the intestinal bacteria penetrate the damaged lining of the gastrointestinal tract. At the same time, the body's ability to fight infection is reduced due to a decrease in the number of white blood cells.

GASTROINTESTINAL TRACT SYNDROME

The gastrointestinal tract (GI) syndrome is produced by acute whole body exposures from 1,000 to 5,000 rads (10-50 gray). Survival is impossible. Death occurs from both the damage to the lining of the GI tract (resulting in *circulatory collapse*) and damage to the hematopoietic system.

Description of Gastrointestinal Tract Lining. Much of the lining of the gastrointestinal tract is covered with small finger-like projections called villi. Villi add to the effective surface area of the lining and thereby increase the capacity of the body to absorb nutrients. The cells on the surface of the villi are constantly migrating towards the tip of the projections where they are sloughed off. Mitotically active cells (crypt cells) at the base of the villi replace those that are lost. The turnover rate of these epithelial cells is high - they have an average life span from 1 to 3 days.

Effect of Radiation on GI Tract Lining. Sufficiently large acute exposures lead to the reproductive death of the rapidly dividing crypt cells. The cells covering the villi continue to be sloughed off but are no longer replaced. This deterioration of the lining of the GI tract then leads to a loss of body fluid, inadequate absorption of nutrients and infection from the intestinal area. Above 1,000 - 1,200 rads (10-12 gray) the crypt cells are completely destroyed thus preventing any chance for recovery.

Progress of the GI Tract Syndrome.

Prodromal Stage. Within a couple of hours of the exposure, the individual will demonstrate a sharp loss of appetite, upset stomach and apathy. Several hours later NVD will occur.

Latent Phase. By the third day after the exposure, the previous symptoms will have disappeared and the victim will appear healthy. The asymptomatic latent phase will last from 1 to 7 days.

Illness. A period of severe illness will follow the latent phase. This will include NVD, fever, apathy, anorexia and loss of weight.

Death. Death occurs within 3 to 12 days of the exposure. Once the cell renewal mechanism of the GI tract has been completely destroyed and cannot be replaced, death is inevitable. The causes of death include fluid and electrolyte losses (*circulatory collapse*) brought about by the destruction of the lining of the GI tract. These fluid losses also account for the loss of weight, diarrhea and thickening of the blood associated with the GI syndrome. Another contributing cause of death is infection. The latter can occur within 24 hours of the exposure as the bacteria that inhabit the GI tract invade the body across the damaged lining. Damage to the hematopoietic system simultaneously reduces the body's ability to cope with the infection.

CENTRAL NERVOUS SYSTEM (CNS) SYNDROME

The CNS syndrome is produces by acute whole body exposures above 5,000 rads (50 gray); exposure of the head alone may have similar effects. Survival is impossible. Death results from *respiratory failure* and/or *brain edema* caused from direct or indirect effects on the CNS.

Although the CNS syndrome is not well understood, it most likely involves a combination of cellular and vascular damage. In other words, there may be direct damage to the brain cells by the radiation and indirect damage mediated by effects on the blood vessels of the brain. The latter are known to be damaged by such doses of radiation. Fluid from the blood is lost through the damaged vessel walls into the skull cavity so the pressure inside the skull builds up. Perhaps pressure on certain areas of the brain, i.e., the respiratory center, may be most important, or it may be the change in the blood supply to the brain.

At these high doses, the individual stages of the central nervous system syndrome becomes so short that they cannot be distinguished. Following such exposures the individual may function coherently for a short while or immediately go into shock. Within hours the symptoms become very severe. Symptoms include vomiting, diarrhea, apathy, disorientation, and tremors. The victim is also likely to fall into a

coma. Death will be due to respiratory failure and/or brain edema and occurs within 30 hours.

1.08.11 Identify risks of radiation exposure to the developing embryo and fetus.

EMBRYOLOGICAL EFFECTS

The Law of Bergonie and Tribondeau indicates that the radiosensitivity of tissue is directly proportional to its reproductive capacity and inversely proportional to the degree of differentiation. It follows that children could be expected to be more radiosensitive than adults, fetuses more radiosensitive than children, and embryos even more radiosensitive.

Both experimental and clinical findings have shown that the human embryo is subject to severe radiation injury. A few of the types of human abnormalities reported in the literature are blindness, cataracts, mental deficiency, coordination defects, deformed arms and legs, and general mental and physical subnormality.

The degree and kind of radiation damage is dependent on the stage of development of the embryo. Most of the major organs in humans are developed during the period from the second to the sixth week post conception. The majority of the gross abnormalities which are produced by irradiation of the embryo occur during this critical period. Experimentally, doses as low as 25 rad (0.25 gray) have been shown to be effective in producing development changes if applied during this time. Irradiation of the embryo after the period of major organ development produces delayed and less obvious undesirable effects, such as changes in mental abilities, sterility, etc. A dose of 400 to 600 rad (4-6 gray) during the first trimester (excluding the first week) of pregnancy is sufficient to cause fetal death and abortion.

1.08.12 Distinguish between the terms "somatic" and "heritable" as they apply to biological effects.

HERITABLE EFFECTS

Human body cells normally contain 46 chromosomes, made up of two similar (but not identical) sets of 23 chromosomes each. The 46 chromosomes of the human are believed to contain on the order of 10_4 genes, and it is these genes that, when passed on to the next generation, will determine the physical and psychological characteristics of the individual.

Genes occur in pairs with each pair determining a body characteristic. For most gene pairs, one gene will dominate in producing a given characteristic. Dominant genes are those which produce their effects even when only one of them is present in an individual, while recessive genes produce their effects only when an individual has two of them which are identical. Consequently a recessive gene may be latent for a number of generations, until the union of sperm and egg cells which both contain the same recessive gene.

At conception, the set of hereditary characters from the father are united with those from the mother. As the individual develops, the 23 chromosome pairs (half from each parent) formed by the union of the egg and sperm are almost always duplicated without change. In some instances, however, the chromosome will fail to duplicate itself in every respect, a change occurring in one or more of the genes. This change, called a mutation, is essentially permanent, for the mutant gene is reproduced in its altered form.

Body cells are called "somatic" cells. Although every somatic cell contains all of the genes, most are not used. For example, a skin cell contains the genes for skin color and for eye color, but the gene for eye color is never used by the skin cell. If the gene for eye color is changed in a skin cell, there is no consequence.

Germ cells reside in the testes or the ovaries and are used to make sperm or ova. If a change occurs in a somatic cell, there may be some effect on the individual, but the change is not passed on to the progeny. However, if a change occurs in a germ cell, no visible injury will be sustained by the individual, but the effect may appear in future generations. Changes in the germ cells are "heritable", i.e., they can be inherited. Thus, somatic effects occur in the exposed individual, and heritable effects may occur in future generations.

It was shown in 1927 that ionizing radiation could produce mutation in the genetic material in animals. This indicates that similar effects are possible in humans, though no genetic effects of radiation have ever been observed in any human population.

Mutations induced by radiation do not differ qualitatively from those which occur naturally, and in any particular instance, it is impossible to determine whether the change occurred naturally or whether it was the result of exposure to radiation. Thus, the net effect of irradiation of the genetic material is to increase the frequency with which mutations occur. Scientists have searched for any such increases in mutation but found none. For example, the survivors of the Hiroshima and Nagasaki bombs have been examined for more than 50 years, but no measurable increase has been observed.

Most of the mutations produced by ionizing radiation are recessive, so that the possibility of a change occurring in the first generation following exposure is slight. However, genetic damage is irreparable, and since a gene determines its

own reproduction, the mutant gene will be reproduced and carried by the offspring. Mutated genes persist from generation to generation and accumulate in number until they are either eliminated by natural selection or are mated with identical genes and become expressed as changes in the inherited characteristics of individuals.

Approximately 99% of all mutations are considered to be undesirable. Heritable damage in humans can result in a decrease in life expectancy, inability to produce offspring, an increased susceptibility to disease, or any number of changes of lesser or greater importance.

Mutations of reproductive cells which produced only subtle changes are usually of more importance to a population than mutations which produce gross abnormalities. The more obvious changes usually lead to early death of the individual and reduce fertility in those that survive. Thus the harmful mutant is eliminated from the population by "natural selection." On the other hand, mutant genes which produce less damage may persist much longer, and thereby do harm, although of a less severe character, to a larger number of individuals. Mutations in somatic cells do not present a hazard to the population as a whole, but only affect the individual exposed.

Mutations of genetic material occur normally as a result of background radiation and ordinary physiological processes within the germ cells (called spontaneous mutations). It is generally believed that even the smallest amount of radiation will cause some increase in the normal mutation frequency, or, in other words, there is no threshold for genetic mutations resulting from exposure to ionizing radiations. However, most geneticists agree that the spontaneous mutation rate may be doubled without seriously endangering future generations. The dose of radiation which will double the natural mutation rate in man (doubling dose) is estimated to be greater than 100 rem (1 sievert) per generation. Since the number of children conceived by an individual generally diminishes after the age of thirty, and since the number of persons occupationally exposed is only a small percentage of the total population, the current regulations are believed to be genetically safe.

Table 1. Doses, Effects, and Sources on a Logarithmic Dose Scale

Dose[a] (rem or rad)	**Death?**	**Effect of Acute Uniform Dose**	**Source of Dose of This Magnitude**
>4,200,000	yes	>10°C temperature rise (water); >20°C temperature rise (paper)	Mail irradiation for biological sterilization of spores
10,000	yes	"prompt, immediate incapacitation"	U.S. Army 1 km from neutron bomb
3,000	yes	6000-9000 rads: tumoricidal dose; cerebrovascular syndrome; desquamation	criticality or severe accident; deliberate radiation therapy
1,000	yes	gastrointestinal syndrome; marrow ablation; erythema, epilation, sterility	1200 rads in leukemia therapy; max dose to Chernobyl fireman
300	?	50% die 60 days no medical care; bone marrow (hematopoietic) syndrome	Japanese A-bomb survivors; fluoroscopy in cardiac catheterization
100	no	mild clinical symptoms in some	teratogenesis in Japanese A bomb survivors unborn children
30	no	no clinical symptoms; chromosome aberrations	planned special exposure; lots of x-rays on same day
10		increased risk of cancer (?) and heritable ill-health (?)	nuclear medicine procedures
3		no observed effects in humans	5 rem/y occupational limit; bone scan, several x-rays
0.3		no observed effects in humans	1 dental x-ray; annual rad worker (NRC); annual background
0.01		no observed effects in humans	flight from Seattle to Tokyo

[a]Doses are in rads above about 100; in rems for all radiation or rads for low-*LET* below 100. (Strom 2003)

Course Title: **Radiological Control Technician**
Module Title: **Radiological Protection Standards**
Module Number: **1.09**

Objectives:

1.09.01 Identify the role of advisory agencies in the development of recommendations for radiological control.

1.09.02 Identify the role of regulatory agencies in the development of standards and regulations for radiological control.

1.09.03 Identify the scope of 10 CFR Part 835.

References:

1. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
2. U.S. Department of Energy, DOE-STD-1098-2008, "Radiological Control Standard".
3. 10 CFR Part 835 (2007) "Occupational Radiation Protection".

HISTORY OF STANDARDS

The task of setting exposure limits is both a vital and yet a very difficult undertaking. It is vital because workers must be protected from the harmful effects of ionizing radiation. It is difficult because of the many factors which enter into the effects which radiation produces. Even though a vast amount of data has been gathered and studied, there are still many areas where much work is needed before firm conclusions can be drawn. Nevertheless, in order to advance in the field of nuclear energy, people must work with radiation. Thus, certain levels must be set which will protect workers from undue exposure.

Because there are still several unknowns which must be evaluated, the setting of limits involves judgments which cannot be wholly based upon the present body of scientific knowledge. For this reason, the concept of an "acceptable risk" is used. In other words, the benefits are weighed against the potential damage and then limits are set at some level at which the most benefit to mankind will accrue. However, since all exposure is assumed to involve risk to the individual, exposures should always be kept as low as practicable. This implies that efforts be continually directed toward improving performance, techniques and safety designs to reduce exposures.

From time to time, these limits will be revised as new knowledge is gained. When some of the assumptions can be replaced by facts, then it becomes prudent to review the limits and perhaps make firmer recommendations. The whole history of the development of exposure limits points out this feature of re-evaluation in the light of current knowledge.

With the discovery of radioactivity and a consequent intensive investigation of the phenomenon, many people were subjected to very high dose rates, and it did not take long for deleterious effects to become manifest. As early as 1897, cases of skin damage began to appear.

Erythema Dose

Early efforts at control were hampered by a lack of quantitative methods. There were no units by which one could assess the amount of radiation. No one even knew what was how much, let alone, too much radiation! As a result of the use of radiation by doctors in treating patients, a unit called the erythema dose came into use. This was a highly qualitative unit; defined in terms of the amount of radiation which would produce a well defined reddening of the skin. It soon became apparent that this dose unit was not at all satisfactory. It varied not only with the type of radiation and the dose rate, but also with the response of different parts of the body. Thus, two people could receive the same supposed fraction of an erythema dose, yet one might show skin effects and the other none. This lack of a

certain value for this unit made protection work more or less of a trial-and-error process.

Around 1914, radiation began to be used in industry. The radium dial-painting process came into being, and x-rays were found useful for showing up flaws in materials. Larger numbers of people were now being exposed. No longer could the vague notion of erythema dose serve the purpose of a protection standard. Yet progress toward better standards still lagged because of lack of knowledge of the many complex factors which enter into radiation effects.

1.09.01 Identify the role of advisory agencies in the development of recommendations for radiological control.

ICRU, ICRP, AND NCRP

In 1925, at the First International Congress of Radiology, the International Commission on Radiological Units and Measurements (ICRU) was formed, mainly because of the lack of a suitable dosage unit of international acceptance. In 1928, this group adopted the definition of an international unit, the Roentgen. For the first time measurements throughout the world could be made in terms of the same unit. Over the years the ICRU has been the main force in defining and adopting units for use on an international basis.

At the Second International Congress of Radiology in 1928, the first international body concerned with protection standards was formed. At first known as the International Xray and Radium Protection Commission, this group is now called the International Commission on Radiological Protection (ICRP). This group discusses and reviews basic protection principles, and these recommendations then serve as a guide from which regulations can be drawn up by each country to suit its needs. Although this group acts only as an advisory board, it has had a tremendous impact on the field of radiation protection.

In 1934, the ICRP made its first recommendation of a tolerance level of exposure: 0.2 R/day. This limit remained in force until 1950. However, because of World War II, the ICRP did not meet between 1937 and 1950. This left much of the study of protection standards during this time to the national committees.

In this regard, one cannot help but mention the work done by the National Committee on Radiation Protection and Measurements (NCRP). This group was formed in the United States in 1929. The work of this body was coordinated by the National Bureau of Standards. The early recommendations of the Committee appeared in the National Bureau of Standards Handbooks. The NCRP recommendations as outlined in Handbooks 20 and 23, which have been superseded by later reports, served as the basis for protection practices during the

days of the Manhattan project. This was the name given to the project developing the atomic bomb. Many members of the NCRP were engaged in this program and were helpful in seeing that protection standards prevailed.

From the standpoint of protection problems, it is hard to believe the dramatic impact that the war years produced. Of course, most of this effect can be traced to the development of the atomic bomb. Before the war, most of the problems concerned rather low energy x-rays. Now, not only were there these to treat, but also other types of radiation with a wide range of energies. Added to this was the large increase of workers in the radiation field. Also, many new techniques and operations became a topic of real concern. New units would be needed to define the dose contributed by radiation other than x-rays. Large amounts of waste were now produced and methods of disposal would have to be worked out. With reactors in use, not only the workers, but also others not connected with the work, would have to be considered. The scope of the radiation field had enlarged to an undreamed of extent.

The NCRP met in 1946 to reorganize. At this time a number of subcommittees were formed to deal with the new problems more effectively. This resulted in the publication of a number of handbooks after the war which represented changes and additions to the old recommendations. The Committee was replaced by a non-profit corporation chartered by Congress in 1964 and is now known as the National Council on Radiation Protection and Measurements. The Council is the successor to the Committee and was formed to carry on the work begun by the Committee.

The Council is made up of the members and the participants who serve on a number of committees. These committees develop proposed recommendations on various aspects of radiation protection and radiation measurements, which when approved by the Council, are published as NCRP Reports. The initial report issued by the Council was NCRP Report No. 32.

The three organizations, ICRU, ICRP and NCRP, have figured prominently in the development of present day radiation protection practices. Although these bodies act as advisory boards only, much of the radiation protection philosophy which has evolved and which has been adopted by various regulatory agencies throughout the world, had its origins in the recommendations of these organizations.

Radiation Exposure Concerns

Over the years, the development of standards for radiation protection has evolved through several phases. Initially, the concern was for the protection of patients and medical personnel from external radiation from the use of x-rays for diagnosis and therapy. World War II produced a shift in emphasis due to the increase in the number, type and uses of radioactive materials. This introduced considerations about internal exposure and the dose to the general public. Finally, a concern over the potential genetic effects of radiation and the impact of long-term exposure at low dose rates emerged.

Data from biological studies seemed to indicate that one could not assume that all effects had a threshold dose. Also, in the case of gene damage, effects could be expected at very low doses. This implied that any dose, no matter how low, carried a certain risk of deleterious effects.

Efforts have been directed toward quantifying the risk associated with a certain level of exposure. If one assumes a non-threshold relationship, then any dose carries some risk of producing damage. Under this assumption, all exposure should be kept at the lowest practical levels. However, several factors need to be considered. Namely, the information available for the quantification of risks is imperfect so that our knowledge of the absolute value of the risks involved is not that complete. In addition, the assumptions of a risk by an individual, in general, presumes the willingness to chance the risk in exchange for some resultant benefit, which, ideally, exceeds the risk. Then, the resultant benefit which accrues, in a sense, justifies the risk. However, the resultant benefits in the case of radiation exposure are also poorly known. Therefore, the balancing of risk versus benefit in order to obtain a net benefit is not easily accomplished. For this reason, the prudent approach, adopted by both the ICRP and the NCRP is to keep exposures as low as reasonably achievable (ALARA).

Down through the years since the discovery of radiation, one can see the care and concern with which the problem of radiation protection has been approached. Back in the early days, the main problem was the gross somatic effects. Now, the main concern has switched from these blatant effects to the more subtle effects of radiation. As knowledge has been gained, it has become quite evident that more knowledge is needed.

In any case, the quest for knowledge in this field has not suffered and more and more groups have joined in the search. In addition to the work of the ICRP, NCRP, and ICRU, the National Academy of Sciences National Research Council has undertaken the study of biological effects. This group consists of a large number of scientists throughout the country. The reports issued by this body are in summary form and the group functions as an advisory body. Its purpose is to supply technical information as a basis from which regulations can be developed. On a world-wide scale, the United Nations has established a Scientific Committee.

Their report on the effects of atomic radiation has helped to supply much needed background information.

The results of continuing reviews of biological data have revealed two types of radiation effects. Those for which a practical threshold dose for occurrence can be demonstrated and those for which there is apparently no threshold. These are referred to as deterministic (nonstochastic) and stochastic effects, respectively. Deterministic effects can be prevented by limiting the dose to the individual to a value below the threshold dose for occurrence of the effects. Since stochastic effects presume that there is no threshold level, and that the probability of the effect occurring increases with dose, any dose represents some probability of producing that effect. For stochastic effects, one can only limit the probability of occurrence to some level (deemed acceptable) by limiting the radiation exposure. The ICRP has based its recommendations for a system of dose limitation on the features discussed above.

ICRP Basic Recommendations

From time-to-time, the ICRP has altered and updated its recommendations. In its current reports, the ICRP recommends a basic system of dose limitation which includes these three interrelated aspects:

(1) No practice shall be adopted unless its introduction produces a positive net benefit.

(2) All exposures shall be kept ALARA, economic and social factors being taken into account.

(3) The equivalent dose to individuals shall not exceed the recommended limits.

