Radiological Control Technician Training

Fundamental Academic Training Instructor's 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:

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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.

References:

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

Instructional Aids:

1.   Overheads
2.   Overhead projector/screen
3.   Chalkboard/whiteboard
4.   Lessons learned

I.   MODULE INTRODUCTION

A. Self Introduction

    1. Name

    2. Phone number

    3. Background

    4. Emergency procedure review

B. Motivation

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, and 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.

C. Overview of Lesson

    1. Fractions

    2. Decimals

    3. Percent

    4. Signed Numbers

    5. Exponents

    6. Square Roots

    7. Scientific Notation

    8. Order of Mathematical Operations

    9. Algebra

    10. Logarithms

                                             O.H.: Objectives

D.   Introduce Objectives

II.   MODULE OUTLINE

A.   Symbols for Basic Operations

     1.   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 notation shown in Table 1 is used to denote the operation to be performed on the numbers.

See Table 1. - "Symbols for Basic Mathematical Operations"

Objective 1.01.01

B.   Fractions

     1.   Whole numbers consist of the normal counting numbers and zero.

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

     2.   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:

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

        a.   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, 25/5, 15/7, or 61/27 are improper fractions.

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

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

        c.   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 fractions. An equivalent fraction is built up, per se, by multiplying the numerator and the denominator by the same non-zero number. For example:

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

    d.   A fraction is reduced by dividing the numerator and the denominator by the same non-zero number. For example:

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

    e.   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.

    f.   A whole number written with a fraction is called a mixed number. 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.

        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.

        4)   Example:

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

  3. Adding and Subtracting Fractions

    a.   Fractions with the Same Denominator

        1)   To add two fractions which have the same denominator:

    a) Add the numerators

    b) Place the sum of step 1 over the common denominator

    c) Reduce fraction in step 2 to lowest terms (if necessary)

2) Example:

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

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

$$\frac{5}{8}-\frac{3}{8}=\frac{5-3}{8}=\frac{2}{8}=\frac{2\div2}{8\div2}=\frac{1}{4}$$

b. Fractions with Different Denominators

1) 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 denominator. Once a common denominator is obtained, the rules given above for the same denominator apply.

2) 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:

$$\frac{1}{3}+\frac{2}{5}=\frac{1\times5}{3\times5}+\frac{2\times3}{5\times3}=\frac{5}{15}+\frac{6}{15}=\frac{11}{15}$$

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

$$\frac{3}{4}-\frac{2}{3}=\frac{3\times3}{4\times3}-\frac{2\times4}{3\times4}=\frac{9}{12}-\frac{8}{12}=\frac{1}{12}$$

4. Multiplying and Dividing Fractions

a. 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.

5) Example:

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

b. 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:

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

5. Reciprocals

a. Two numbers whose product is 1 are called reciprocals, or multiplicative inverses. For example:

1) 5 and $\frac{1}{5}$ are reciprocals because $5 \times \frac{1}{5} = 1$

2) $\frac{4}{5}$ and $\frac{5}{4}$ are reciprocals because $\frac{4}{5} \times \frac{5}{4} = 1$

3) 1 is its own reciprocal because $1 \times 1 = 1$

4) 0 has no reciprocal because 0 times any number is 0 not 1

b. 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 $\dfrac{1}{a}$ such that

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

c. Now, look at the following product:

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

6. Relationship of multiplication to division

a. The operation of division is really just inverted multiplication (reciprocals). Notice from the above examples the reciprocal of a fraction is merely "switching" the numerator and denominator. The number 5 is really 5/1, and the reciprocal of 5 is 1/5. Likewise, the reciprocal of 2/3 is 3/2.

b. 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.

3) Examples:

(1/2)/3 = 1 / (2/3) = 1 x 3/2 = 3/2

C. Decimals

Objective 1.01.02

1. A decimal is another way of expressing a fraction or mixed number. It is simply the numerical result of division (and fractions are division). Recall that our number system is based on 10 ("deci" in "decimal" means ten) and is a place-value system; 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).

See Fig. 1 - "Decimal Places"

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

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

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

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

4. Addition and Subtraction of Decimals

    a. 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.)

        Subtrahend - a number that is to be subtracted from the minuend).

        3) Place the decimal point in the answer in line with the other decimal points.

        4) Examples:

21.3	654.200
+4.2	-26.888
25.5	627.312

5. Multiplying Decimals

    a. 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.