Federal Policy on Radiation Matters

Because of the scope of the nuclear energy field in this country, the Federal Radiation Council (FRC) was formed in 1959 (Public Law 86-373). This body advised the President concerning radiation matters and provided guidance for all Federal agencies in setting standards and in working with the States. While in existence, the Council issued eight staff reports. The FRC was abolished by Reorganization Plan No. 3 in 1970, and its responsibilities were transferred to the newly formed U.S. Environmental Protection Agency (EPA). The Office of Radiation Programs (ORP) of the EPA took over the activities of the FRC.

While in existence, the FRC provided the basic general philosophy of the Federal policy on radiation matters. This guidance was contained in their first two reports. Each Federal agency had the responsibility to determine specific regulations in its area of jurisdiction. In some cases, the guides could be exceeded but "...only after

the Federal agency having jurisdiction over the matter has carefully considered the reason for doing so in light of the recommendations in this staff report."

The recommendations of the FRC were approved in 1960 and formed the basis of the Federal radiation protection guidance. In 1981, the EPA drafted proposed revised recommendations in the Federal Register regarding occupational exposure, and solicited comments. Following review of the comments, and discussions during an interagency review, the conclusion was reached to revise the previous Federal guidance. The EPA believes that it is appropriate to adopt the general features of the ICRP approach in radiation protection guidance for use by Federal agencies for occupational exposure. The revised EPA guidance was approved and issued in January 1987. The recommendations replaced portions of the previous guidance which applied to workers exposed to ionizing radiation but did not change the previous guidance for exposure of the general public.

With respect to the Federal policy concerning radiation protection for diagnostic x-rays, the Bureau of Radiological Health of the U.S. Department of Health and Human Services has developed a set of recommendations which serve as the radiation protection guidance.

1.09.02 Identify the role of regulatory agencies in the development of standards and regulations for radiological control.

REGULATING AGENCIES

So far, our attention has been directed to those groups which supply recommendations for exposure levels and safe practices. The rest of this section will be concerned with the organizations which are charged with developing regulations. Of prime interest will be those groups which regulate radiation matters in this country.

Under the Atomic Energy Act of 1954, the United States Atomic Energy commission (AEC) was given the responsibility of regulating the atomic energy industry. The Act authorized the AEC to set up a licensing program to be augmented by whatever rules or regulations are deemed appropriate. The bases for these rules are: to protect the public health and safety, and provide for national defense and security. Under this mandate, the AEC was concerned with the development of regulatory guides.

The Energy Reorganization Act of 1974 abolished the AEC and established two agencies to perform the functions of the AEC. The U.S. Nuclear Regulatory Commission (NRC) has taken over the licensing and regulatory functions. The following materials are licensed and under NRC control: uranium and thorium or ores containing .05 % of these materials, special nuclear material (plutonium, U-

233, U enriched in U-233 or U-235), and by-product material (radioactive material resulting from producing or utilizing special nuclear material). The regulations of the NRC are set forth in the Code of Federal Regulations (CFR), Title 10. Part 20, Standards for Protection Against Radiation, deals specifically with the regulations for control of radiation hazards by the licensee. Other parts of Title 10 deal with licensing and regulatory requirements associated with the use of source, special nuclear material and byproduct material.

As part of its duties, the NRC is charged with the task of seeing that these measures prevail. This aspect requires inspection and review in order to assure this. This function is carried out by NRC personnel (inspectors) at regular intervals. Their job is to make the inspections and report their findings. In the event that a failure to comply is noted, the licensee is required to correct this.

Many of the states have taken up the task of setting up their own safety standards. The NRC has been directed to assist the states to assure that the state and Commission programs are compatible. These states are referred to as Agreement States.

The 1974, the Energy Research and Development Administration (ERDA) assumed responsibility of the remaining functions of the AEC. These activities related to energy research and development. In 1977, the U.S. Department of Energy (DOE) replaced ERDA. The DOE had issued occupational radiation protection standards which pertained to its own activities and to those of its contractors, not subject to licensing. These standards appeared in the DOE Orders, which replaced the Manual Chapters of the AEC. Standards specifically applicable to radiation protection were contained in DOE Order 5480.11. "Radiation Protection for Occupational Workers," and DOE/EH-0256T, the "Radiological Control Manual"; however DOE Order 5480.11 was replaced by 10 CFR 835 and the Radiological Control Manual is now a DOE standard (guidance) (DOE-STD-1098-2008).

1.09.03 Identify the scope of 10 CFR 835.

10 CFR 835

Rule 10 CFR 835, "Occupational Radiation Protection," was implemented because of the Price-Anderson Amendments Act (PAAA). Rule 10 CFR 835 allows DOE to convert the contractual standards in Orders to enforceable rules, thus enhancing contractor accountability for safety. The rule is supported by DOE issued Guidance Documents and a site-specific Radiation Protection Program (RPP). Full compliance with the rule was required by January 1, 1996. Similar to the NRC, the DOE is charged with inspections and enforcement of its contractors to see that they are in compliance with DOE Orders and rules. DOE may assess

civil penalties (including fines and jail time) to any person who has by action or omission knowingly and willfully violated, caused to be violated, attempted to violate, or conspired to violate any section of 10 CFR 835.

10 CFR 835 requires DOE activities be conducted with a written radiation protection program. And, some sites may still be contractually obligated to adhere to provisions of the DOE Radiological Control Standard.

The scope of 10 CFR 835 establishes radiation protection standards, limits, and program requirements for protecting individuals from ionizing radiation resulting from the conduct of DOE operations.

Safety in the shipment of radioactive substances is principally the responsibility of the U.S. Department of Transportation (DOT). Title 49 Transportation, of the CFRs, deals with hazardous shipments including radioactive materials.

From time-to-time, changes need to be made in various regulations. The CFR is revised through submission of changes proposed by an agency and the Federal Government to other governmental and private agencies and to the general public. Except for emergency rules, CFRs are revised by 1) identifying changes in the Semi-Annual Regulatory Agenda; 2) requesting comments in the Federal Register, with a schedule for receiving them; 3) holding public meetings (if required); 4) publishing a preliminary rule; 5) allowing a comment period; 6) publishing a draft rule; 7) allowing a comment period; and 8) publishing a final rule with an effective date. Other agencies of the Federal Government having an interest in the regulations for the shipment of radioactive substances are: Interstate Commerce Commission, Coast Guard, Federal Aviation Agency, Postal Service, DOE and the NRC. The Department of Transportation has made an effort to make its labeling system conform with the regulations of the International Atomic Energy Agency.

SITE SPECIFIC DOE ORDERS/STANDARDS

Insert site specific information addressing DOE Orders/Standards applicable to radiological control at the site, based on contracts.

DOE RADIOLOGICAL CONTROL STANDARD (RCS)

Radiological Control Policy

A key element of the Radiation Protection Guidance to the Federal Agencies for Occupational Exposure approved by President Reagan on January 20, 1987, and a fundamental principle underlying the RCS is:

"There should not be any occupational exposure of workers to ionizing radiation without the expectation of an overall benefit from the activity causing the exposure."

The Department of Energy is firmly committed to having a Radiological Control Program of the highest quality. This applies to those DOE activities that manage radiation and radioactive materials and that may potentially result in radiation exposure to workers, the public or the environment.

ALARA

Personal radiation exposure shall be maintained As-Low-As-Reasonably-Achievable (ALARA). Radiation exposure of the work force and public shall be controlled such that radiation exposures are well below regulatory limits and that there is no radiation exposure without commensurate benefit.

Ownership

Each person involved in radiological work is expected to demonstrate responsibility and accountability through an informed, disciplined and cautious attitude toward radiation and radioactivity.

Excellence

Excellent performance is evident when radiation exposures are maintained well below regulatory limits, contamination is minimal, radioactivity is well controlled and radiological spills or uncontrolled releases are prevented. Continuing improvement is essential to excellence in radiological control.

Standard Applicability and Control

The RCS recommends practices for the conduct of radiological control activities. The RCS states DOE's positions and views on the best courses of action currently available in the area of radiological controls. Accordingly, the provisions in the RCS should be viewed by contractors as an acceptable technique, method or solution for fulfilling their duties and responsibilities. The RCS should be used by DOE in evaluating the performance of its contractors.

The RCS is not a substitute for Regulations; it is intended to be consistent with all relevant statutory and regulatory requirements and shall be revised whenever necessary to ensure such consistency. Some of the RCS provisions, however, challenge the user to go well beyond minimum requirements. Following the course of action delineated in the RCS will result in achieving and surpassing related statutory or regulatory requirements.

1. The RCS is a living document. DOE intends to review and update provisions on a periodic basis to incorporate lessons learned and suggestions for improvement. The Chief, Health, Safety and Security Officer is responsible for this task. Recommendations to correct or improve the RCS are encouraged and should be sent to the Radiological Control Program Advisor of the Program Secretarial Official responsible for the affected work activity. Information copies should also be sent to the other members of the Radiological Control Coordinating Committee. The Program Secretarial Official will transmit such recommendations to the Office of Health, Safety and Security for consideration. The recommended wording of the change, as well as the basis and justification for the change, should be included.

2. The Department of Energy intends to incorporate by reference the provisions in the RCS into contracts or regulatory plans, as appropriate. These incorporated provisions shall be enforceable pursuant to the contract or underlying regulations. When incorporating a provision, DOE should approve an implementation plan that includes a compliance schedule.

3. In those cases where contractors or subcontractors are used to conduct DOE-funded radiological activities at DOE and non-DOE sites or facilities, and such organizations do not possess a U.S. Nuclear Regulatory Commission (NRC) or Agreement State license for the proposed activity, the application of the RCS is recommended. The lead Program Secretarial Official and the Office of Health, Safety and Security should be included in the review and concurrence process in these situations. In those cases at non-DOE sites or facilities where a specific activity is being conducted pursuant to an NRC or Agreement State license, the provisions of the RCS are not binding to that activity.

4. The RCS should be kept current and should be entered into the contractor document control system.

5. The provisions of the RCS do not apply to facilities and activities of the Naval Nuclear Propulsion Program, which are separately covered under Executive Order 12344 (42 U.S.C 7158, note) and patients undergoing medical treatment at a DOE or DOE-funded facility.

Compliance

The RCS is a guidance document and compliance is not mandatory, unless the contractor is contractually obligated to follow provisions of the RCS.

Site-Specific Manual

1. A Site-Specific Radiological Control Manual should be issued and endorsed by the contractor senior site executive. The Site-Specific Radiological Control Manual does not require review or approval by the DOE. One approach in the development of Site-Specific Radiological Control Manuals is to invoke the provisions of the RCS as written with site specific additions, supplements and clarifications clearly indicated, included in the appropriate chapters and directly referenced to the corresponding Article. The contractor senior site executive is that person at a DOE contractor-operated facility or site who has final on-site corporate authority and is often called President, General Manager, Site Manager or Director.

2. Management policies, requirements, expectations and objectives for the site Radiological Control Program should be clearly and unambiguously stated.

3. The Site-Specific Manual should be kept current and entered into the contractor document control system.

4. Where a site has multiple facilities, there should be one manual for the site and one Radiological Control Organization. If a prime contractor manages several DOE sites, effort should be made to have one corporate Radiological Control Manual that applies to all of that prime contractor's DOE sites. For a site that has multiple prime contractors, a common manual, with facility, contractor or building specific guidance to accommodate unique considerations, should be issued and endorsed by each contractor's senior site executive. For prime contractors who manage several sites but who also operate sites with more than one prime contractor, the site manual should take precedence over the corporate Radiological Control Manual.

5. Subcontractors should comply with the Site-Specific Radiological Control Manual.

6. Where DOE employees are conducting the transport of nuclear devices or components, a Program Specific Radiological Control Manual, based upon the provisions of the RCS, should be issued and approved by the DOE Field Office Manager. Controlled copies of such Manuals should be provided to the lead Program Secretarial Official.

Application of Requirements

1. The RCS assumes that most facilities or sites have organizations in place that generally meet the requirements presented in the text. It is not the intent of the RCS to unnecessarily create new or separate organizations if those functions can be incorporated into existing ones. For example, the Radiological Awareness Committee functions may be performed by an existing safety committee. It is expected, however, that the existing committee charter be revised to reflect the requirements and emphasis of the RCS. Similarly, titles such as Radiological Control Manager and Radiological Control Technician that are used in the RCS may locally be designated differently. A phased approach to transition to the use of the titles of positions in the RCS should be adopted. Corresponding position descriptions and organizational charts should be revised to accurately reflect required radiological responsibilities.

2. The degree of program formality and extent of the associated administrative process are expected to be commensurate with the radioactive material contamination and dose potential. For example, a site with an annual collective effective dose of one person-rem or less, that works with small quantities of unsealed radioactive material, would not be expected to have an ALARA program as complex as one required at higher dose sites. At low dose sites some program elements may be satisfied by brief policy statements.

Course Title: **Radiological Control Technician**
Module Title: **ALARA**
Module Number: **1.10**

Objectives:

1.10.01 Describe the assumptions on which the current ALARA philosophy is based.

1.10.02 Identify the ALARA philosophy for collective personnel exposure and individual exposure.

1.10.03 Identify the scope of an effective radiological ALARA program.

1.10.04 Identify the purposes for conducting pre-job and/or post-job ALARA reviews.

1.10.05 Identify RCT responsibilities for ALARA implementation.

INTRODUCTION

All personnel at a facility must be committed to the ALARA philosophy. The RCT can play a major role in establishing and maintaining that commitment by understanding its concepts. This lesson will familiarize the student with the ALARA concepts and the essential components of an effective ALARA program.

References:

1. NCRP Report No. 91 (1987) "Recommendations on Limits for Exposure to Ionizing Radiation".
2. U.S. Department of Energy, DOE-STD-1098-2008, "Radiological Control Standard".
3. 10 CFR Part 835 (2007), “Occupational Radiation Protection”.
4. ICRP Publication 37 "Cost-Benefit Analysis in the Optimization of Radiation Protection".

1.10.01 Describe the assumptions on which the current ALARA philosophy is based.

ALARA PHILOSOPHY

ALARA is an acronym for *As Low As Reasonably Achievable*. This term is based on the belief that exposure to certain agents could cause undesirable effects. The concept also implies that there is a relationship between the amount of exposure and the possibility of an effect; there is a risk involved in receiving the exposure. The basis for the ALARA philosophy is quite simple; if you reduce your exposure to certain agents, you reduce the potential risk of an unwanted effect. This basic philosophy is used for a number of agents. Radiation is only one of these agents. Since RCTs are concerned with radiation, its effects, and maintaining radiological controls, we use the ALARA concept to maintain exposures at an acceptable level. We use this concept to help other workers understand why we sometimes place controls and limitations on the work they perform.

WHY ALARA?

The ALARA philosophy is based on the assumption that exposure to radiation (among other agents) poses a risk. The cautious assumption that a proportional relationship exists between dose and effect for all doses (non-threshold concept) is the basis for ALARA. There may be some risk associated with any dose. This is also called the linear nonthreshold model of exposure.

The effects of high doses of radiation delivered acutely are well established and characterized. The challenge is in determining the effects of low-level doses over extended periods of time. Studies have been performed over the years and are ongoing still.

The studies that have shown measurable results are those of atomic bomb survivors and individuals involved in Nuclear incidents. These have shown that there is a relationship between dose and biological effects. However, these effects are only measurable at the higher doses. At lower levels there are some people who believe that small amounts of exposure are actually beneficial. As a practice, it is a generally accepted practice to limit radiation exposure to reasonable levels and take a conservative approach. Consideration must be given to what is an acceptable level of exposure to receive while completing a job or task. Careful analysis must be made to determine the benefits of the exposure received versus the benefit in completing the task or job. Many factors must be reviewed including; the total dose to be received, additional shielding possibilities, cost involved, overall risk to the workers based on dose, and whether the job or task really needs to be done.

OBJECTIVES OF ALARA PROGRAMS

The DOE and other regulating agencies have through their Orders and CFRs mandated that there should not be any occupational exposure of workers to ionizing radiation without the expectation of an overall benefit from the activity causing the exposure. All personal radiation exposure shall be maintained As-Low-As-Reasonably Achievable (ALARA).

Every facility and the DOE Complex, as a whole, will strive to keep radiation exposure to the work force and public well below regulatory limits and ensure that there is no radiation exposure without commensurate benefit. For a facility to meet its ALARA objectives it should first establish a program to maintain exposures ALARA. This program should be updated throughout the evolution of the facility. The program should consider:

- Design and modification of the facility and selected equipment and components to integrate the ALARA concepts.
- Updating the ALARA procedures and plans to reflect the current need of the facility.
- The availability of equipment, instrumentation and facilities necessary for ALARA program.
- Training facility workers and management as well as radiological control personnel in ALARA programs and reduction techniques.
- Overall cost or job completion benefit versus the risk involved in receiving the exposure.

ALARA CONCERNS

Implementation of ALARA concepts should be carried out through all phases of a facilities lifetime.

ALARA Program concerns include:

Engineering Features

- Discharge of radioactive liquid to the environment
- Control of contamination
- Efficiency of maintenance, decontamination and operations should be maximized
- Components should be selected to minimize the buildup of radioactivity

- Support facilities should be provided for donning and removal of protective clothing and for personnel monitoring
- Shielding requirements
- Ergonomics consideration
- Access control designed for hazard level
- Surfaces that can be decontaminated or removed
- Equipment that can be decontaminated

Area Arrangement
- Traffic patterns to allow access yet prevent unnecessary exposure
- Equipment separation
- Valve locations
- Component laydown/storage areas

Operations
- Inspection tour - access, mirrors, visibility
- Inservice Inspections - use of remote control equipment, TV, Snap on insulation, platforms, etc.
- Remote readout instrumentation
- Remote valve/equipment operators
- Sampling stations, piping, valving, hoods, sinks

Maintenance Needs
- Adequate lighting, electric outlets, other utilities
- Removal and storage areas for insulation/shrouding
- Relocation of components to low dose areas
- Workspace for maintenance personnel
- Lifting equipment
- Conditions that could cause or promote the spread of contamination, such as a leaking roof or piping need to be identified and corrected on a priority basis

Radiological Control Needs
- Access control
- Shielding adequacy and access plugs
- Temporary shielding and support structures
- Adequate ventilation
- Breathing air
- Contamination control - drip pans, curbs, drains, and routing
- Decontamination facilities
- Radiation monitoring equipment
- Communications

1.10.02 Identify the ALARA philosophy for collective personnel exposure and individual exposure.

COLLECTIVE DOSE PHILOSOPHY

When trying to adopt a conservative approach to reducing exposure to personnel it is important to keep two concepts in mind:

- Individual dose
- Collective dose

Individual dose is defined as the total dose received by a radiological worker due to occupational exposures. The DOE has established annual limits and each facility may have their own administrative guidelines to keep exposures low. It is extremely important for workers to understand that regardless of the controls and administrative guidelines that are set in place, ultimately, keeping their exposure low is their own responsibility.

Collective dose is defined as the total individual doses in a group or a population. This concept must be considered in the overall effectiveness of a program just as the individual dose must be kept in mind. Spreading dose among more workers versus higher individual exposures for fewer workers is a major ALARA issue. The DOE would like to see an overall reduction in both individual and collective doses used as the basis for determining the effectiveness of a facilities ALARA program.

While each DOE facility may handle the issue of collective versus individual dose differently, many situations may cause a facility to use both approaches. It is important however, that facilities avoid increasing the total number of workers to reduce the collective dose statistics. The focus should be on the reduction of risk for all workers based on sound work practices, current state of technology, economic factors, and social conditions. It is however, equally as important to ensure that exposure to other hazards has not increased as a result of lower exposure to radiation.

1.10.03 Identify the scope of an effective radiological ALARA program.

SCOPE OF ALARA PROGRAM

The ALARA program must be incorporated in everyday, routine functions as well as nonroutine, higher risk tasks. The involvement and commitment of all facility personnel, not just radiological control personnel, is also necessary to achieve the reduction of external and internal exposure.

For an activity to take place that includes exposure to radiation, the following conditions should be satisfied:

- The risks associated with projected radiation exposures should be small when compared to the benefit derived. This should be assessed for each activity.

- Further reduction in projected exposure is evaluated against the effort required to accomplish such reduction and is not reasonable.

Ownership

Each individual involved in radiological work must demonstrate responsibility and accountability through an informed, disciplined and cautious attitude toward radiation and radioactivity. Every one has responsibilities in this area.

Management responsibilities:

- Design and implement ALARA program
- Provide resources such as tools, equipment, adequate personnel
- Create and support ALARA Review Committee
- Approve ALARA goals
- Design and implement worker training

RCT responsibilities:

- Perform the functions of assisting and guiding workers in the radiological aspects of the job
- Knowledge of conditions at the work site
- Knowledge of work activities to be performed
- Identification of protective clothing and equipment requirements
- Identification of dose reduction techniques
- During work conduct, maintaining awareness of conditions
- Correction of worker mistakes
- Response to abnormal events

ALARA "group" - including facility/RC supervision/management responsibilities:

- Evaluate worker suggestions and provide feedback in a timely manner
- Participate in pre-and post-work meetings
- Keep abreast of ALARA techniques pertinent to operations on site
- Track facility performance in comparison to stated goals

ALARA REVIEWS

1.10.04 Identify the purposes for conducting pre-job and/or post-job ALARA reviews.

To ensure the ALARA concepts are incorporated into radiological work, it is often necessary to conduct ALARA reviews. These reviews can be conducted in many different ways and each facility may have its own preferences. Regardless of what each facility calls them, they are an important part of maintaining exposures at a reasonable level. These reviews are called by various names, the following is an attempt to outline what they are and how they are used;

Pre-job ALARA Reviews

For every task involving radiological work, sufficient radiation protection controls should be specified in procedures and work plans to define and meet requirements. Applicable ALARA practices shall be factored into the plans and procedures for each task or type of task. The practices shall be communicated to the workers through their supervision and Rad Con personnel to ensure that the worker is able to maintain their exposure ALARA.

Proposed ALARA protective measures shall be evaluated to ensure the costs are justified. This includes exposure cost as well as the financial costs. This type of review (Pre-job ALARA review) is usually performed by the ALARA group. The RCT may assist this process by supplying survey data to the ALARA group.

Pre-Job Briefing

The RCT has more responsibility at the pre-job briefing. Pre-job briefings are held with employees who will be involved in work activities involving radiological conditions. The technician will identify the effective dose reduction measures for the conditions, where the workers should stand to reduce their exposure, routes to take to minimize exposure, contamination control techniques, etc. Also workers should communicate the needs of the job to the RCT, tools required, length of the job, system breaches, etc.

Procedures will be reviewed, worker qualifications are verified, emergency procedures will be discussed. The RCT should be the leader in this discussion, but should be flexible to allow input from all the individuals involved in the work.

This should be an open forum where all questions need to be answered. By the end of the meeting, everyone should know what is expected of them, how to do it, and the conditions under which it is to be done.

To assist the RCT an ALARA pre-job briefing checklist may be used. This can consist of:

1) Scope of work to be performed
2) Radiological conditions of the workplace
3) Procedural and RWP requirements
4) Special radiological control requirements
5) Radiologically limiting conditions, such as contamination or radiation levels that may void the RWP
6) Radiological Control Hold Points
7) Communications and coordination with other groups
8) Provisions for housekeeping and final cleanup
9) Emergency response provisions.

Post-Job ALARA Reviews

Jobs determined by procedure and by unusual circumstances may require a Post-job ALARA review. This will ensure the overall effectiveness of job planning and implementation. These reviews are handled usually by the ALARA group. The RCT will participate by giving survey data and their opinions on how the job was performed and ways it may be performed better in the future. It is important to note that the good portions of the job must be stressed. This process is not just for the things that went wrong.

Unusual exposure events are investigated in this process to determine the root cause of things that did go wrong. Recommendations are made and corrective actions are then taken to prevent future reoccurrences of these events.

Post-Job Debriefing

A post-job debriefing gives the RCT and the workers the opportunity to critique the work performance. Although this will not affect the dose already received for a particular job it can be effective tool in reducing the doses that may be received the next time that job is performed. The information discussed at post-work meetings may include discussions of what went wrong and what could have been done differently to reduce the exposures received as well as what went right. The workers want to hear the good aspects of a job. This will help reinforce good practices so that they will continue to do them in the future. The Post-work briefings rely heavily on the input of each worker for information on how best to reduce exposure the next time that job is performed. Typical questions asked a post-job debriefing are:

1) Were there any problems performing the job in accord with the procedure?
2) Did you have the tools and equipment needed to perform the work? Could special tools ease the job?
3) Were there any unexpected conditions noted during the work? Could these conditions have been anticipated?
4) Were there any unexpected delays in the performance of the job? What was the cause of the delay?
5) Was temporary shielding used? Could the use of temporary shielding reduce exposures received for this job?

Do not limit yourself to just these questions. The briefing should be a dynamic exchange of information between all parties.

RADIOLOGICAL CONTROL TECHNICIANS

1.10.05 Identify RCT responsibilities for ALARA implementation.

The responsibilities of the Radiological Control Technician are many concerning the ALARA program. The RCT should participate in the ALARA Review process. The RCT can be instrumental in Pre-job briefings or reviews. They may help in identifying Radiological concerns and hold points. They could also assist in:

1) Tool and equipment requirements

2) Area Set-up

3) Worker preparation

4) Conduct of the job

The RCT is tasked with assisting other workers in maintaining their exposures ALARA. The RCT must be aware of their own exposure reduction needs. The RCT is expected to observe the worker to ensure that the radiological control requirements pertinent to the hazards present are taken and followed properly.

If the technician notices the worker not following good radiological work practices, on the spot corrections should be made. The technique that the RCT uses to convey problem corrections to the worker will have a direct bearing on the effectiveness of the correction. Do not talk "down" to the worker. Treat them as equals and explain your reasons for the change. This will be more effective than yelling or bossing the worker.

The RCT, however, does have Stop Work Authority. This is granted to all employees and all radiological control personnel. It is not something to be used lightly. The Rad Con Standard states three reasons when to exercise this authority when:

1) Inadequate radiological control

2) Radiological controls not being implemented

3) Radiological controls hold point not being satisfied

Before the RCT stops a job all the ramifications must be considered. It is important to keep in mind that SAFETY is ALWAYS the first concern.

Course Title: **Radiological Control Technician**
Module Title: **External Exposure Control**
Module Number: **1.11**

Objectives :

1.11.01 Identify the four basic methods for minimizing personnel external exposure.

1.11.02 Using the Exposure Rate = 6CEN equation, calculate the gamma exposure rate for specific radionuclides.

1.11.03 Identify "source reduction" techniques for minimizing personnel external exposures.

1.11.04 Identify "time-saving" techniques for minimizing personnel external exposures.

1.11.05 Using the stay time equation, calculate an individual's remaining allowable equivalent dose or stay time.

1.11.06 Identify "distance to radiation sources" techniques for minimizing personnel external exposures.

1.11.07 Using the point source equation (inverse square law), calculate the exposure rate or distance for a point source of radiation.

1.11.08 Using the line source equation, calculate the exposure rate or distance for a line source of radiation.

1.11.09 Identify how exposure rate varies depending on the distance from a surface (plane) source of radiation, and identify examples of plane sources.

1.11.10 Identify the definition and units of "mass attenuation coefficient" and "linear attenuation coefficient".

1.11.11 Identify the definition and units of "density thickness."

1.11.12 Identify the density-thickness values, in mg/cm^2, for the skin, the lens of the eye and the whole body.

1.11.13 Calculate shielding thickness or exposure rates for gamma/x-ray radiation using the equations.

INTRODUCTION

The external exposure reduction and control measures available are of primary importance to the everyday tasks performed by the RCT. In this lesson, we will address the DOE and Facility Administrative Exposure limits and the basic methods used for reducing radiation exposure. Various techniques such as time, distance, and shielding that are used to help reduce external exposure controls will be discussed. These techniques are useful to maintain personnel exposure below administrative and federal limits.

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1. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago
2. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
3. "Health Physics and Radiological Health Handbook"; Shleien; 1992.

BASIC METHODS FOR EXPOSURE REDUCTION

The goal of radiological control is embodied in the acronym "ALARA" which stands for As Low As Reasonably Achievable.

The Radiological Control organization shall make whatever reasonable efforts it can to reduce exposure to the lowest levels, taking into account economic and practical considerations.

1.11.01	*Identify the four basic methods for minimizing personnel external exposure.*

There are four basic methods available to reduce external exposure to personnel:

- **Reduce** the amount of **source** material (or reduce emission rate for electronically-generated radiation).
- Reduce the amount of **time** of exposure to the source of radiation.
- Increase the **distance** from the source of radiation.
- Reduce the radiation intensity by using **shielding** between the source and personnel.

EXPOSURE RATE DETERMINATION

In order to use the basic methods for controlling exposure, the technician must be able to determine the intensity of the radiation fields. The following equations are used to make this determination.

1.11.02	*Using the Exposure Rate = 6CEN equation, calculate the gamma exposure rate for*

A "rule-of-thumb" method to determine the radiation field intensity for simple sources of radioactive material is the *curie/meter/rem* rule.

1 Ci @ 1 meter = 1 R/hr

This thumb rule only applies to Cobalt-60. For other gamma emitters another equation can be used to estimate the dose rate at 1 foot or 1 meter.

To determine the gamma radiation field intensity (**I**) *in R/hr* at one foot from a radioactive point source use the following equation:

$$I_{1\,ft} = 6CEN$$

where:

C = source activity *in Curies* (Ci)
E = gamma energy *in MeV*
N = number of gammas per disintegration (photon yield)

1) Accurate to within ±20% for gamma energies between 0.05 MeV and 3 MeV.
2) If N is not given, assume 100% photon yield (1.00 photons/disintegration).
3) If more than one photon energy is given, take the sum of each photon multiplied by its percentage, i.e.
$[(\gamma_1)(\%_1) + (\gamma_2)(\%_2) + \cdots + (\gamma_n)(\%_n)]$.

For distances given in meters the equation may be written as:

$$l_{1m} = 0.5CEN$$

For short distances greater than 1 foot from the source, the inverse square law can be applied with reference to the dose rate at 1 foot, resulting in the following equation:

$$\mathrm{I} = \frac{(6\mathrm{CEN})(1^2)}{\mathrm{d}^2}$$

where: **d** = distance in feet;

For metric distances the equation becomes:

$$\mathrm{I} = \frac{(0.5\mathrm{CEN})(1^2)}{\mathrm{d}^2}$$

where: **d** = distance in meters

Example:

Determine the exposure rate at 10 ft for a 8 Ci point source of ^{60}Co that emits a 1.173 and 1.332 MeV gamma, both at 100% of the disintegrations.

$$lat10\,ft = \frac{\left[(6)(6)\left(\sum 1.173(1) + 1.332(1)\right)\right]\left[1^2\right]}{(10\,ft)^2} = 1.2R/hr$$

Sample Problem 1.11-1

Determine the exposure rate at 1 ft for a 1-Ci point source of Cesium-137 that emits a 662 keV gamma in 85% of the disintegrations.

Sample Problem 1.11-2

Estimate the exposure rate at 2 meters from a 1.8 Ci point source of ^{60}Co that emits two gammas (1.173 MeV and 1.332 MeV) for every disintegration.

Sample Problem 1.11-3

Calculate the exposure rate at 1 foot for a 400-mCi ^{192}Ir which emits the following gammas: 0.316 MeV (87%), 0.486 MeV (52%), 0.308 MeV (32%), 0.295 MeV (30%).

Note: Ir-192 emits other gammas at lower percentages, but these are not included.

SOURCE REDUCTION

1.11.03	*Identify "source reduction" techniques for minimizing personnel external exposures.*

The first method that should be employed to reduce personnel external exposure is source reduction. If a source can be eliminated or if its hazard potential can be significantly reduced, then other engineering means may not be necessary.

Various techniques are employed to accomplish external exposure reduction using source reduction.

Allow natural decay to reduce source strength

If the radioisotopes involved are short-lived, then waiting to perform the task may significantly reduce the hazard.

Sample Problem 1.11-4

A contaminated system pump has been replaced with a rebuilt pump and the replaced pump must be rebuilt prior to the next replacement. Assume the 1 Ci mixture of radionuclides contained in the pump has a half-life of 40 days. In 80 days what would the original activity in the pump be reduced to?

By waiting for natural decay to reduce the source strength, a considerable savings in external exposure can be achieved.

Move the source material to another location

- Decon the equipment or material through mechanical or chemical means to remove the source material prior to working in the area or on the equipment.
- Reduce the source material in the system by flushing equipment with hot water or chemical solutions and collect it in a less frequently occupied area.
- Discharge or remove the resin or filtering media prior to working in the area or on the system.
- Move the radioactive source (e.g., a drum, barrel or calibration source) to another location prior to starting work.

TIME SAVINGS

1.11.04	*Identify "time-saving" techniques for minimizing personnel external exposures.*

Personnel working in radiation fields must limit their exposure time so that they do not exceed their established permissible dose limits and are able to keep exposures ALARA. The longer the time spent in the radiation field, the greater the exposure to the individual; therefore, the amount of time spent in radiation fields should be reduced. The Radiological Control Technician needs to be aware that radiation exposures are directly proportional to the time spent in the field. If the amount of time is doubled, then the amount of exposure received is doubled. Various techniques are employed to reduce personnel external exposure by reducing the amount of time spent in radiation fields:

- Analyze and train using **mock-ups** of the work site. A particular task can be analyzed on a mock-up of the system to determine the quickest and most efficient method to perform the task. The team of workers assigned to the task can rehearse, without radioactive materials, so that problems can be worked out and the efficiency of the team increased prior to any exposure. By determining the most efficient method and rehearsing the task, the amount of time, and therefore the exposure, can be reduced.

- Use of **pre-job briefings** is an important part of any good ALARA program. Discussions at the pre-job briefing with the individuals assigned to the task can identify any potential problems not previously identified. Identifying personnel responsibilities and the points at which various individuals are required to be present can reduce the overall time required to perform the job.

- **Review job** history files. Review the files from previously completed tasks of the same nature to identify previous problems and spots where time could be saved.

- **Pre-stage all tools and equipment**. All tools should be staged prior to entry to prevent the worker from waiting in a radiation field for a tool to arrive by messenger or helper.

- **Pre-assemble equipment and tools outside the area**. Equipment that can be preassembled should be preassembled prior to any entry into the radiation field. Tools that require assembly, pre-testing, and/or calibration should be performed outside the radiation field.

- Use **time-limiting devices**. Time limitations for workers can be monitored and limited using various devices such as stopwatches, alarming dosimeters, or radio-transmitting dosimeters.

- Use **communication devices** such as walkie-talkies. Poor communication can lead to incorrect or poor quality work and prolonged waiting in the radiation field while supervisors or experts are contacted. Communication devices such as walkie-talkies or radio headsets can alleviate these problems and reduce the amount of time that is spent in the radiation field.

- Use a **team of** workers instead of allowing one individual to receive all of the exposure. Even if a task requires a minimum amount of time, if it would cause one individual to receive an exposure greater than allowable, a team of workers should be used to reduce the individual exposures. If a team of workers is used, good communications are necessary to ensure the total exposure for the job does not increase significantly.

- Use **experienced personnel**. The total time required to perform a job is reduced if experts are used instead of inexperienced personnel. Inexperienced personnel should not be trained in significant radiation fields.

1.11.05	*Using the stay time equation, calculate an individual's remaining allowable equivalent dose or stay time.*

The exposure received by personnel will increase as the time spent in the radiation field increases. The exposure received (X) is equal to the radiation field intensity times the exposure time, or:

$$X = \left(\frac{R}{t}\right)T$$

where:

$$\frac{R}{t} = \textit{dose rate}$$

$$T = \textit{length of time exposed}$$

Sample Problem 1.11-5

A worker is performing valve maintenance in a 120 mR/hr gamma radiation field and expects the work to take 90 minutes. What will his total exposure be for the job?

When the time allowed in a radiation field is calculated to prevent a worker from exceeding an allowable equivalent dose, it is called "stay time". Stay time is calculated as follows:

$$\textbf{Stay Time} = \frac{H_{allowable} - H_{received}}{\textbf{equivalent dose rate}}$$

where:

$H_{allowable}$ = *maximum allowable equivalent dose*

$H_{recieved}$ = *equivalent dose already accumulated*

Sample Problem 1.11-6

A worker must enter a 2.5 R/hr gamma radiation field to perform work as part of a team working on a radioactive effluent tank. His accumulated equivalent dose for the month is 120 mrem. If the monthly ALARA guideline is 600 mrem, what is his stay time in the area?

Sample Problem 1.11-7

An individual must enter a mixed gamma/neutron radiation field for emergency repair work. The radiation field consists of 2,500 mR/hr gamma, and 500 mrad/hr thermal neutron. Assuming the individual has received 340 mrem of his allowable 600 mrem for the month, what is the maximum stay time allowed?

Sample Problem 1.11-8

Assume the work in the previous example must take 35 min. to be completed, and a group of workers, with no previous exposure for the month, is available. How many additional workers (in addition to the first worker in Example 1.11-7) are needed to complete the emergency task if no one individual exceeds the ALARA monthly guideline?

DISTANCE

1.11.06	*Identify "distance to radiation sources" techniques for minimizing personnel external exposures.*

The intensity of the radiation field decreases as the distance from the source increases. Therefore, increasing the distance will reduce the amount of exposure received. *In many cases, especially when working with point sources, increasing the distance from the source is more effective than decreasing the time spent in the radiation field.*

Theoretically, a point source is an imaginary point in space from which all the radiation is assumed to be emanating. While this kind of source is not real (all real sources have dimensions), any geometrically small source of radiation behaves as a point source when one is more than a few source dimensions away. Radiation from a source is emitted equally in all directions. Thus, the photons spread out to cover a greater area as the distance from the point source increases. The effect is analogous to the way light spreads out as we move away from a single source of light such as a light bulb.

The radiation intensity for a point source decreases according to the **Inverse Square Law** which states that as the distance from a point source changes the dose rate decreases or increases by the square of the ratio of the distances from the source. The inverse square law becomes inaccurate close to the source (i.e., about 10 times the diameter of the source).

Calculations to show the relationship will be used later in this section.

Various techniques are employed to accomplish external exposure reduction by increasing the distance:

Remote handling tools/remote control devices

Tools, such as tongs or long-handled tools, are an effective means of increasing the distance from a point source to a worker. For very high radiation fields, remote control devices may be appropriate, especially if the task is performed frequently.

Remote observation by cameras or indicators

Gauges or meters can be moved to a location remote from the source of radiation. Closed-circuit television and video cameras can be used to allow observation of work activities or system operations from a location remote to the source of radiation.

Move work to another location

If the source of radiation can not be reduced, then possibly the work can be moved to a low exposure area. For example, if a pump or valve needs reworking, then an

exposure savings could be achieved by removing the component from the system and performing all repair work in a lower exposure area.

Maximize the distance

Maximize the distance during work from the source when possible. For workers or inspectors not actively engaged in the work activity in the radiation field, moving to a lower exposure rate "waiting" area can be effective. Identifying "low dose rate waiting areas" can notify workers of the location of the lowest exposure rate in an area or room. Be aware of the location of radiation sources at the worksite and locate the worker at a point farthest from the source. Work at arm's length and do not lie on or hug radioactive components.

Posting of areas

Posting of radiological areas based on radiation level is a method for increasing the distance between the workers and the radiation source.

Extendable instruments

Extendable radiation survey instruments, such as the Eberline Teletector, can reduce the exposure to the surveyor by increasing the distance.

POINT SOURCE CALCULATIONS

1.11.07	*Using the point source equation (inverse square law), calculate the exposure rate or distance for a point source of radiation.*

As previously mentioned, the exposure rate is inversely proportional to the square of the distance from the source. The mathematical equation is:

$$l_1 \left(d_1\right)^2 = l_2 \left(d_2\right)^2$$

where:

$l_1 =$ *exposure rate at 1st distance* $\left(d_1\right)$

$l_2 =$ *exposure rate at 2nd distance* $\left(d_2\right)$

$d_1 =$ *1st (known) distance*

$d_2 =$ *2nd (unknown) distance*

1) Assuming the attenuation of the radiation in the intervening space is negligible.
2) Assuming the dimensions of the source and the detector are small compared with the distance between them.

By algebraic manipulation, the equation can be used to determine the distance from a point source for a given exposure rate or the exposure rate at a given distance.