4) Examples:

$$
\begin{array}{r}
5.28 \\
\times\,3.7 \\
\hline
3696 \\
1584 \\
\hline
19.536
\end{array}
$$

$$
\begin{array}{r}
0.04 \\
\times\,0.957 \\
\hline
028 \\
020 \\
036 \\
000 \\
\hline
0.03828
\end{array}
$$

6. Division of Decimals

    a. The steps for division of decimals are as follows:

        1) Move the decimal point of the divisor 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.

        4) Example:

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

Divisor - The number by which a dividend is divided.

Dividend - a number to be divided.

7. Decimal Forms

    a. 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 decimal. 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 numbers.

b. On the other hand, fractions like 1/3, 2/7, 5/11, and 7/13 result in a non-terminating or infinite decimal. 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 numbers. Note that even though irrational numbers are non-terminating, some (e.g., 1/3 and 5/11) are repeating or periodic decimals because the same digit or block of digits repeats unendingly. For example:

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

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

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

D. Fraction to Decimal Conversion   Objective 1.01.03

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:

$$
\begin{array}{r}
0.75 \\
4\overline{)3.00} \\
\underline{28} \\
20 \\
\underline{20} \\
0
\end{array}
$$

E. Percent   Objective 1.01.04

1. 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.

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

3. Converting Decimal to Percent

a.   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:

$$\frac{1}{8} = 0.\underline{12}5 = 12.5\%$$

b.   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:

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

c.   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.

4. Converting Percent to Decimal

a.   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:

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

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

F. Signed Numbers   Objective 1.01.05

1. 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.

2. 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.

3. 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: $|5|$.

4. Operations with Signed Numbers

    a. 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. 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.

    See Fig. 2 - "Number Line"

    b. 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.

    c. 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.

5. Adding and Subtracting Signed Numbers

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

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

b. To add two numbers with opposite signs, 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

c. 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

d. If the sum of two signed numbers is 0, the numbers are called additive inverses or opposites. For example:

7 - 3 = 4 is the same as: 7 + (-3) = 4

8 - 2 = 6 is the same as: 8 + (-2) = 6

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

f. 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) « add +8
(Answer = 13)

6 - 11 = 6 + (-11) « add -11
(Answer = -5)

−4 - (-7) = -4 + (+7) « add +7
(Answer = 3)

6. Multiplying and Dividing Signed Numbers

a. 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:

(+) × (+) = (+)
(+) × (-) = (-)
(-) × (-) = (+)
(-) × (+) = (-)

    b.   Examples:

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

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

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

    d.   Examples:

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

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

    e.   Remember that multiplication is really a short form of addition. When we say $+4 \times (3)$, 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 $-24 \div (-6)$, 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.

G. Exponents

<div align="right">Objective 1.01.06</div>

   1.   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 $3 \times 3 \times 3 \times 3$. In this case, 4 is the exponent, and 3 is the base.

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

   3.   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.

4. 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.

5. 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.

6. Addition and Subtraction

   a. 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.

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

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

7. Multiplication

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

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

   b. 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,

   $$3^2 \times 3^3 = 3^{(2+3)} = 3^5 = 243$$

8. Division

    a. 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:

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

    b. 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,

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

    c. 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:

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

9. Exponent Raised to a Power

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

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

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

    $(5^2)^3 = 5^{(2\times3)} = 5^6 = 15,625$

10. Product Raised to a Power

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

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

b.   Example:

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

c.   This same result can also be obtained like this:

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

11.   Mixed Product and Exponents Raised to a Power

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

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

b.   Example:

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

12.   Fraction Raised to a Power

a.   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.

13.   Negative Exponents and Powers

a.   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:

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

b.   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.

14. Fractional Exponents

   a. 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 the square root of a^1, or a. In other words, $a^{1/2} = \sqrt{a}$.

15. Calculator Method

   a. 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 $\boxed{y^x}$ key.

      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.

Objective 1.01.07

H. Square Roots

1. 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.

2. 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.

3. 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.

4. 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."

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

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

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

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

7. Therefore, the rule is that every positive real number *a* has two square roots: $\sqrt{a}$ and $-\sqrt{a}$.

8. 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.

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

   a. For any non-negative real numbers *a* and *b*:

   $$\sqrt{a \cdot b} = \sqrt{a} \cdot \sqrt{b}$$

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

10. Calculator Method

    a. 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.

11. Other roots

    a. 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 $2 \times 2 \times 2 = 8$. 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 $\sqrt[3]{a}$.

    b. 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.

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

I. Scientific Notation   Objective 1.01.08

1. 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 notation, 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.