Sample Problem 1.11-9

A 1 Ci point source of ^{137}Cs has a gamma exposure rate of 3.38 R/hr at 1 ft. What would the exposure rate be at 3 ft?

Sample Problem 1.11-10

A 1 Ci point source of ^{60}Co has an exposure rate of 15.03 R/hr at 1 ft. At what distance would the exposure rate be 100 mR/hr?

The inverse square law holds true only for point sources; however, it gives a good approximation when the source dimensions are smaller than the distance from the source to the exposure point. Some sources, such as a pipe or tank, cannot be treated as a point source. These sources must be treated as line sources or large surface sources.

LINE SOURCE CALCULATIONS

1.11.08 Using the line source equation, calculate the exposure rate or distance for a line source of radiation.

The actual calculations for a line source involve calculus; however, the mathematics can be simplified if the line source is treated as a series of point sources placed side by side along the length of the source.

If the line source is treated in this manner, the relationship between distance and exposure rate can be written mathematically as:

$$l_1(d_1) = l_2(d_2)$$

i.e. the exposure rate is inversely proportional to the distance from the source.

1) Assuming the source material is distributed evenly along the line.
2) Assuming the point at which the exposure rate is calculated is on a line perpendicular to the center of the line source.
3) Assuming the width or diameter of the line is small compared to the length.
4) Valid to a point that is one half the distance of the longest dimension of the line source (L/2), beyond which the point source formula should be used.

Sample Problem 1.11-11

A small diameter pipe containing radioactive resin has a length of 10 ft. The exposure rate at 1 foot is 5 R/hr. What is the exposure rate at 4 ft?

Sample Problem 1.11-12

What would the exposure rate be at 15 feet for the same small diameter pipe?

PLANAR OR SURFACE SOURCES

1.11.09	*Identify how exposure rate varies depending on the distance from a surface (plane) source of radiation, and identify examples of plane sources.*

Planar or surface sources of radiation can be the floor or wall of a room, a large cylindrical or rectangular tank or any other type of geometry where the width or diameter is not small compared to the length. Accurate calculations for these types of sources require the use of calculus; however, a relationship can be described for how exposure rate varies with distance from the source.

When the distance to the plane source is small compared to the longest dimension, then the exposure rate falls off a little slower than 1/d (i.e. not as quickly as a line source).

As the distance from the plane source increases, then the exposure rate drops off at a rate approaching $1/d^2$.

The exposure rate versus distance calculations can be used to make an estimate of the radiation intensity at various distances. These estimates are valuable tools to estimate and verify the readings obtained from exposure rate meters.

MASS ATTENUATION COEFFICIENT

1.11.10	*Identify the definition and units of "mass attenuation coefficient" and "linear attenuation coefficient".*

The linear attenuation coefficient, μ, used in the photon attenuation equation is dependent on photon energy, chemical composition of the absorber (Z), and the physical density of the absorber. The linear attenuation is the probability of a photon interaction per path length and therefore has units of $(\text{length})^{-1}$ (typically cm^{-1}). When multiplied by length (as done in the exponent of e in the attenuation equation) the product is a unitless quantity as mathematically required for an exponent.

The linear attenuation coefficient will clearly change depending on the physical density of the absorber. It is desirable to express the probability of an interaction as a function of the amount of absorber encountered rather than the path length. This would be to represent the probability of an interaction by a value that is independent of density.

This is done by dividing the linear attenuation coefficient by the physical density, thus, "normalizing" the linear attenuation coefficient to the density of the material. The mass attenuation coefficient is the quantity obtained by dividing the linear attenuation coefficient by the physical density.

Mathematically:

$$\mu_m = \mu_l / \rho$$

where: μ_m = mass attenuation coefficient
μ_l = linear attenuation coefficient
ρ = physical density

When the units of the linear attenuation coefficient are cm^{-1} and the units of physical density are mg/cm^3 then the units of mass attenuation coefficient become cm^2/mg.

1.11.11	*Identify the definition and units of "density thickness".*
1.11.12	*Identify the density-thickness values, in mg/cm^2, for the skin, lens of the eye and the whole body.*

DENSITY-THICKNESS

The mass attenuation coefficient μ_m is used in the attenuation equation (from Lesson 1.07):

$$I = I_0 e^{-\mu_m x}$$

where: I = shielded (attenuated) radiation intensity
I_0 = unshielded radiation intensity
μ_m = mass attenuation coefficient
x = density-thickness value

When μ_m is used in the attenuation equation, x must have units of mg/cm^2 to cancel out the units of μ_m. With these units, x is called *density-thickness*. Density-thickness is a value equal to the product of the density of the absorbing material and its thickness. This value is given in units of mg/cm^2.

Recall that the density of any material is a measure of its mass per unit volume, as compared to the density of water. Water has a density of 1 g/cm^3, or 1000 mg/cm^3. According to ICRP 15, the density of soft human tissue is equal to 1000 mg/cm^3. Using this value we can calculate density-thickness values for various depths that radiation may penetrate into the human body and cause damage. For purposes of reporting radiation dose in accordance with 10 CFR 835, the tissue depths of concern are the skin (shallow dose), the lens of the eye, and the whole body (deep dose).

Table 1. Density-thickness Values for Human Body

Tissue	Depth	Density-thickness
Skin (shallow dose)	0.007 cm	7 mg/cm^2
Lens of the eye	0.3 cm	300 mg/cm^2
Whole body (deep dose)	1.0 cm	1000 mg/cm^2

The concept of "density-thickness" is important to discussions of radiation attenuation by human tissue, as well as detector shielding and windows, and dosimetry filters. Although materials may have different densities and thicknesses, if their density-thickness values are the same, they will attenuate radiation in a similar manner. For example, a piece of mylar used as a detector window with a density of 7 mg/cm^2 will attenuate radiation similarly to the skin of the human body.

These values can be used to design radiation detection instrumentation such that detector windows and shields have the same or similar density-thickness values. For example, some instruments use a detector window of 7 mg/cm^2. Any radiation passing the detector window would also penetrate to the basal layer of the skin on the human body and deposit energy in living tissue.

External dosimetry can be designed around these values such that equivalent dose is determined for the skin of the whole body, lens of the eye, and whole body. For example, a dosimeter filter may be designed as 1000 mg/cm^2. Any radiation passing this filter would also pass through the skin of the whole body and deposit energy in vital human organs.

SHIELDING CALCULATIONS

1.11.13 Calculate shielding thickness or exposure rates for gamma/x-ray radiation using the equations.

The simplest method for determining the effectiveness of the shielding material is using the concepts of half-value layers (HVL) and tenth-value layers (TVL).

One **half-value layer** is defined as the amount of shielding material required to reduce the radiation intensity to **one-half** of the unshielded value.

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$$

The symbol **μ** is known as the *linear attenuation coefficient* and is obtained from standard tables for various shielding materials.

One **tenth-value layer** is defined as the amount of shielding material required to reduce the radiation intensity to **one-tenth** of the unshielded value.

$$TVL = \frac{\ln(10)}{\mu} = \frac{2.3026}{\mu}$$

Both of these concepts are dependent on the energy of the photon radiation and a chart can be constructed to show the HVL and TVL values for photon energies.

Table 2. Half-Value Layers

Photon Energy (keV)	HVL (cm)			
	Lead (11.35 g/cm^3)	Iron (7.86 g/cm^3)	Concrete (2.4 g/cm^3)	Water (1.0 g/cm^3)
500	0.38	1.0	3.3	7.2
1000	0.86	1.5	4.5	9.8
1500	1.2	1.8	5.6	12.0
2000	1.3	2.1	6.4	14.0
3000	1.5	2.4	7.9	17.5

The basic calculational approach to photon shielding is to determine the existing exposure rate, decide on the desired exposure rate after shielding and then calculate how many HVL or TVL will be needed. The basic equation for using the HVL concept is:

$$l = l_0 \left(\frac{1}{2}\right)^n$$

where:

l = *Shielded exposure rate*

l_0 = *unshielded exposure rate*

$$n = \text{no. of HLVs} = \frac{\text{shieldthicknes}(cm)}{\text{HVLthickness}(cm)}$$

The basic equation for using the TVL concept is:

$$l = l_0 \left(\frac{1}{10} \right)^n$$

where:

l = shielded exposure rate

l_0 = *unshielded exposure rate*

$$n = no.\ of\ HLVs = \frac{shieldthicknes(cm)}{HVLthickness(cm)}$$

Sample Problem 1.11-13

Calculate the shielded exposure rate from a 500 mR/hr ^{137}Cs source with 5 cm of lead shielding. The HVL for ^{137}Cs and lead is 0.65 cm.

Sample Problem 1.11-14

Calculate the shielded exposure rate from a 7.4 R/hr ^{137}Cs source with 4 cm of lead shielding. The HVL for ^{137}Cs and lead is 0.65 cm.

Sample Problem 1.11-15

Calculate the #TVL and the thickness of lead required to reduce the exposure rate from a 7.5R/hr ^{60}Co source to less than 100 mR/hr. One TVL for ^{60}Co and lead is 4.0 cm.

Sample Problem 1.11-16

Calculate the #TVL and the thickness of lead required to reduce the exposure rate from a 450 mR/hr ^{60}Co source to less than 5 mR/hr. One TVL for ^{60}Co and lead is 4.0 cm.

SAMPLE PROBLEM ANSWERS:

1. 3.38 R/hr
2. 0.564 R/hr *or* 564 mR/hr
3. 1.715 R/hr
4. 0.25 Ci
5. 180 mR
6. 11.5 min
7. 3.9 min
8. 4 additional (each may stay maximum of 9 min)
9. 0.376 R/hr *or* 376 mR/hr
10. 12.26 ft
11. 1.25 R
12. 0.111 R/hr *or* 111 mR/hr at 15 ft
13. 2.4 mR/hr
14. 0.104 R/hr *or* 104 mR/hr
15. #TVL = 1.88; lead thickness = 7.5 cm
16. #TVL = 1.95; lead thickness = 7.8 cm

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Course Title: **Radiological Control Technician**
Module Title: **Internal Exposure Control**
Module Number: **1.12**

Objectives :

1.12.01 Identify four ways in which radioactive materials can enter the body.

1.12.02 Given a pathway for radioactive materials into the body, identify one method to prevent or minimize entry by that pathway.

1.12.03 Identify the definition and distinguish between the terms "Annual Limit on Intake" (ALI) and "Derived Air Concentration" (DAC).

1.12.04 Identify the basis for determining Annual Limit on Intake (ALI).

1.12.05 Identify the definition of "reference man".

1.12.06 Identify a method of using DACs to minimize internal exposure potential.

1.12.07 Identify three factors that govern the behavior of radioactive materials in the body.

1.12.08 Identify the two natural mechanisms which reduce the quantity of a radionuclide in the body.

1.12.09 Identify the relationship between the physical, biological and effective half lives.

1.12.10 Given the physical and biological half lives, calculate the effective half life.

1.12.11 Given a method used by medical personnel to increase the elimination rate of radioactive materials from the body, identify how and why that method works.

INTRODUCTION

Radiological control involves the protection of mankind and his environment from the harmful effects of exposure to radiation or radioactive materials. The tasks that make up the responsibilities of the RCT include those actions used to minimize the potential exposure of workers and include efforts at reduction of both internal and external exposures. This lesson is designed to familiarize the technician with those actions necessary to minimize the entry of radioactive materials into the body and the basis for those actions. Major topics include:

- Modes of entry into the body
- Preventive measures, their use, and their basis
- Metabolism of materials and elimination processes
- Assessment methods
- Definitions.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
2. "DOE Radiological Control Standard"; U.S. Department of Energy, 2008.
3. 10 CFR Part 835 (2007) "Occupational Radiation Protection".
4. "Health Physics and Radiological Health Handbook"; Shleien; 1992.

ENTRY OF RADIOACTIVE MATERIALS INTO THE BODY

1.12.01	*Identify four ways in which radioactive materials can enter the body.*

Knowledge of the ways in which radioactive materials enter the body is essential for two reasons. How radioactive material gets into the body must be known in order to design and implement measures to prevent entry. The mode of entry by which particular materials get into the body can influence the behavior of the materials.

Modes of Entry

Inhalation: Materials enter the body in the air that is breathed.

Ingestion: Materials enter the body through the mouth.

Absorption: Material enters the body through intact skin.

Entry through wounds:

(1) *Penetration:* Materials enter (passively) through existing wounds which were not adequately covered.

(2) *Injection*: Materials enter (forcefully) through wounds incurred on the job.

1.12.02	*Given a pathway for radioactive materials into the body, identify one method to prevent or minimize entry by that pathway.specific radionuclides.*

Preventive Measures

Inhalation: assessment of conditions, use of engineering controls, respiratory protection equipment

Ingestion: proper radiological controls and work practices

Absorption: assessment of conditions and protective clothing

Entry through wounds: not allowing contamination near a wound by work restriction or proper radiological controls if an injury occurs in a contaminated area.

Note that the preventive measures are designed to do one of two things: (1) minimize the amount of radioactive materials present which are available to enter the body, or (2) block the pathway from the source of radioactive materials into the body.

1.12.03	*Identify the definition and distinguish between the terms "Annual Limit on Intake" (ALI) and "Derived Air Concentration" (DAC).*
1.12.04	*Identify the basis for determining Annual Limit on Intake (ALI).*
1.12.05	*Identify the definition of "reference man".*
1.12.06	*Identify a method of using DACs to minimize internal exposure potential.*

ANNUAL LIMIT ON INTAKE AND DERIVED AIR CONCENTRATION

Assimilation of radioactive materials in the workplace occurs most often as a result of inhalation of airborne radioactive contaminants. With some nuclides, specifically tritium, absorption through the skin is also a major concern. To ease the control in the workplace, two limiting values have been calculated and are available for use in limiting the inhalation of radioactive materials. These limiting values are: Annual Limit on Intake (ALI) and Derived Air Concentration (DAC).

Annual Limit on Intake is the quantity of a single radionuclide which, if inhaled or ingested in one year, would irradiate a person, represented by reference man (ICRP Publication 23), to the limiting value for control of the workplace.

Derived Air Concentration is the quantity obtained by dividing the ALI for any given radionuclide by the volume of air breathed by an average worker during a working year ($2.4E3m^3$). The derivation of the Annual Limit on Intake is based on known metabolic processes for the nuclides involved and reference man.

Reference man defines the physiological makeup of an average man in terms of factors required for dose calculations and includes such items as height and other dimensions, mass, size and mass of organs. The metabolic processes are specific to the chemical and physical (solubility, particle size, etc.) form of the nuclide when they are known. When they are not known, the worst case information, or the most conservative conditions, are used. With all of this information and the limitations on the amount of dose allowed, the amount of a particular nuclide that would result in that dose can be calculated. The resulting quantities are the values that are listed for Annual Limits on Intake.

According to ICRP 23, reference man breathes at an average rate of 20 liters per minute, or 0.02 m^3/min. In the course of one working year, the total volume breathed would be:

$$\frac{0.02\text{m}^3}{\text{min}} \times \frac{60\text{min}}{\text{hr}} \times \frac{8\text{hrs.}}{\text{day}} \times \frac{5\text{days}}{\text{week}} \times \frac{50\text{weeks}}{\text{year}} = 2400\text{m}^3$$

As stated above, the DAC is equal to the ALI divided by the volume of air breathed by the average worker during a working year; that is:

$$DAC = \frac{ALI}{2400m^3}$$

10 CFR 835 "Occupational Radiation Protection," Section 1003 "Workplace Controls" states:

> During routine operations, the combination of physical design features and administrative controls shall provide that:
>
> (a) The anticipated occupational dose to general employees shall not exceed the limits established at § 835.202; and
>
> (b) The ALARA process is utilized for personnel exposures to ionizing radiation.

The mentioned subpart E (835.403 "Area Monitoring") establishes the requirements for air monitoring in the workplace. It states:

> (a) Monitoring of airborne radioactivity shall be performed:
>
> > (1) Where an individual is likely to receive an exposure of 40 or more DAC-hours in a year; or
> >
> > (2) As necessary to characterize the airborne radioactivity hazard where respiratory protective devices for protection against airborne radionuclides have been prescribed.
>
> (b) Real-time air monitoring shall be performed as necessary to detect and provide warning of airborne radioactivity concentrations that warrant immediate action to terminate inhalation of airborne radioactive material.

For control purposes within the facilities, we can take several preventive actions using these DAC values. Obviously, the measures used to minimize the concentration of airborne contaminants that exist remain the primary means of minimizing potential exposure. Minimizing the concentrations to below DAC values helps insure that workers could not exceed the ALI even if they were in the area continuously for long durations

and breathing air at those concentrations. In fact, 10 CFR 835 defines Airborne Radioactivity Areas as any area, accessible to individuals, where: (1) The concentration of airborne radioactivity, above natural background, exceeds or is likely to exceed the derived air concentration (DAC) values listed in appendix A or appendix C of Part 835; or (2) An individual present in the area without respiratory protection could receive an intake exceeding 12 DAC-hours in a week. Section 835.603 states that the words "Caution, Airborne Radioactivity Area" or "Danger, Airborne Radioactivity Area" shall be posted at each airborne radioactivity area.

Minimizing the stay of workers in airborne areas to short periods of time and augmenting installed engineering controls with respiratory protection equipment are two ways to reduce the concentration of contaminants in the air the workers are actually breathing.

The limitations imposed, in terms of dosage to exposed workers, are expressed as an annual limit. 10 CFR 835 does not specifically establish monthly or quarterly limitations; conceivably, a worker could be allowed to receive his/her full allocation of dose in a single event. In practice, this is not acceptable. Concentrations of contaminants in the air are monitored by continuous monitoring equipment and are supplemented by grab sampling as required. Engineering controls are augmented with respiratory protection equipment when airborne contaminants exceed or potentially exceed DAC values.

MOVEMENT OF RADIOACTIVE MATERIALS THROUGH THE BODY

1.12.07	*Identify three factors that govern the behavior of radioactive materials in the body.*

Unlike external exposure monitoring, there is no simple device which can be placed on or in the body to determine the quantities of radioactive materials in the body or the dose received by the individual as a result of irradiation of body tissues by these materials. Thus, when radioactive material enters the body, the assessment methods must be based on what happens to the materials, or what the body does with them.

Knowledge of normal metabolic processes within the body can be applied to radioactive materials. The body does not possess the ability to differentiate between a non-radioactive atom and a radioactive atom of the same element. Therefore, in terms of metabolic processes, the material is handled the same way.

Once the material is in the body, then its behavior is governed by the chemical form, its location in the body, and the body's need for that material.

- **Chemical form**: solubility
- **Location**: pathways
- **Body's need**: intake and incorporation vs. elimination.

Intake and Uptake

Two terms that are used frequently when discussing the entry of radioactive materials into the body are *intake* and *uptake*. Though sometimes used interchangeably, there is a difference between them.

Intake: the amount of radionuclide taken into the body

Uptake: the amount of radionuclide deposited in the body which makes its way into the body fluids or systemic system (i.e. blood).

Uptake is an older term used with earlier lung models used in assessing maximum permissible body burdens (ICRP 2). Intake is a newer term used with newer reference man models. (Intake is defined in the 10 CFR 835 Implementation Guide).

NORMAL METABOLIC PATHWAYS FOR MATERIALS IN THE BODY

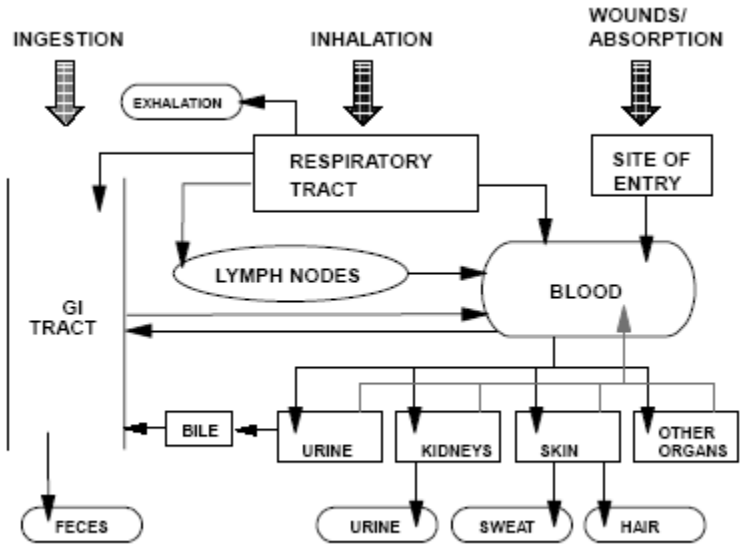

FIGURE 1. Metabolic Pathways

Inhaled Radioactive Materials

General pathways are

- Exhalation
- Deposition in lungs with eventual transfer to GI tract or retention
- Transport to body fluids
- Transfer to lymph nodes with eventual movement to body fluids
- Retention in lymph nodes.