2. Converting From Standard Form To Scientific Notation

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

    a. 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.

    b. 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:

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

$$7\underline{00} = 7 \times 10^2$$

2) Suppose you want to express 0.0014 in scientific notation.

$$0.\underline{0014} = 1.4 \times 10^{-3}$$

3. Converting from Scientific Notation to Standard Form

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

   $$1.96 \times 10^5 = 1.\underline{96000} = 196,000$$

   $$2.27 \times 10^{-2} = 0\underline{02}.27 = 0.0227$$

   b. 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.

   c. 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.

   d. 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.

4. Addition and Subtraction Using Scientific Notation   Objective 1.01.09

   a. 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.

b. For example:

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

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

$$\begin{array}{r} 35.4 \times 10^4 \\ +\,35.4 \times 10^4 \\ \hline 37.91 \times 10^4 \end{array} \quad = 3.79 \times 10^5$$

5. Multiplication and Division Using Scientific Notation

a. 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}.

b. 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.

c. Example: Perform the following calculation using scientific notation:

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

1) Write each term in scientific notation:

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

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:

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

6. "E" Notation

a. 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:

$3.79 \times 10^5 = 3.79E5$

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

$5.89 \times 10^0 = 5.89E0$

7. Using "E" Notation with a Calculator

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

1) Enter the significant digits.

2) Press the $\boxed{E}$ or $\boxed{\text{EXP}}$ key. (Actual key label may vary.)

3) Enter the power of 10. If the power is negative press the $\boxed{+/!}$ key in conjunction with entering the power.

J. Order of Mathematical Operations   Objective 1.01.010

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

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

    b. Simplify all powers.

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

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

2. For example:

$(3 + 1)^2 \times 3 \ ! \ 14 \div 2$

    a. Simplify parentheses.

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

    b. Simplify powers.

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

    c. Perform multiplication and division left to right.

    $$\underbrace{16 \times 3} - \underbrace{14 \div 2}$$

    d. Perform subtraction.

    $48 - 7 = 41$ *(Final Answer)*

K. Algebra

Objective 1.01.011

1. Algebra is the branch of mathematics which deals with the manipulation of words and letters, generically called symbols, 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.

2. 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

3. 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 $A = lw$

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

5. Variables vs. Numbers

    When words or letters are used to represent numbers, they are called variables. 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.

6. Properties of Variables

    a. 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:

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

b. 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:

   1) Monomials

        12 z $\frac{2}{3}r$ $-4x^3$

   2) Polynomials

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

7. Equations

a. 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.

b. 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.

8. Algebraic Manipulation

a. 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.

b. 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.

c. Here are the general forms for algebraic manipulation of equations. For the real numbers a, b, c and n:　　　　See Table 2. - "Rules for Algebraic Manipulation"

1) Addition

If $a = b$, then $a + c = b + c$

2) Subtraction

If $a = b$, then $a - c = b - c$

3) Multiplication

If $a = b$, then $a \times c = b \times c$

4) Division

If $a = b$, then $a \div c = b \div c$

5) Involution　　　　Involution - raising to an exponent.

If $a = b$, then $a^n = b^n$

6) Evolution　　　　Evolution - taking a root.

If $a = b$, then $\sqrt[n]{a} = \sqrt[n]{b}$

9. Manipulating and Solving Linear Equations

a. 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:

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

b. 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:

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

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

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

$$x = 2$$

c. 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:

Solve for x in the equation:

$3x - 5 = x + 3$

1) Subtract x from both sides:

$3x - 5 - x = x + 3 - x$

2) Combine like terms and cancel:

$2x - 5 = 3$

3) Add 5 to both sides:

$2x - 5 + 5 = 3 + 5$

4) -5 and +5 cancel:

$2x = 8$

5) Divide both sides by 2:

$$\frac{2x}{2} = \frac{8}{2}$$

6) 2 over 2 cancels. Reduce.

$x = 4$

10. Quadratic Equations

   a. 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.

   b. Example:

   Solve for a in the equation:

   $a + b = c$

   1) Subtract b from both sides:

   $a + b - b = c - b$

   2) $+b$ and $-b$ cancels, leaving:

   $a = c - b$

   c. Example:

   Solve for a in the equation:

   $ab = c$

   1) Divide both sides by b:

   $$\frac{ab}{b} = \frac{c}{b}$$

   2) b over b cancels, leaving:

   $$a = \frac{c}{b}$$

    d. 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 order. Here is an example which shows how this is done.