Once in the bodily fluids, possibilities include:

- Transfer to specific organ
- Filtration and elimination by kidneys
- Transport and removal from body fluids through circulatory systems (perspiration)

Insoluble particulates

- Lung retention time based on particle size and density
- Removal in mucous to digestive tract
- Elimination in fecal waste

Soluble particulate materials

- Retention in lungs based on size and density - some exhalation
- Some removed to GI tract for elimination or to body fluids
- Transfer to body fluids via lymph nodes or directly from lungs
- Some retention in lymph nodes
- Body fluids to tissue or organ of interest
- Excretion

Ingested Radioactive Materials

For elements not used by the body, absorption by ingestion is poor, and most materials will pass straight through the body. Materials pass through stomach to small intestine where transport of soluble materials to body fluids will occur. From body fluids, materials go to the organs and/or are removed through normal biological elimination processes.

Soluble Materials

- Transfer to body fluids in intestines
- Circulation, absorption, incorporation in tissues and organs
- Elimination in urine

Insoluble Materials

- Passes straight through
- Elimination in feces

Absorbed Radioactive Materials

Many radioactive nuclides have been reported as absorbable through the skin. These nuclides include tritium, iodine, and some of the transuranics in an acidic form. Except for tritium, most of these do not pose any considerable concern because of the relative percentages absorbed as opposed to entry through inhalation. The most important of these is tritium as water vapor (e.g. if you were surrounded by a cloud of tritium existing as water vapor, you would receive 1/3 of your total exposure through absorption through the skin). Once absorbed into the body, tritium exchanged freely with hydrogen, disperses throughout the body almost immediately, and irradiates bodily tissues throughout the body.

Target Organs

Some elements are collected in target organs. As an example, iodine is collected by the thyroid gland. Major dose to the thyroid could be expected as a result of gamma and beta interactions emitted by iodine collected in the thyroid gland. The radiation emitted from iodine in the thyroid also can irradiate other nearby parts of the body. Gamma radiation can penetrate tissue very easily and cause interactions in parts of the body in which no iodine is located. Since all the iodine in the body is not in the thyroid gland, other parts of the body would also be irradiated as the iodine circulates throughout the body.

Other elements are processed differently. Some are distributed freely throughout body fluids. Some are collected in specific organs such as the kidneys, spleen or bone. Some materials which enter as particulate materials may spend the majority of their stay in the body in the lungs and are excreted through the digestive tract. Knowledge of material behavior is critical to assessing parts of the body affected and subsequent impact to the health of the individual involved.

1.12.08	*Identify the two natural mechanisms which reduce the quantity of a radionuclide in the body.*
1.12.09	*Identify the relationship between the physical, biological and effective half lives.*
1.12.10	*Given the physical and biological half lives, calculate the effective half life.*

NATURAL ELIMINATION PROCESSES

Once radioactive materials enter the body, there are two mechanisms which result in reduction of the quantities present.

Normal Biological Elimination

Radioactive materials that have been incorporated by biological functions into the body tissues and organs are eliminated from the body as are their non-radioactive counterparts. These materials are eliminated through the normal biological elimination processes of exhalation, perspiration, urination, and defecation. In most instances, when the body is not overwhelmed, biological elimination follows first order kinetics. In other words, each element has a measurable *biological half-life* which is the time required to reduce the amount of material in the body to one-half of its original value. If the body functions are overwhelmed, they are considered to be saturated. During the time period in which the body is saturated, the elimination rates may be vastly different and the concept of a biological half-life is not applicable. The biological half-life is independent of the physical or radiological half-life. Examples of measured biological half-lives include ^{3}H - 10 days and ^{60}Co - 9.5 days. (Note: these values will change slightly from one reference to another.)

Radioactive Decay

Each radioactive nuclide has a distinctive decay rate which is not influenced by any physical process, including biological functions. The amount of time required for one half of the material in the body to decay is called the radiological or *physical half life*. Radioactive decay will result in reduction of the quantity of the original nuclides deposited in the body. However, it is important to remember that the daughters of these nuclides may also be radioactive. Since most decay processes result in the transformation of one element to another, it is quite likely that decay processes would introduce completely different concerns for internal dose assessments

Effective Half-life

The combined processes of biological elimination and physical decay result in the removal of radioactive materials at a faster rate than the individual reduction rate produced by either method. This means that:

$$T_e < T_b, T_p$$

The removal rate as a result of the combined processes is measured as an effective half-life and is calculated using the following formula:

$$T_e = \frac{T_b \times T_p}{T_b + T_p}$$

where: T_e = effective half-life
T_b = biological half-life
T_p = physical half-life

Another way that this is expressed is the effective removal constant, λ_e, which is the composite of the physical decay constant λ_p and the biological elimination constant λ_b.

$$\lambda_e = \lambda_b + \lambda_p$$

EXAMPLE 1.12-1

Determine the effective half-life of tritium if the biological half-life is 10 days and the physical half-life is 12.3 years.

Solution found at the end of this module.

EXAMPLE 1.12-2

Determine the effective half-life of ^{59}Fe if the biological half-life is 2000 days and the physical half-life is 44.56 days.

Solution found at the end of this module.

1.12.11	*Given a method used by medical personnel to increase the elimination rate of radioactive materials from the body, identify how and why that method works.*

MEDICAL ELIMINATION-RATE INCREASE METHODS

Once the presence of radioactive material in the body is known, there are steps that can be taken by medical personnel to increase the elimination rates (biological), thus reducing the dose received as a result of the intake/uptake. **The important thing to remember about the use of any materials discussed below is that these methods *should be used only under the direction of a licensed physician*.**

Blocking Agents

A *blocking agent* saturates the metabolic processes in a specific tissue with the stable element and reduces uptake of the radioactive forms of the element. As a rule, these must be administered prior to or almost immediately after the intake for maximum effectiveness and must be in a form that is readily absorbed. The most well known example of this is stable iodine, as potassium iodide, which is used to saturate the thyroid gland, thus preventing uptake of radioactive iodine in the thyroid.

Diluting Agents

A *diluting agent* is a compound which includes a stable form of the nuclide of concern. By introducing a large number of stable atoms, the statistical probability of the body incorporating radioactive atoms is reduced. A good example is increasing water intake following ^{3}H exposure. Diluting agents can also involve the use of different elements which the body processes in the same way. This type of treatment is called *displacement therapy.* A common form of this is the use of calcium to reduce deposition of strontium. The compound used must be as readily absorbed and metabolized as the compound that contains the radioisotope.

Mobilizing Agents

A *mobilizing agent* is a compound that increases the natural turnover process, thus releasing some forms of radioisotopes from body tissues. Usually most effective within two weeks after exposure; however, use for extended periods may produce less dramatic reductions.

Chelating Agents

A *chelating agent* is a compound which acts on insoluble compounds to form a soluble complex ion which can then be removed through the kidneys. Commonly used to enhance

elimination of transuranics and other metals. Therapy is most effective when begun immediately after exposure if metallic ions are still in circulation and is less effective once metallic ions are incorporated into cells or deposited in tissue such as bone.

Common chelating agents include EDTA and DTPA

- CaNa-2 EDTA - commonly used in cases of lead poisoning, also effective against zinc, copper, cadmium, chromium, manganese, and nickel

- CaNa-3 DTPA - transuranics such as plutonium and americium

Diuretics

Diuretics increase urinary excretion of sodium and water. Diuretics are used to reduce internal exposure, however its use has been limited. Applications could include ^{3}H, ^{42}K, ^{38}Cl and others. Diuretics can lead to dehydration and other complications if not performed properly.

Expectorants and Inhalants

These are used to increase flow of respiratory tract excretions. Thus far this type of therapy has not been proven successful in removing radioactive particles from all areas of lungs.

Lung Lavage

This method involves multiple flushing of lungs with appropriate fluid to remove radioactive materials in the lungs. Usually limited to applications where resulting exposures would result in appearance of acute or subacute radiation effects.

SAMPLE PROBLEM SOLUTIONS

Sample Problem 1.12-1

$$\frac{12.3yrs}{1} \times \frac{365.25days}{1yr} = 4492.6days$$

$$T_e = \frac{10days \times 4492.6days}{10days \times 4492.6days}$$

$$T_e = 9.9978days$$

Sample Problem 1.12-2

$$T_e = \frac{2000days \times 44.56days}{2000days + 44.56days}$$

$$T_e = 43.589days$$

Course Title: **Radiological Control Technician**
Module Title: **Radiation Detector Theory**
Module Number: **1.13**

Objectives:

1.13.01 Identify the three fundamental laws associated with electrical charges.

1.13.02 Identify the definition of current, voltage and resistance and their respective units.

1.13.03 Select the function of the detector and readout circuitry components in a radiation measurement system.

1.13.04 Identify the parameters that affect the number of ion pairs collected in a gas filled detector.

1.13.05 Given a graph of the gas amplification curve, identify the regions of the curve.

1.13.06 Identify the characteristics of a detector operated in each of the useful regions of the gas amplification curve.

1.13.07 Identify the definition of the following terms:
a. Resolving time
b. Dead time
c. Recovery time

1.13.08 Identify the methods employed with gas-filled detectors to discriminate between various types of radiation and various radiation energies.

1.13.09 Identify how a scintillation detector and associated components operate to detect and measure radiation.

1.13.10 Identify how neutron detectors detect neutrons and provide an electrical signal.

1.13.11 Identify the principles of detection, advantages and disadvantages of a GeLi detector and an HPGe detector.

INTRODUCTION

In all aspects of radiological control, a knowledge of the characteristic and magnitude of the radiation field is essential in evaluating the degree of radiological hazard present. Radiation itself can not be detected directly. Because of this, radiation detection is

accomplished by analysis of the effects produced by the radiation as it interacts in a material. Numerous different methods of accomplishing this analysis have been developed

and implemented with varying degrees of success. Several of these have found extensive application in radiological control.

References

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
2. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
3. "Radiation Detection and Measurement"; Knoll, Glenn F.; Wiley & Sons; 2000.

Sources of Matter

Electrical theory is founded in the theory of the structure of matter. The term "matter" is used to describe anything that has weight and occupies space. Matter exists in one of three forms: liquid, solid, or gas, and it can be identified and measured. All matter is composed of atoms.

Atoms are the key to understanding electricity because atoms contain electrically charged particles. For example, the hydrogen atom contains one proton, which is positively charged, and one electron, which is negatively charged.

All atoms contain protons and *electrons*. Protons are always located in the center of the atom, an area called the nucleus. Electrons orbit around the nucleus. Protons are always positively charged, and electrons are always negatively charged, but the value of each charge is the same. In other words, if a proton has a charge of +1, then an electron has a charge of -1.

1.13.01 Identify the three fundamental laws associated with electrical charges.

Fundamental Laws for electrical charges:

1. **Opposite electrical charges of equal value cancel each other out.**
2. **Opposite electrical charges attract each other.**
3. **Like electrical charges repel each other.**

A proton and electron cancel each other out because a +1 charge cancels out a -1 charge. Therefore, when an atom contains an equal number of protons and electrons, the opposite charges cancel each other out, making the atom electrical neutral.

Because opposite charges attract each other, an atom tends to retain its general structure. The negatively charged electrons keep orbiting around the nucleus because they are attracted to the positively charged protons. A particle that is orbiting around another tends to move away from the second particle unless it is prevented from doing so. The attraction between the electron and the nucleus keeps the electron in orbit around the nucleus.

Movement of Electrons

Under certain circumstances, it is possible to remove some electrons from their orbits. A source of energy is required to detach electrons from their orbits, and a steady supply of energy is necessary to keep the detached electrons moving. The movement of electrons is what the term *electric current* actually refers to. Materials in which the energy required

to detach electrons from their orbits is low (such as copper and silver) readily conduct electric current and are known as *conductors*. Materials in which the energy required to

detach electrons from their orbits is very high (such as air and paper) resist the flow of electric current and are known as *insulators*.

Seven Sources of Energy

There are seven basic sources of energy that can be used to detach electrons from their orbits and sustain electric current. They are (1) friction, (2) heat, (3) pressure, (4) light, (5) chemical action, (6) magnetism, and (7) radiation. Friction, heat, pressure, and light are used primarily in specialized applications. Chemical action and magnetism are more commonly used to produce large amounts of electricity for general use.

Friction is the rubbing of one material against another. The rubbing causes electrons to leave one material and move to the other. As the electrons are transferred, a positive charge builds up on the material that is losing electrons, and a negative charge builds up on the material that is gaining electrons. The type of electricity produced by friction is called *static electricity*. Static electricity is more often a nuisance than a useful source of electricity.

A thermocouple is a common example of an electrical device that uses **heat** as its source of energy. The design of a thermocouple is based on the fact that heat will cause a small amount of electricity to move across the junction of two dissimilar metals. Two metals commonly used to make a thermocouple are copper and iron. Heat energy applied at the junction of the wires causes electrons to leave the copper wire and move to the iron wire. This movement of electrons is electric current, which can be measured. The amount of current flow is related to the temperature at the junction of the wire.

Pressure can be applied to certain types of crystals to produce electricity. The application of pressure to such crystals releases electrons from their orbits and thus causes current to flow. Some types of pressure measuring devices make use of this effect.

In some materials, **light** can cause atoms to release electrons. When this happens, current flows through the material. This current, produced by what is called a *photoelectric effect*, can be used to operate devices such as those that control the operation of street lights. Daylight shining on special material in this type of device produces a small current. The current operates a switch that shuts the light off in the morning. As long as there is current through the switch, the light remains off. At nightfall, there is no light to produce the current, so the light comes on.

Chemical action is one of the most common sources of energy used to produce electricity. Certain types of chemical reactions create electricity by separating the positive and negative charges in atoms. Batteries depend on chemical reactions to produce electricity.

Magnetism is the major source of energy used to produce electricity in large quantities because it is the most practical method. Generators use an effect of magnetism called *magnetic induction* to produce electric current. Magnetic induction is the generation of electric current in a conductor due to the relative motion between the conductor and a magnetic field. For example, if a conductor is moved between the conductor and a

magnetic field. For example, if a conductor is moved between the poles of a magnet, electrons will flow through the conductor.

Ionizing **radiation** can remove electrons from atoms and thereby create a flow of electrons or current. This includes alpha, beta, and gamma radiation.

1.13.02 Identify the definition of current, voltage and resistance and their respective units.

BASIC ELECTRICAL QUANTITIES

Current

Electrical current is the movement, or flow, of electrons past a given point in a circuit. Current is measured in units called amperes. An ampere actually refers to the rate of flow of electrons. One ampere is the flow of 6.24×10^{18} electrons past a given point in 1 second (one coulomb/second).

There are two types of current: direct current and alternating current. Direct current (DC) flows in only one direction. The flow of electrons in a DC circuit is similar to the flow of water in a piping system. Alternating current (AC) reverses direction as it flows. The electrons in an AC circuit flow back and forth continuously. Direct current is used to explain most of the concepts in this unit because direct current is easier to illustrate and to understand. In general, the concepts covered can be applied to alternating current as well, with some minor variations, which will be noted when they are applicable.

Voltage

Voltage is the electrical potential difference that causes electrons to flow in a circuit. Voltage is measured in units called volts. The voltage source in an electric circuit is similar to the pump in a piping system. The voltage source pushes electrons through the circuit in much the same way that the pump pushes water through the pipes. In industrial facilities, two common sources of voltage are batteries and generators.

Resistance

Resistance is the electrical quantity that opposes electron flow in a circuit. Resistance is measured in units called ohms. An *ohm* is defined as the amount of resistance that allows one ampere of current to flow in a circuit when there is one volt of force pushing the current.

All materials offer some resistance to current flow. The materials most often used in the manufacture of electrical equipment are generally classified as either insulators or conductors, depending on the amount of resistance they provide. Insulators offer a great deal of resistance to current flow, while conductors offer very little resistance.

Ohm's Law

The relationship between current, voltage, and resistance was described by George Simon Ohm in a form that is commonly referred to as Ohm's Law. Ohm's Law states that current is equal to voltage divided by resistance. This law is often expressed using symbols for each quantity. Using these symbols, Ohm's Law can be expressed as:

$$I = \frac{E}{R}$$

where: I = current (A)
E = voltage (V)
R = resistance (Ω)

The form of Ohm's Law can be changed to show two other aspects of the relationship between current, voltage, and resistance. The first of these is that voltage equals current times resistance, or E = IR; and the second is that resistance equals voltage divided by current, or R = E/I. Ohm's Law can be used in the appropriate form to determine one quantity (current, voltage, or resistance) in an electrical circuit if the other two are known, or to predict the effect that a change in one quantity will have on another.

1.13.03 Select the function of the detector and readout circuitry components in a radiation measurement system.

MEASUREMENT SYSTEMS

All radiation measurement systems consist of a detector and some sort of a readout circuitry. A detector may be combined with appropriate circuitry to form an instrument, or the detector and the readout may be separate (TLD + film, for example). (See Figure 1)

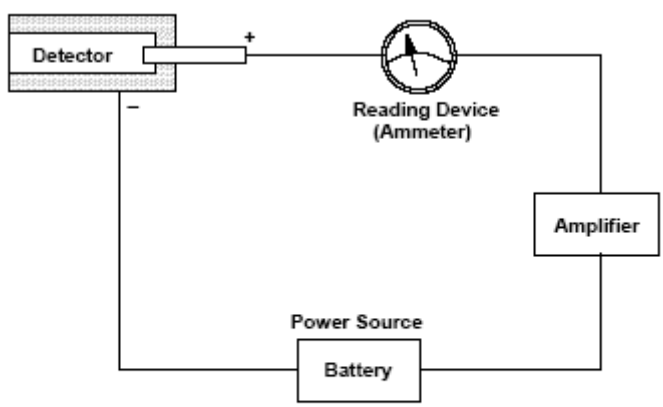

Figure 1. Basic Radiation Measurement System

Detector Function

In the detector, the incident radiation interacts with the detector material to produce an observable effect, be it a chemical change or creation of an electrical signal.

With a few exceptions, the effect caused by radiation incident on a detector is not permanent.

In these detectors the effect is observed as it occurs and yields a signal in terms of events per unit time. These detectors are typically used in association with rate meters, instruments which read out in terms of cpm, mR/hr, etc.

The exceptions occur mostly in dosimetry instruments. In these detectors, the effects are accumulated for analysis at a later time. Thus, instead of events per unit time, the accumulated effect caused by all events is measured. These detectors are often classified as integrating detectors.

Detectors are characterized by the type of interaction which produces the effect and the way in which the detector is operated.

Ionization Detectors

In ionization detectors, the incident radiation creates ion pairs in the detector. The ionization media can be either gas (most common) or solid (semi-conductors). Gas filled chambers can be operated as either ion chambers, proportional counters, or Geiger-Mueller (GM) tubes. A typical solid ionization detector is a GeLi detector used in a multichannel analyzer.

Excitation Detectors

In excitation detectors, the incident radiation excites the atoms of the detector material. The atoms give off the excess energy in the form of visible light. Thermoluminescent dosimeters (TLD) and scintillation detectors fall in this category.

Chemical Detectors

In chemical detectors, the incident radiation causes ionization or excitation of the detector media thereby causing chemical changes which can be analyzed. Film badges are an example of a chemical detector.

Other Detectors

There are a number of detectors that don't use ionization, excitation, or chemical changes. Examples are Cerenkov detectors, Activation foils, and Biological detectors.

1.13.03	*Select the function of the detector and readout circuitry components in a radiation measurement system.*

Readout Circuitry

Readout circuitry measures and analyzes the produced effect and provides a usable output indication.

There are two major categories of readouts. One is the rate meter, the other is the counter. Within these categories, there can be numerous different circuit arrangements.

Rate meters are used with detectors that supply either an electric pulse or current. These instruments provide an indication in terms of cpm, or mR/hr. Most radiological control instruments with a meter indication are rate meters.

Counters are used with detectors which supply a pulse. Each pulse is counted individually. The output indication is in terms of total events, either counts or dose. Most often, these counters are timer operated. Laboratory counters fall in this category. Often, laboratory counters are called *scalers*. More complex electronic systems, such as multi-channel analyzers and low background counting systems, are used to that provide more detailed and specific data than simple scalers.

Detector Yield

As all detectors measure radiation as a function of its observed effects, a correlation must be made between the effect and the incident radiation. For example, for all photons that enter a detector, only 25% may create an output pulse. This detector would be said to have a yield of 25%.

The less than 100% yield is caused by factors, such as size and shape of the detector; the characteristics of the detector materials; the energy of the radiation; and the probability of ionization for the radiation in the detector materials. The yield is concerned only with the detector.

Note, however, that detector yield is only a factor in overall instrument response to radiation. The position of the detector relative to the source, scatter, and self absorption of the radiation by the source itself are some of the factors involved.

GAS FILLED DETECTORS

Basic Construction

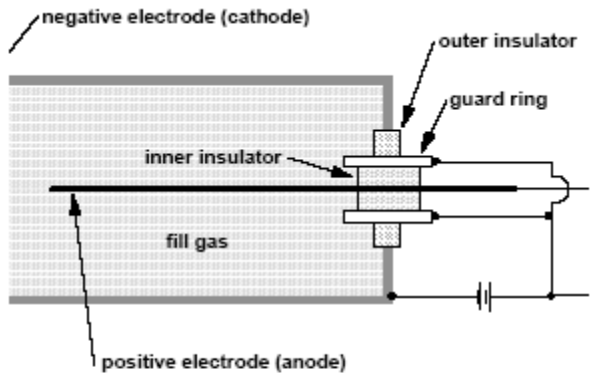

Figure 2. Basic Gas-filled Detector

Any contained gas volume that has a pair of electrodes can serve as a gas filled ionization detector. The detector can be almost any shape or size but is usually cylindrical. The cylinder walls are usually used as one electrode and an axial wire mounted in the center is used as the other electrode. Insulators support the axial electrode. It should be noted that the size, shape, and configuration is a function of the desired detector characteristics. *(See Figure 2)*

The gas used in the detector can be almost any gaseous mixture that will ionize, including air. Some ionization detectors, particularly ionization chambers use only air, while other detectors use gas mixtures that ionize more readily to obtain the desired detector response.

Basic Theory

A gaseous mixture in a normal undisturbed state has positive and negative charges which are balanced such that no net charge is observed. When a particle or ray interacts with the gas atoms or molecules (and in some gases, the detector materials), energy is added to the gas and one or more electrons may be split off of the parent atom or molecule. The most common process results in a single negatively charged electron, leaving behind a positively charged atom. Together the negative electron and positive atom (minus one electron) are called an *ion-pair*.

If left undisturbed, the negative ions can be collected by a positive ion and return to a neutral state.

If a voltage potential is established across the two electrodes, electric fields are set up in the gas volume between the electrons. In most detectors, the center electrode is positively charged, and the shell of the detector is negatively charged. If an ion pair is created

between the electrodes, the electron will be attracted to the center electrode, while the positively charged ion will be attracted to the detector shell. When either ion reaches the electrode, electric currents are set up. Because of mass differences, the electron reaches the electrode first. It takes up to 1,000 times longer for the positive ion to reach the side.

The amount of current flow is representative of the energy and number of radiation events that caused ionization. The readout circuitry analyzes this current and provides an indication of the amount of radiation that has been detected.

1.13.04 Identify the parameters that affect the number of ion pairs collected in a gas-filled detector.

Ion Pair Production

For a gas filled ionization detector to be of value for radiological control purposes, the manner in which the response varies as a function of the energy, quantity, and type of radiation must be known. **Factors such as the size and shape of the detector, the pressure and composition of the gas, the size of the voltage potential across the electrodes, the material of construction, the type of radiation, the quantity of radiation, and the energy of the radiation can all affect the response of the detector.** Detectors for a special purpose are designed to incorporate the optimum characteristics necessary to obtain the desired response.

Type of Radiation

Each type of radiation has a specific probability of interaction with the detector media. This probability varies with the energy of the incident radiation and the characteristics of the detector gas. The probability of interaction is expressed in terms of specific ionization with units of ion pairs per centimeter. A radiation with a high specific ionization, such as alpha, will produce more ion pairs in each centimeter that it travels than will a radiation with a low specific ionization such as gamma. In Table 1, note the magnitude of the difference between the specific ionization for the three types of radiation.

Energy of the Radiation

Review of the data in Table 1 will reveal that, generally, the probability of interaction between the incident particle radiation and the detector gas (and therefore the production of ions) decreases with increasing radiation energy. In photon interactions, the overall probability of interaction increases because of the increasing contribution of the pair production reactions. As the energy of the particle radiation decreases, the probability of interaction increases, not only in the gas, but also in the materials of construction. Low energy radiations may be attenuated by the walls of the detector and not reach the gas volume. Obviously, this must be accounted for in the design of the detector.

Table 1. Specific Ionization In Air at STP.

Radiation	Energy	Ion pairs/cm
Alpha	3 MeV	55,000
	6 MeV	40,000
Beta	0.5 MeV	110
	1 MeV	92
	3 MeV	77
Gamma	0.5 MeV	0.6
	1 MeV	1.1
	3 MeV	2.5

Quantity of Radiation

As the number of radiation events striking a detector increases, the overall probability of an interaction occurring with the formation of an ion pair increases. In addition, the number of ion pairs created increases and therefore detector response increases.

Detector Size

The probability of an interaction occurring between the incident radiation and a gas atom increases as the number of atoms present increases. A larger detector volume offers more "targets" for the incident radiation, resulting in a larger number of ion pairs. Since, each radiation has a specific ionization in terms of ion pairs per centimeter, increasing the detector size also increases the length of the path that the radiation traverses through the detector. The longer the path, the larger the number of ion pairs.

Type of Detector Gas

The amount of energy expended in the creation of an ion pair is a function of the type of radiation, the energy of the radiation, and the characteristics of the absorber (in this case, the gas). This energy is referred to as the ionization potential, or W-Value, and is expressed in units of electron volts per ion pair. Typical gases have W-Values of 25-50 eV, with an average of about 34 eV per ion pair.

Detector Gas Pressure

In the section on detector size, it was shown the probability of interaction increases with detector size. In many cases, there is a practical limit to detector size. Instead of increasing detector size to increase the number of "target" atoms, increasing the pressure of the gas will accomplish the same goal. Gas under pressure has a higher density (more atoms per cm^3) than a gas not under pressure, and therefore offers more targets, a higher probability of interaction, and greater ion pair production. For example, increasing the pressure of a typical gas to 100 psig increases the density by about 7 times.

Voltage Potential Across the Electrodes

Once the ion pair is created, it must be collected in order to produce an output pulse or current flow from the detector. If left undisturbed, the ion pairs will recombine, and not be collected. If a voltage potential is applied across the electrodes, a field is created in the detectors, and the ion pairs will be accelerated towards the electrodes.

The stronger the field, the stronger the acceleration. As the velocity of the electron increases, the electron may cause one or more ionizations on its own. This process is known as *secondary ionization*. The secondary ion pairs are accelerated towards the electrode and collected, resulting in a stronger pulse than would have been created by the ions from primary ionization.

Effect of Voltage Potential on the Detector Process

If the applied voltage potential is varied from 0 to a high value, and the pulse size recorded, a response curve will be observed. For the purposes of discussion, this curve is broken into six regions. The ion chamber region, the proportional region, and the Geiger-Mueller region are useful for detector designs used in radiological control. Other regions are not useful. In the recombination region, the applied voltage is insufficient to collect all of the ion pairs before some of them recombine. In the limited proportional region, neither the output current nor the number of output pulses are proportional to the radiation level. Calibration is impossible. In the continuous discharge region, the voltage is sufficient to cause arcing and breakdown of the detector gas.

1.13.05 Given a graph of the gas amplification curve, identify the regions of the curve.

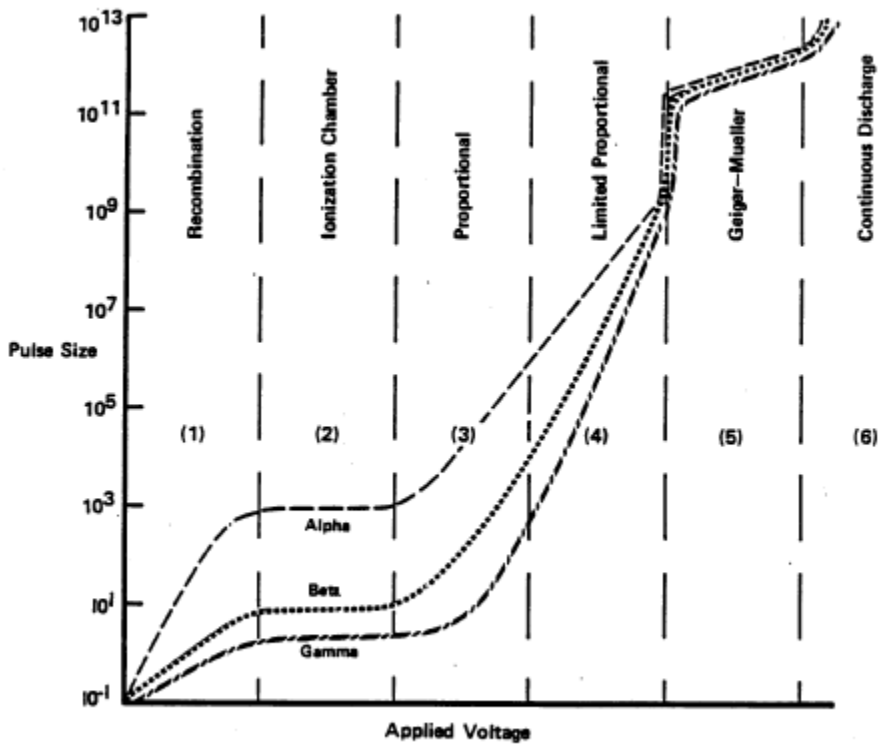

Figure 3. Six-region Curve for Gas-filled Detectors

1.13.06 Identify the characteristics of a detector operated in each of the useful regions of the gas amplification curve.

Ion Chamber Detectors

As the voltage to the detector is increased, a point is reached at which essentially all of the ions are collected before they can recombine. No secondary ionization or gas amplification occurs. At this point, the output current of the detector will be at a maximum for a given radiation intensity and will be proportional to that incident radiation intensity. Also, the output current will be relatively independent of small fluctuations in the power supply.

The output of a gas-filled detector when 100% of the primary ion pairs are collected is called the *saturation* current.

Advantages

- Output current is independent of detector operating voltage. Observe the flat region of the curve in the ion chamber region. As a result, less regulated and thereby less expensive and more portable power supplies can be used with ion chamber instruments, and still offer a reasonably accurate response.

- Since the number of primary ion pairs is a function of the energy deposited in the detector by the incident radiation, the ion chamber response is directly proportional to the dose rate.

- Since exposure (x) is defined in terms of ionization of air by photons, an air-filled ion chamber, when used for photon radiation, yields the true exposure rate.

Disadvantages

- Since only primary ion pairs created by each radiation event are collected, the output currents are small. Independent current pulses large enough to measure are not formed by each ionizing event. Instead, the total current output created by many ionizing events is measured. Therefore, the sensitivity of a small ion chamber is very poor because a few ionizing events per minute do not create sufficient currents to be measured. A typical commercial portable ion chamber has a detector which produces a current of about 2 E-14 amps per mR/hr.

- Another consequence of the small output current is the effect humidity can have on the instrument response. The electronics associated with the detector must have a high impedance (approximately 1 E15 ohms) to measure currents this small. The instrument incorporates insulators designed to maintain this high impedance. High humidity conditions can cause the formation of condensation on those insulators. (The resistance of relatively pure water is approximately 1 E7 ohms per centimeter.) This condensation creates leakage paths which causes erroneous instrument response.

- Since anything which changes the density of the gas affects the response, changes in barometric pressure (or altitude) and/or ambient temperature can affect instrument response in some cases. This is particularly the case with thin-walled chambers, vented chambers, or chambers with windows. For instance, the response of a typical commercial portable ion chamber instrument decreases by 2% for each 10 degree increase in temperature, or decreases by 2.3% for each inch of mercury decrease in barometric pressure (4.6% per psig).

<u>Typical Applications</u>

Portable survey instruments used for measuring dose rates are typically ion chamber instruments. Ion chambers may also be used in several installed monitor systems such as the Area Radiation Monitor Systems (ARMS) and the various Process Radiation Monitors (PRMs).

Proportional Detectors

As the voltage on the detector is increased beyond the ion chamber region, the ions created by primary ionization are accelerated by the electric field towards the electrode. Unlike the ion chamber region, however, the primary ions gain enough energy in the acceleration to produce secondary ionization pairs. These newly formed secondary ions are also accelerated, causing additional ionizations. The large number of events, known as an avalanche, creates a single, large electrical pulse.

In a proportional detector, the detector output is proportional to the total ionization product in the detector. For a constant voltage, the ratio between the primary ionizations and the total number of ions produced is a constant and is known as the *Gas Amplification Factor*. The gas amplification factors for typical proportional detectors range from a few hundred to about a million. Compare this with a Gas Amplification Factor of only 1 for ion chamber detectors.

Since the gas amplification in a proportional detector is large, the output pulses are large enough to be measured directly and individually. Since a single pulse is produced for each incident radiation particle or photon, it is feasible to directly measure the number of incident particles or photons which interacted with the detector. For this reason, a proportional detector is often used as a "proportional counter" and is normally used in instruments which read out in events per unit time, such as counts per minute. The total current, which is a function of the number of the pulses and the pulse magnitude, could be measured as is done with ion chamber detectors but this is only done in one type of portable dose rate instrument.

As with the ion chamber detector, increasing radiation energy, or high specific ionization radiations, will result in a larger pulse. Since we can measure the individual pulse, it is possible to analyze both the rate of incidence and the energy or type of radiation with a proportional counter. This allows for discrimination of different types of radiation or different radiation energies by varying the high voltage (which affects the gas amplification factor). When the voltage is increased, for example, the detectors output also increases.

1.13.07 Identify the definition of the following terms:
a. Resolving time
b. Dead time
c. Recovery time

Resolving Time

After the ion avalanche occurs, it takes a finite time for the ions to be collected and for the pulse to be generated. Similarly, it takes a finite period of time for the pulse to decay. If another ionizing event occurs elsewhere in the detector during this period, another avalanche may be initiated. When the ions reach the electrodes, they are collected along with remaining ions from the first event. The resulting pulse may not be distinguishable as two pulses by the associated electronics. The resulting reading will underestimate the

actual radiation field. The period of time between events, such that two distinguishable pulses result, is known as *resolving time*. **Resolving time is the total amount of time from a measurable detector response before another pulse can be measured**. In the proportional region, the resolving time is short, usually in the range of 0.5 to 1 nano seconds. This resolving time does not lead to problems at low count rates, but can result in a considerable error at high count rates. It should be noted that usually the associated electronics will have a resolving time longer than that of the detector.

Counter Construction

Proportional counters can be constructed using self-contained gas volumes or with continuously cleaning gas volumes. The latter is usually called a *gas flow proportional counter*. The detectors can also be constructed with the sample holder integral to the detector, eliminating the need for a detector window.

- Cylindrical Counter - This configuration is typical of the proportional counters used in portable survey instruments. The fill gas is commonly a hydrocarbon gas such as P-10 (methane and argon), but other gases have been employed. For example, BF_3 gas (boron trifluoride) is often used in detectors designed to count neutrons.

- Window 2π Gas Flow Hemispherical Counter - In this detector the gas volume is replenished continuously, ensuring a constant supply of target atoms. *(See Figure 4)* P-10 is the most commonly used counting gas. The geometry of the detector is such that, theoretically, almost 50% of the radiation's emitted from the source would be available for detection. (The terms 2π and 4π refer to the number of steradians around a point source in space. There are 2 steradians in a hemisphere, 4 in a sphere.) In reality, the actual percentage may be somewhat higher due to backscatter.

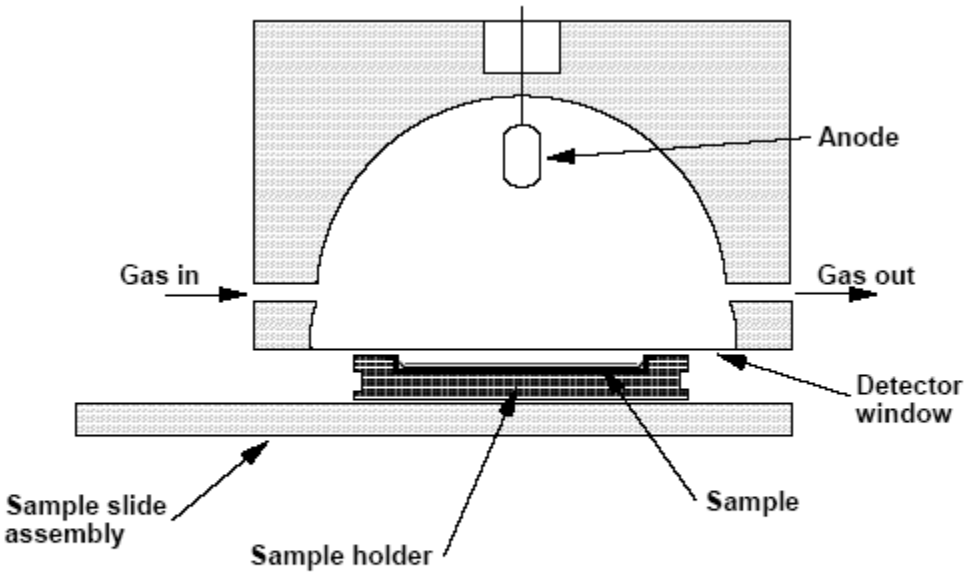

Figure 4. Basic 2π Proportional Detector w/ Window

- Windowless 2π Gas Flow Hemispherical Counter - This counter is similar to the 2π gas flow counter with the window. In fact, many of the gas flow proportional counters commercially available can be converted between window and windowless operation by a simple modification. In this counter, the source is effectively within the detector. This allows for the counting of low energy or low penetrating power radiation's which would have been stopped by the detector

- window.

- 4π Gas Flow Spherical Counter - With this counter, the source material to be analyzed is deposited on an extremely thin membrane. This membrane is then positioned between the chamber halves, and the gas purge started. This detector approaches the ideal 4π geometry. Because of the relative difficulty of use, this counter finds little application at power stations.

- Gas Flow, Flat - This is a commercially available alpha counter which is used in a portable alpha survey instrument. The counting gas is propane.

Proportional Counter Advantages

- A proportional counter can be used to discriminate between the different types of radiation.

- A proportional counter output signal is larger and therefore a single ionizing event can be recorded (good sensitivity).

- When measuring current output, a proportional detector is useful for dose rates since the output signal is proportional to the energy deposited by ionization and therefore proportional to the dose rate.

Proportional Counter Disadvantages

- A proportional counter is sensitive to high voltage changes because of the effect on the gas amplification factor. As a result, more highly regulated power supplies are necessary for proportional counters.

Typical Applications

Proportional counters find wide application in power stations. Gas flow proportional counters are commonly used for alpha/or beta counting on laboratory samples. Proportional counters are commonly used for neutron monitoring, from portable neutron survey instruments to nuclear reactor neutron flux instruments.

Geiger-Mueller Detectors

As the voltage on the detector is increased beyond the proportional region, the detector enters the limited proportional region. As mentioned before, this region is unusable for radiological control purposes. In this region the small individual avalanches which occur within the tube start to interfere with each other. This interference is unpredictable and reduces the overall output signal.

As the voltage is increased further, the secondary ions are also accelerated to very high velocities and gain sufficient energy to cause ionization themselves. These tertiary ionizations spread rapidly throughout the tube causing an avalanche. The avalanche, caused by a single ionization, results in a single very large pulse. The avalanche continues until the fields created by the produced ions interfere with the field created by the high voltage potential across the detector. When this occurs, the amount of acceleration decreases preventing further secondary ionization and halting the avalanche.

The output pulse size is a function of the gas amplification which occurs. In a GM tube, the gas amplification can range upwards from about 1 E8. Since the number of ions eventually produced and collected have no relation to the initial incident ionizing event, the pulse size is independent of radiation energy or specific ionization (a 0.1 MeV gamma creates the same size pulse as a 0.5 MeV gamma). For this reason, GM tubes cannot discriminate against different radiation types or radiation energies.

Any radiation event with sufficient energy to create the first ion pair can create a large pulse. For this reason, the GM detector is more sensitive than the ion chamber or proportional counter.

A GM detector can also be avalanched by the small amount of energy released by a positive ion when it is neutralized at the cathode. To prevent this undesirable occurrence, a quenching gas is added to the counting gas. Thus, instead of causing ionization, this excess energy is expended in dissociating the quenching gas molecules.

Dead Time and Recovery Time

In the discussion on proportional counters, we found that if the ionizing events occurred at too fast a rate, the output pulses created by these events may overlap, and as such cannot be counted as individual pulses. Although the resulting pulse is larger, the two pulses which caused it are approximately the same size (gas amplification remains relatively constant). The time between incident events such that individually distinguishable, measurable, pulses result is known as the resolving time. This time is about 100-200 μsec.

In GM detectors, resolving time has greater impact on detector response. **Resolving time is the time from the initial measured pulse until another pulse can be measured by the electronics.** Resolving time is controlled by the electronics.

Dead time is the time from the initial pulse until another pulse can be produced by the detector.

Recovery time is the time from the initial full size pulse to the next full size pulse produced by the detector. The recovery time includes a smaller interval of time known as the dead time. During the dead time, the detector can not respond to another ionizing event. The dead time occurs because of the effect that the large number of positive ions have on the voltage potential across the detector. In the recovery time, the detector can respond, but because of a reduced gas amplification factor, the output pulses are too small to measure. In most common day-to-day use, the resolving time is usually called the dead time since for all practical purposes, the detector is "dead" until a pulse large enough to trigger the electronics is created.

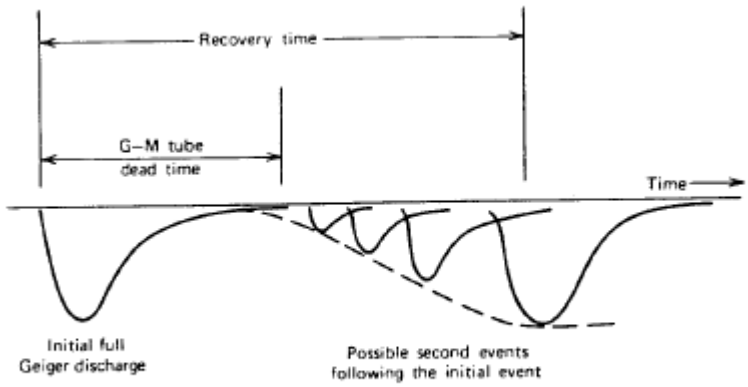

Figure 5. Dead Time of a GM Detector

The following sequence of events should help to explain the processes involved in GM detection.

- At time zero, the voltage potential across the detector is maximum. An incident radiation causes ionization, resulting in an ion pair.

- These ion pairs are accelerated towards the center electrode, thereby gaining energy.

- The primary ion pairs cause secondary ionization. The ion pairs created by the secondary ionization begin to accelerate towards the center electrode, thereby gaining energy. Since the potential is greatest near the center electrode, the bulk of the ionization occurs near the center electrode.

- The secondary ion pairs cause additional ionization and ion pairs. These ion pairs are accelerated and begin to cause ionization of their own. This process continues and an avalanche occurs.

- The negative ions (electrons) are collected by the center electrode and form a pulse. The positive ions form a cloud surrounding the center electrode. This ion cloud reduces the voltage potential across the detector. With a reduced voltage potential the gas amplification factor decreases such that secondary ionization stops, thereby halting the avalanche.

The events described above occur very rapidly, in the range of a fraction of microsecond. During this period the positive ion cloud is relatively stationary. The positive ion cloud is the cause of both the dead time and recovery time. Continuing:

- The positive ion cloud starts to drift towards the shell of the detector.

- As the cloud drifts, the voltage potential starts to increase.

- After about a microsecond (typically) the voltage potential is high enough to collect the electrons from another ionization should they occur. This is the end of

the dead time. If another event does occur, the pulse will be very small and probably not measurable as the detector voltage is in the ion chamber region.

- As the ion cloud continues to drift, the voltage potential continues to increase and gas amplification starts to occur. The detector is now in the proportional region. An event which occurs now will result in a large pulse. Whether or not this pulse is measured is a function of the input sensitivity of the electronic package.

- Eventually the gas amplification factor will increase to the point where an avalanche can occur when the positive ions reach the detector shell and are neutralized. At this point the detector has recovered and is ready for another radiation event. This time is about μ100-300 sec in typical detectors.

- During neutralization, the positive ions may release photons which in themselves could cause an avalanche if no quenching gas was present. Instead, the photons react with the molecules of the quenching gas, thereby dissipating their energy.

The effect of the long resolving time in a GM detector is to reduce the ability of the detector to measure high dose rates accurately. For example, with a 200 μsec resolving time, a count rate of 10,000 cpm will be measured as 9,700 cpm, an error of 3%. At 100,000 cpm, the measured count rate will be 75,000, an error of 25%.

There is another effect in GM detectors that is related to resolving time. If the incident radiation events occur at an extremely high rate, a string of small pulses will occur. These pulses prevent the GM detector from completely recovering. Since a full size pulse does not occur, the electronics will not indicate that any radiation is present.

GM Detector Construction

Although there is no technical reason why GM detectors cannot be operated as gas flow detectors, this is not commonly done. Almost all GM detectors which are encountered in radiological control work are cylindrical in construction.

Advantages of GM Detectors

- GM detectors are relatively independent of the pressure and temperature effects which affect ion chamber detectors. This is because of the magnitude of the output pulse.

- GM detectors require less highly regulated power supplies. This is because the pulse repetition rate is measured and not the pulse height.

- GM detectors are generally more sensitive to low energy and low intensity radiations than are proportional or ion chamber detectors.

  (There are exceptions.)

- GM detectors can be used with simpler electronics packages. The input sensitivity of a typical GM survey instrument is 300-800 millivolt, while the input sensitivity of a typical proportional survey instrument is 2 millivolt.

Disadvantages of GM Detectors

- GM detector response is not related to the energy deposited; therefore GM detectors can not be used to directly measure true dose, as can be done with an ion chamber instrument.

- GM detectors have a typically large recovery time. This limits their use in extremely high radiation fields. Dead time in a GM detector can be reduced by reducing the physical size of the detector. However, the smaller the detector, the lower the sensitivity. For this reason, wide range GM survey instruments, such as the Teletector or the E520, commonly have two GM detectors - one for the low ranges, one for the high ranges.

- GM detectors can not discriminate against different types of radiation (α, β, γ), nor against various radiation energies. This is because the size of the GM avalanche is independent of the primary ionization which created it.

Typical Applications

GM detectors are widely used in portable survey instruments at nuclear power facilities due to their ruggedness and the simplicity of the associated electronics. GM detectors are also used for personal monitoring for contamination (friskers), for process monitoring, and for area radiation monitoring. In addition, GM detectors are often used for laboratory counting when just a gross count is desired.

Comparison of the Various Radiation Detectors

When comparing the various detectors, one should keep in mind that exceptions are possible, (e.g. a large, pressurized ion chamber may be more sensitive than a small GM detector, even though, as a class, GM detectors are more sensitive than ion chambers.)

1.13.08 Identify the methods employed with gas-filled detectors to discriminate between various types of radiation and various radiation energies.

DISCRIMINATION

In the sections above, discrimination of radiation types and radiation energies was introduced. Discrimination plays an important role in radiation measurement. In nuclear power stations, "pure" radiation fields seldom exist. There is usually a combination of gamma, neutron, beta, and sometimes alpha. These radiation types also exist at various radiation energies.

In the complex radiation fields such as this, it becomes difficult to measure one radiation in the presence of others - a detector that responds to alpha and beta radiation will often also respond to gamma. Discrimination makes it possible to separate (to some extent) the different radiation types or radiation energies.

Physical Discrimination

Shielding

Shielding is the most common method of discriminating against certain radiation types or energies in radiation measurements. A thin metal window will stop the majority of alpha particles. A thicker metal window will stop beta particles. Unfortunately, this process only works by discriminating against lower energies or radiations with low penetrating power. Gamma radiations cannot be shielded against without affecting response to beta or alpha.

Shielding is sometimes used on GM detectors to obtain a smoother energy response curve.

Detector Gas Fill

Each type of radiation has a specific ionization factor in a particular gas. In addition, each different detector gas has a different response to various radiation energies. By employing the most advantageous gas, a detector can be constructed that will have a higher yield for a specific radiation type or radiation energy than it will for other radiation types or energies.

A specific example of this is the use of BF_3 gas in proportional detectors to measure neutrons. In these detectors, the incident neutron fissions boron into lithium and an alpha particle. This alpha particle has a much higher specific ionization than does a gamma photon. The pulses created by neutrons are much larger than those created by gamma. The electronics sort out the pulses by pulse height.

Electronic Discrimination

In the previous sections, we found that in the ionization chamber and proportional regions, the output pulse height was a function of the specific ionization of the radiation, and the incident radiation energy. Because of the small pulse size, ion chambers are usually not used for discrimination. Proportional counters are often used to discriminate between radiations and sometimes between radiation energies. The proportional gas flow counter used in counting rooms to measure alpha and/or beta sources is an example of such an application.

Analyzing pulse heights is the primary method of electronic discrimination. Almost all electronic packages used with radiation detectors have an adjustable input sensitivity (often called discriminator level). By adjusting the input sensitivity to the desired value, we can chose the minimum pulse height which will be measured. All pulses smaller than this preselected pulse height will be rejected and not counted. For example, if we have set the input sensitivity to measure only the large alpha pulses, the smaller beta or gamma pulses will be ignored. The readout, then, will indicate only alpha radiation.

Some electronics packages also have an adjustable upper discriminator. In these circuits, pulses that are too large will not be counted. The resulting band between the lower and upper discriminators is called a window. Only pulses which fall within the window will be counted. By changing the upper and lower discriminators, an unknown radiation field or sample can be analyzed to determine which type of radiation or which energies of radiation exist in the field or in the sample. This process is called pulse height analysis.

In proportional counters, it is common practice to leave the discriminators on one setting and to vary the high voltage supply instead. As you remember, increasing the high voltage, increases the gas amplification factor, which in turn increases pulse height, and vice versa. Thus, alpha radiation would be measured at one voltage, alpha and beta at a higher voltage (subtracting the alpha count from the alpha + beta count yields the beta count).

1.13.09 Identify how a scintillation detector and associated components operate to detect and measure radiation.

SCINTILLATION DETECTORS

Scintillation detectors measure radiation by analyzing the effects of the excitation of the detector material by the incident radiation. Scintillation is the process by which a material emits light when excited. In a scintillation detector, this emitted light is collected and measured to provide an indication of the amount of incident radiation. Numerous materials scintillate - liquids, solids, and gases. A common example is a television picture tube. The coating on the screen is excited by the electron beam, and emits light. A material which scintillates is commonly called a phosphor or a fluor. The scintillations are commonly detected by a photomultiplier tube (PMT).

Scintillation Detector Components

Each scintillation detector is comprised of two major components, the phosphor or fluor, and the photomultiplier tube. Various different phosphors and photomultiplier tubes are available, and numerous combinations of these are possible. The combination chosen is selected to achieve the desired response to radiation and other requirements of a particular application.

Phosphors and Fluors

There are four classes of phosphors of interest in field applications of scintillation: organic crystals, organic liquids, inorganic crystals, and inorganic powders. The theory of operation, use, and response of these phosphors varies. Each will be discussed individually.

Organic Crystals

Organic crystal phosphors are normally aromatic hydrocarbons which contain benzene rings. The most common organic crystal is anthracene. Anthracene offers a high response

to beta radiation and is commonly used in beta phosphors. The decay time (which is a major part of scintillation resolving time) is on the order of 3 E-8 seconds.

Gamma photons do not interact often or create a large pulse from interactions in the low density anthracene (1.25 g/cm^3). Therefore, it is easy to detect only beta in the presence of a mixed beta and gamma field.

In organic crystals, the incident radiation raises the molecules of the phosphor to a higher energy state. Upon decay back to the ground state, these molecules emit light.

Organic Liquids

Organic liquid phosphors, usually called *fluors*, are comprised of organic material suspended in an organic solvent. The organic material, usually called the solute, is the scintillator. The solvent absorbs the radiation and transfers energy to the solute. The mixture of solute and solvent is commonly called a "cocktail." Numerous mixtures are available. These mixtures have a typical decay time of 2 - 8 E-9 seconds (0.002 - 0.008 µsec) and a density of 0.86 g/cm^3.

The organic liquid fluor operates as follows: The incident radiation interacts with the molecules of the solvent, exciting the molecules. By a process not well understood, the excited molecules transfer their energy to the molecules of the solute. The molecules of the solute return to the ground state by emission of a light photon.

Inorganic Crystals

Inorganic crystals are comprised of inorganic salts, normally halides, which contain small quantities of impurities, called activators. The most commonly used inorganic crystal scintillator is sodium iodide, activated with thallium - commonly subscripted NaI(Tl). NaI(Tl) crystals have a high density - 3.7 g/cm^3, which allows for improved gamma photon response. The decay time is about 3 E-7 seconds (0.3 µsec). NaI(Tl) has a high response to beta particles; however, the need to hermetically seal a NaI(Tl) crystal to prevent deterioration, limits the actual beta response.

Inorganic crystals operate as follows:

- An incident photon interacts with the crystal atoms (NaI) exciting the atom and raising valence band electrons to the conductance band, leaving a "hole" in the valence band.

- Some of these electrons and holes recombine to form an "exciton." The excitons, free holes, and free electrons drift through the crystal.

- The impurity centers (T1) capture the excitons, free holes, and free electrons. This capture raises the impurity center to an excited state.

- The impurity center will decay back to the ground state, and in doing so, emits a light photon, which is proportional to the energy of the incident radiation.

Inorganic Powders

Zinc Sulfide activated with Silver (ZnS(Ag)) is an inorganic powder which is commonly used as a phosphor in alpha scintillators. ZnS(Ag) scintillators have a high density, 4.1 g/cm3, and a relatively high response to beta and alpha radiation's. The response of this scintillator to beta and gamma is minimized by the use of ZnS(Ag) as a thin film which is within the alpha interaction range, but too thin for that of beta or gamma. ZnS(Ag) emits two light photons one at 4-10 E-8 seconds (0.04 - 0.1 µsec), and another at 4-10 E-5 seconds (40 - 100 µsec).

Inorganic powders operate with a mechanism similar to that of inorganic crystals.

Photomultiplier Tubes

The purpose of the photomultiplier tube is to detect the scintillations and to provide an output signal proportional to the amount of scintillations. In doing this, photomultiplier tubes can provide amplifications of 1 E6 and higher.

Construction

Construction details vary from design to design, however, all photomultipliers have typical components. These common components are: the photocathode, the dynode assembly, an anode, voltage divider network, and shell. These components perform as follows: *(See Figure 6)*

- Photocathode - made of an antimony - cesium composite. The purpose of the photocathode is to convert the light photons to electrons (called photoelectrons).

- Dynode Assembly - A series of electrodes used to amplify the signal. Each successive dynode has a higher voltage potential. The voltage gradient along the tube accelerates the electrons towards the anode. This works as follows: the photoelectron strikes the first dynode freeing one or more electrons. These electrons are drawn towards the second dynode. At the second dynode each electron frees one or more additional electrons. This process continues until the electron cascade reaches the anode. Through this process, the initial photoelectron is amplified, up to 10^6 times and higher. For an amplification of 10^6 an average of 4 electrons is freed by each incident electron reacting with each dynode (10 dynodes - $4^{10} = 10^6$).

- Anode - The anode collects the electrons and generates an output pulse.

- Voltage Divider Network - Splits the high voltage supply into the various potentials required by the dynodes.

- Shell - Supports the other components and seals the tube from stray light and stray electric/magnetic fields.

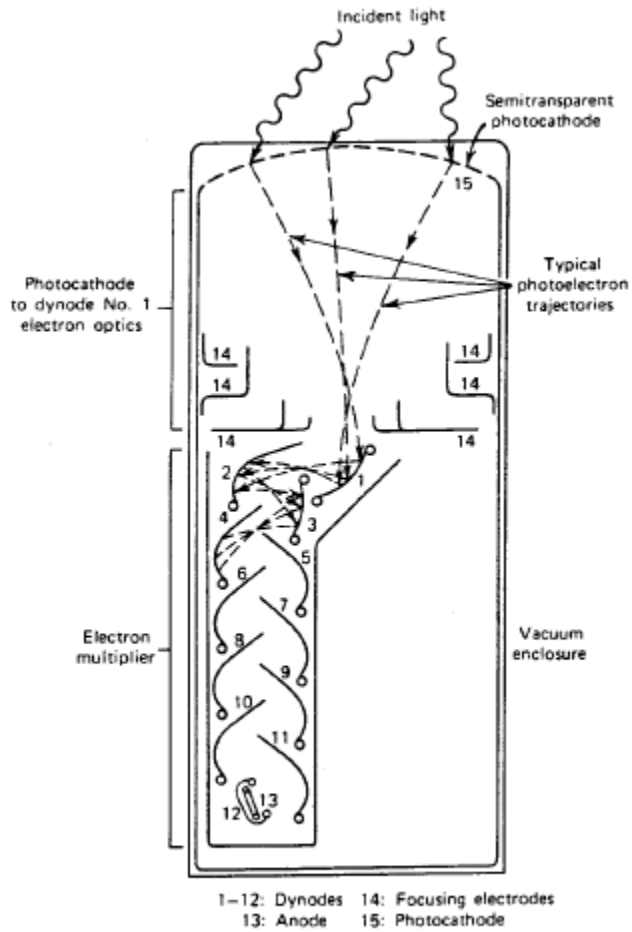

Figure 6. Photomultiplier Tube

Output

The photomultiplier tube provides an output pulse which is proportional to the incident photons. The size of the pulse is a function of the energy of the light photon, and of the electron multiplication. Varying the HV to the photomultiplier varies the pulse height.

It is possible for stray electrons to be amplified by the dynode, creating an output pulse while no photon entered the tube. Those electrons can be spontaneously emitted from the photocathode or by the dynodes themselves. This output signal is commonly called dark current. Dark current increases with photomultiplier tube temperature, hence, temperature changes may cause the detector to "drift."

Applications of Scintillation Detectors

Inorganic Crystals - NaI(Tl)

NaI(Tl) scintillation detectors are commonly used in applications where high gamma sensitivity and a high energy resolution is desired.

- The solid nature of the crystal "offers" more targets to a photon than does a GM detector. For this reason, gamma scintillators typically have higher yields than equivalently sized GM detectors.

- The light output of the crystal is a function of the incident photon energy. The output signal of the photomultiplier tube is a function of the light input, and therefore is proportional to the energy of the incident radiation. This characteristic allows scintillators to be used to perform pulse height analysis for radiation energy. The NaI(Tl) scintillator has a higher energy resolution than a proportional counter, allowing for more accurate energy determinations. Resolution is the characteristic of a detector to be able to differentiate between two close radiation energies. The higher the resolution, the closer the radiation energies can be to each other and still be differentiated. It should be noted that recent advances with semiconductor detectors have provided detectors with even better resolution than NaI(Tl).

Liquid Scintillation Detectors

Crystal scintillation detectors such as NaI(Tl) have two limiting characteristics. The crystals are 2π in nature; this fact lowers the possible efficiency of the detector. The crystals need to be hermetically sealed. The materials used for sealing attenuate lower energy radiation and both beta and alpha radiations.

Liquid scintillation units have been developed to remedy these situations for those applications where it is desired to measure radiation of low energy or low penetrating ability.

In liquid scintillation units, the fluor is mixed with the material to be analyzed (usually a liquid). This vessel containing the fluor-sample mixture is then placed in a photomultiplier tube array. (One or more PMTs may be used.)

In this manner, it is possible to analyze low energy beta emitters such as tritium (0.019 MeV) and/or carbon-14 (0.16 MeV), and to approximate 4π geometry.

Advantages of Scintillation Detectors

- Ability to discriminate between alpha, beta, gamma radiations and between different radiation energies with a moderate resolution.
- (NaI(Tl)): High gamma sensitivity.
- (Liquid): Extremely low energy response.
- (ZnS(Ag): Most advantageous alpha detector.

Disadvantages

- (NaI(Tl)): No beta or alpha response, poor low energy gamma response.
- (Liquid): Relatively cumbersome. Solution is one time use only.
- Requires a regulated power supply for pulse height analysis.

- (NaI(Tl) and ZnS(Ag)): Detector is not a solid state device, needs to be handled with care.

1.13.10 Identify how neutron detectors detect neutrons and provide an electrical signal.

NEUTRON DETECTION

Because neutrons do not interact with material to form ions, they must be detected indirectly. Several techniques are used.

Slow Neutron Detection

Boron Activation

When slow neutrons strike an atom of Boron-10, an alpha particle is emitted. This alpha particle, in turn, produces ionizations which can be measured. A detector is lined with Boron-10 or filled with Boron trifluoride, BF_3, gas. These detectors are usually operated in the ion chamber region or the proportional region. Boron activation is the most commonly used method for slow neutron detection.

Photographic film can be made sensitive to slow neutrons by adding boron.

Fission Chambers

A slow neutron will cause an atom of U-235 to fission, with the two fission fragments produced having a high kinetic energy and causing ionization to the material they pass through. Thus, by coating one of the electrodes of an ionization chamber with a thin layer of uranium enriched in U-235, a detector sensitive to slow neutrons is formed.

Scintillation

Scintillation detectors can be designed to detect slow neutrons by incorporating boron or lithium in the scintillation crystal. The neutrons interact with the boron or lithium atoms to produce an alpha particle, which then produces ionization and scintillation.

Slow Neutron Thermoluminescence

Thermoluminescent dosimeters can be designed to detect slow neutrons by incorporating lithium-6 in the crystal.

Activation Foils

Various materials have the ability to absorb neutrons of a specific energy and become radioactive through the radiative capture process. By measuring the radioactivity of thin foils such as gold, silver or indium, we can determine the amount of neutrons to which the

foils were exposed. Commercially available criticality accident dosimeters often utilize this method.

Fast Neutron Detection

Proton Recoil (Ion Chamber/Proportional)

When fast neutrons undergo elastic scatterings with hydrogen atoms, they frequently strike the hydrogen atom with enough force to knock the proton nucleus away from the orbiting electron. This energetic proton then produces ionization which can be measured. Most devices for measuring fast neutrons use an ionization detector operated in either the ion chamber or proportional region.

Thermalization (Slowing Down Fast Neutrons)

There are several methods for detecting slow neutrons, and few methods for detecting fast neutrons. Therefore, one technique for measuring fast neutrons is to convert them to slow neutrons, and then measure the slow neutrons. In this technique, a sheet of cadmium is placed on the outside of the detector to absorb any slow neutrons which might be present.

A thickness of paraffin, or another good moderator, is placed under the cadmium to convert the fast neutrons to slow ones. One of the slow neutron detectors is positioned inside the paraffin to measure the slow neutrons, thereby measuring the original fast neutrons.

Commercial Application - Dose Rate Instrument

Neutrons are not detected with any degree of efficiency by common ion chambers, GM tubes, or proportional counters. Any detection of neutrons by these detectors is due to absorption of neutrons by detector materials or hydrogen recoil. The detection efficiency can be increased by the utilization of materials with high neutron absorption cross section. The basic material typically used is Boron. Boron can be used either as a coating or as a gas, in the form of BF_3. Boron, when it absorbs a neutron, emits an alpha particle according to the following reaction:

$$^{10}B + {}^{1}n \rightarrow {}^{7}Li + \alpha$$

The alpha particle causes ionization and gas amplification provides a usable electrical signal. This reaction occurs only for thermal neutrons. Fast and intermediate neutrons must be converted to thermal neutrons before they can be detected using Boron. Typical thermalizing materials are paraffin and polyethylene.

Because of the energy dependence of neutron interaction, and the wide range of neutron energies, the response curve of the detector is not linear. Attempts are made in design to have the detector response curve approximate the quality factor versus energy curve by placing a sphere or cylinder of polyethylene around the detector. (Polyethylene closely approximates human tissue in composition.) Other techniques such as controlled loading

with cadmium, boron, or radially drilled holes are used to make the detector response more equivalent to dose rate.

The NBS released a table of the average flux to obtain 100 mrem/hr for various neutron energies. (See Table 2) The goal of shield and detector design is to approximate this relationship.

Table 2. Neutron Flux/Dose Relationship

Average Flux (n/cm^2-sec)	
Neutron Energy in MeV	**To obtain 1 mrem/hr**
0.0001	268
0.02	200
0.1	110
1.0	32
2.5	8.0
5.0	7.2
7.5	6.8
10-30	4.0

SEMICONDUCTOR DETECTORS

1.13.11 Identify the principles of detection, advantages and disadvantages of a GeLi detector and an HPGe detector.

Principles of Semiconductor Detectors

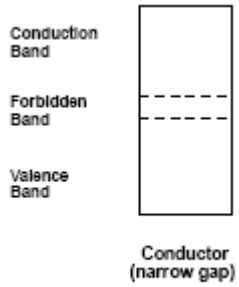

Figure 7. Conductor

In a crystal, the atoms are packed so tightly together that the energy states of individual atoms are modified. This modification splits the states into a number of closely spaced energy levels or bands. The top most band (called the *conduction band*) has unfilled energy levels. In a conducting solid, the group of "filled bands" are in direct contact with the group of "unfilled bands," so electrons are easily moved into the conduction band.

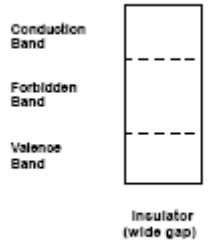

Figure 8. Insulator

In a good insulator, there is a large enough gap between the group of filled bands and the group of unfilled bands so that a large amount of energy is required to move an electron to the conduction band.

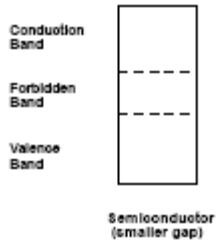

Figure 9. Semiconductor

A semiconductor has a smaller gap between the two groups of bands so that under certain conditions, electrons can be moved to the conduction band. (For example, heating the material will move at least some electrons to the conduction band.)

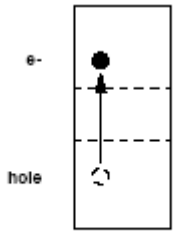

Figure 10. Electron Hole

When an electron is moved to a higher band, that is, from valence to conduction, a vacancy occurs in the band which it left. This vacancy is called a hole.

If a strong electric field is applied to the crystal, the electron in the conduction band moves in accordance with the applied field. Similarly, in the group of filled bands, an electron from a lower energy band moves up to fill the hole (vacancy) in the valence band. The hole it leaves behind is filled by an electron from yet a lower energy band. This process continues, so the net effect is that the hole appears to move down through the energy bands in the filled group. Thus, the electron moves in one direction in the unfilled group of bands, while the hole moves in the opposite direction in the filled group of bands. This can be likened to a line of cars awaiting a toll booth, the toll booth being the forbidden band. As a car leaves the "filled valence band" for the unfilled conductance band, a hole is formed. The next car in line fills this hole, and creates a hole, and so on. Consequently, the hole appears to move back through the line of cars.

Any impurities in the crystalline structure can affect the conducting ability of the crystalline solid. There are always some impurities in a semiconductor, no matter how "pure" it is. However, in the fabrication of semiconductors, impurities are intentionally added under controlled conditions. If the impurity added has an excess of outer electrons, it is known as a donor impurity, because the "extra" electron can easily be raided or donated to the conduction band. In effect the presence of this donor impurity decreases the "gap" between the group of filled bands and the group of unfilled bands. Since conduction occurs by the movement of a negative charge, the substance is known as an n-type material. Similarly, if the impurity does not contain enough outer electrons, a vacancy or hole exists. This hole can easily accept electrons from other energy levels in the group of filled bands, and is called an acceptor substance. Although electrons move to fill holes, as described above, the appearance is that the holes move in the opposite direction. Since this impurity gives the appearance of positive holes moving, it is known as a p-type material.

Since any crystalline material has some impurities in it, a given semiconductor will be an n-type or a p-type depending on which concentration of impurity is higher. If the number of n-type impurities is exactly equal to the number of p-type impurities, the crystalline material is referred to as an "intrinsic semiconductor."

A semiconductor that has been "doped" with the proper amount of the correct type of impurity to make the energy gap between the two groups of bands just right, makes a good radiation detector. A charged particle loses energy by creating electron-hole pairs.

If the semiconductor is connected to an external electrical field, the collection of electron-hole pairs can lead to an induced charge in the external circuit much as the collect of electron-positive atom pairs (ion pairs) is used to measure radiation in an ion chamber. Therefore, the semi-conductor detector relies on the collection of electron-hole pairs to produce a usable electrical signal.

One disadvantage of the semiconductor "detector" is that the impurities, in addition to controlling the size of the energy gap also act as traps. As electrons (or holes) move through the crystalline material, they are attracted to the impurity areas or centers because

these impurity centers usually have a net charge. The carrier (electron or hole) may be trapped for awhile at the impurity center and then released. As it begins to move again, it

may be trapped at another impurity center and then released again. If the electron or hole is delayed long enough during transit through the crystal, it may not add to the electrical output.

Thus, although the carrier is not actually lost, the net effect on readout is that it is lost. Another disadvantage of the semiconductor detector is that the presence of impurities in the crystal is hard to control to keep the energy gap where it is desired. A newer technique, the junction counter, has been developed to overcome these disadvantages.

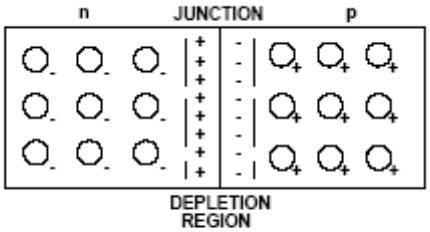

Figure 11. n-p Junction

In a semiconductor junction counter, an n-type substance is united with a p-type substance. When the two are diffused together to make a diffused junction, a depletion layer is created between the two materials. (This depletion layer is formed by the diffusion of electrons from the n-type material into the p-type material and the diffusion of holes from the p-type material into the n-type material.) This results in a narrow region which is depleted of carriers and which behaves like an insulator bounded by conducting electrodes. That is, a net charge on each side of the depletion region impedes the further transfer of charge. This charge is positive in the n-region and negative in the p-region. This barrier can be broken if we apply an external voltage to the system and apply it with the proper bias. A "forward bias" is applied when we connect the positive electrode to the p-region. In this case, the barrier breaks down and electrons flow across the junction. However, if we apply a "reverse bias" (negative electrode connected to the p-region), the barrier height is increased and the depleted region is extended.

A further advancement in junction counters is the p-n type. This counter has an intrinsic region between the n and p surface layers. (An intrinsic semiconductor was discussed earlier and is effectively a pure semiconductor.) The presence of an intrinsic region effectively creates a thicker depletion area. A Ge(Li) detector is an example of this type of detector.

Lithium (an n-type material) is diffused into p-type germanium. The n-p junction that results is put under reverse bias, and the temperature of the material is raised. Under these conditions, the lithium ions drift through the germanium, balancing n and p material and forming an intrinsic region.

The heat and bias are removed and the crystal cooled quickly to liquid nitrogen temperatures. This intrinsic region serves as the region in which interactions can take place. The intrinsic region can be thought of as a built-in depletion region.

Due to the large size of the depletion region and the reduced mobility of the electrons and holes due to the depressed temperature, a high charge is necessary to cause conduction. The charge is chosen high enough to collect ion pairs, but low enough to prevent noise.

Due to the increased stopping power of germanium over air at -321 ^{o}F the energy required to create an ion pair is only 2.96 eV compared to 33.7 eV for air. This means that by theory, a germanium detector will respond to any radiation that will create ion pairs. In actuality, however, the response to radiations other than gamma is limited by the materials surrounding the detector, material necessary to maintain temperature. Another consideration limiting response is the geometry of the crystal. The most efficient response occurs when the interaction takes place in the center of the intrinsic region, this can only occur for gamma.

Radiation interacts with atoms in the intrinsic region to produce electron hole pairs. The presence of ion pairs in the depletion region causes current flow. This is similar to a transistor, in that instead of inducing charges in the center section (the base in a transistor) by a battery or an other source, the charge is induced by the creation of ion pairs. Since it is not necessary for the ion produced to reach the p and n region to be collected, as in a gas filled chamber, the response is faster.

Since the number of ion pairs produced is a function of the incident energy, and the resulting current is a function of the amount of ion pairs, Ge(Li) response is in terms of energy.

GeLi Systems

A typical Ge(Li) detector system consists of a vacuum enclosed Ge(Li) crystal which is coaxial in shape and attached to a copper cold finger through an agate insulator. The crystal is under a vacuum to prevent frost forming on the crystal, and damage caused by impurities in the air. The cold finger is immersed in liquid nitrogen in a dewar.

The crystal is subject to failure should its temperature be raised to room temperature due to lithium ion drift and increased electron noise.

Advantages of Ge(Li) Detectors

GeLi detectors offer an advantage of high resolution (i.e. the ability to differentiate between closely adjacent gamma photopeaks. It can resolve the 3 photopeaks of ^{95}Zr/Nb whereas this would appear as 1 photopeak with NaI(Tl) detectors.

GeLi also has a short response time and a more linear energy response than NaI(Tl).

Small size crystals offer the best resolution but the efficiency of detection is lowered.

Disadvantages of Ge(Li) Detectors

GeLi systems can only be used for gamma photon detection. A cryogenic (liquid nitrogen) system is required to cool the detector and this adds to the initial cost as well as a continuing operation cost.

Because detectors are presently limited to less than 100-300 cc in size, the efficiency of counting is low compared to NaI. Counting times in excess of 1,000 minutes are necessary for environmental samples.

Intrinsic Germanium Detectors

One of the major disadvantages of GeLi detectors is the requirement that the crystal must always be kept cooled by liquid nitrogen. If the detector is ever allowed to reach room temperature, the lithium ions will drift and an effective intrinsic/depletion region (the area of electron-hole pair formation) will no longer exist. The detector can be returned to the manufacturer for redrifting, but the process is expensive and time consuming. The detector may be less efficient than before the redrifting. The bulky size of the liquid nitrogen dewar also places limitations on the uses of a GeLi detector. A semiconductor detector that could be operated and/or stored at room temperature would have advantages for use in installed effluent monitors or portable units.

Principles of Operation

In natural germanium of normal purity, the depletion region is only a few millimeters thick. The crystal is, in effect, a conductor due to the impurities in the crystal. Resistance is very low in the crystal, and detected electron flow (noise) may be caused by conditions other than radiation (e.g., heat). As a result, the natural crystal is virtually useless for radiation detection.

The use of the lithium drifting process in GeLi detectors creates an artificial depletion/intrinsic zone of 10-15 mm. The GeLi detector is a semiconductor. The resistance is greater than the resistance for a natural germanium crystal, and by applying the correct voltage to the crystal, most non-radiation events that induce electron flow can be eliminated. GeLi detectors are used in radiation detection; however, the crystal must be maintained at the temperature of liquid nitrogen to maintain the depletion/intrinsic zone.

If an extremely pure germanium crystal is created, the crystal's resistance will be sufficiently big so that a depletion region of 10mm can be obtained by using a reverse bias voltage, instead of drifting lithium through the germanium as is done in GeLi detectors. This pure germanium crystal would have, like GeLi crystals, semiconductor properties, and by applying the correct voltage could be used to collect electrons induced by radiation. Recently, processes for creating germanium in a very high state of purity have been developed. This, in turn, has led to the development of a semiconductor that

can be stored at room temperature. The pure germanium crystals are usually called "intrinsic germanium" or "high purity germanium" (abbreviated HPGe) detectors. HPGe crystals are perhaps the most highly purified material that has even been produced.

Note that in the above paragraph it was stated that the HPGe crystals could be stored at room temperature. This is because HPGe crystals are not lithium drifted. However, there was no mention of operating detectors with the crystals at room temperature. In order to reduce unwanted detector noise (caused by reduced resistance at room temperature) the detector must be operated at the temperature of liquid nitrogen. Experience has shown that

the crystals can be cycled between room and cold temperatures without damage. Most manufacturers, however, recommend that the detectors be continuously maintained at liquid nitrogen temperatures if possible.

Advantages of HPGe's

HPGe's offer high resolution as an advantage. Additionally, the dewar used for storing the liquid nitrogen coolant for HPGe detectors can be smaller than the dewar used for GeLi detectors. HPGe detectors are more portable. The main advantage is that should the detector be allowed to rise to room temperature (with no voltage applied) the detector need only be returned to and stabilized at liquid nitrogen temperatures to be used.

Disadvantages of HPGe's

Even though the dewar is smaller for the HPGe detector they still require liquid nitrogen cooling and tend to be fairly expensive.

CONDENSER R-METER AND CHAMBER

Method of Detection

The condenser chamber is an integrating, air wall tissue equivalent ionization chamber used to measure exposure to X or gamma radiation. The chamber generally consists of a Bakelite shell, coated on the inner surface with graphite to make it conducting, and an insulated central electrode. The chamber is mounted at one end of a shielded stem containing a solid dielectric storage condenser. The chambers vary is size and shape depending on their exposure range. The smaller the chamber volume the higher the exposure it is capable of measuring.

The Condenser R-Meter performs two functions. It applies a charge to the chamber and, after exposure, serves as a read-out device to determine the amount of exposure. It contains a line-operated d.c. power supply, which provides a charging voltage of approximately 500 volts. The read-out device is a string electrometer. Functionally, this is a d.c. voltmeter with infinite input resistance. It is a descendant of the gold leaf electroscope which was used as a detector in the early days of radiation physics. Instead of a gold leaf, this instrument uses a platinum coated quartz fiber, bent into a horseshoe

shape and soldered at each end to a horseshoe shaped support. When a charge is applied to the fiber support and a nearby deflecting electrode, the fiber is attracted toward the electrode to an extent proportional to the applied charge. A small light bulb casts a shadow of the fiber on a scale, which is observed through an optical system. In operation, the chamber is connected to the charger-reader, the charging switch is rotated to "charge" and the electrometer is adjusted to zero on the scale. This puts a full charge on the chamber, which can then be disconnected and placed wherever exposure is to be measured. After the exposure, the chamber is again plugged into the charger-reader and the residual charge is read. Since the loss of charge is proportional to the exposure, the scale can be calibrated in roentgens.

The Condenser R-Meter is a secondary standard. It must be calibrated against a primary standard, the free-air chamber. The Condenser R-Meter, in turn, can be used to calibrate other survey instruments. The protective cap must always be on the chamber when the exposure is made.

Range

Condenser chambers vary in size. The total exposure a chamber measures decreases as the chamber volume increases. Chambers are generally available which enable us to cover exposure ranges from several mR up to 250 R.

Energy Response

Condenser chambers vary in wall material and thickness as well as in size. The choice of wall material and thickness off-sets the energy dependence of the chambers.

Use

The condenser chambers are generally used to calibrate X and gamma radiation sources, and for making surveys of X-ray equipment. Condenser chambers may also be used to measure neutron radiation. Some chambers are boron lined and measure the ionization from the alpha particles emitted in the boron-thermal neutron reaction. Other chambers are made of tissue equivalent material to measure the absorbed dose of any ionizing radiation.