Solve for *a* in the equation:

$$\frac{a+b}{c} = d$$

    1) Multiply both sides by *c*:

$$c \cdot \frac{(a+b)}{c} = d \cdot c$$

    2) *c* over *c* cancels:

$$a + b = dc$$

    3) Subtract *b* from both sides:

$$a + b - b = dc - b$$

    4) *b* - *b* cancels, leaving:

$$a = dc - b$$

    e. 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:

Solve for *d* in the equation:

$$ab^2 = cd^2$$

    1) Divide both sides by *c*:

$$\frac{ab^2}{c} = \frac{cd^2}{c}$$

2) *c* over *c* cancels:

$$\frac{ab^2}{c} = d^2$$

3) Take the square root of both sides:

$$\sqrt{\frac{ab^2}{c}} = \sqrt{d^2}$$

4) Square root of square cancels, leaving:

$$\sqrt{\frac{ab^2}{c}} = d$$

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 interest, 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*

a.　To solve for *b*:

　　$2x - y^2 = 3a - b$

b.　Add *b* to both sides:

　　$2x - y^2 + b = 3a - b + b$

c.　$b + b$ cancels:

　　$2x - y^2 + b = 3a$

d.　Transpose $2x - y^2$ to right side:

　　$b = 3a - 2x + y^2$

e.   Substitute known values:

$b = 3(3) - 2(5) + (-4)^2$

f.   Perform operations:

b = 9 - 10 + 16

g.   Simplify:

$b = 15$

Objective 1.01.012

L.   Logarithms

1.   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 logarithms. 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.

2.   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.

3.   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. The general relationship and form are as follows:

If $n = B^x$;

where B > 0 and B ≠ 1;

then: $\log_B n = x$

4.   For example:

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

5. 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.

6. Here are some additional examples:

    $2^3 = 8 \rightarrow \log_2 8 = 3$

    $4^{3/2} = 8 \rightarrow \log_4 8 = 3/2$

7. Before the development of the pocket 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.

$$\frac{(895)^3 (0.0247)^{\frac{1}{2}} (93,800)}{(0.00186)(4.53)^2}$$

8. However, using logarithms the above expression could be evaluated in a matter of minutes. Thus, logarithms, or logs, 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.

9. Properties of Logarithms

    a. 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:

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

    b. Let us say that:

        $u = a^x$ and $v = a^y$

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

$x = \log_a u$ and

$y = \log_a v$

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

e.   If we write this in logarithmic form it would be:

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

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

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

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

See Table 3 - "Rules for Logarithms"

10. Base Ten Logarithms

a.   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 logarithms.

b.   Observe the patterns in the number line and table. Notice the relationship between the power of ten and the logarithm.

Refer students to number of line showing powers of 10 and Table 4 - "Log to Power of 10 Relationship."

c.   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 $10^{2.722}$. 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.

d.   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 mantissa. For example, in the logarithm of 527.3, which equals 2.722, the characteristic is 2 and the mantissa is 0.722. The mantissas of most logarithms are rounded off to a specified number of significant digits. Typically, mantissas are rounded off to three, four, five or more significant digits.

11. Log-Table Method

    a.   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.

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

    b.   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.

    c.   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 maintained to ensure appropriate accuracy in the answers.

12. Calculator Method

Right margin notes:

See Table 5 - "Four-place Logarithms"

Do examples in the study guide.

See Table 6 - "Mantissa for Successive Significant Digits."

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:

a.   Enter the number.

b.   Press the ☐log☐ key. The number displayed is the logarithm of the number entered in step 1.

13. Natural Logarithms

a.   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.

b.   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 logarithms.

c.   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 $\ln n = x$

d.   For example:

1) $\ln 2 = 0.693147$

which means that $e^{0.693147...} = 2$.

2) $\ln 10 = 2.302585$

which means that $e^{2.302585...} = 10$.

3) $\ln e = 1$

which means that $e^1 = e$

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.

f.   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.

g.   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.

14. Antilogarithms

a.   An antilogarithm, 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 $\log^{-1}$ 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 $10^x = n$

b.   For example:

$\log^{-1} 3$ which means $10^3 = 1000$ Refer also to example in study guide.

c. On a scientific calculator the base 10 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 of entered in
        step 1. In other words, 10 raised to that power.

See Table 7 -
"Summary of Log
Definitions."

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

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

e. For example:

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

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

    1) Enter the number.

    2) Press the $\boxed{\text{Ln}^{-1}}$ 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.

14. Solving for Variables as Exponents

    a. 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.

        $2356 = 3^x$

    b. 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) Since a logarithm is an exponent, and this is an exponent raised to a power, this statement can now be rewritten using the laws of exponents, which say that the exponent and power are multiplied:

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

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

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

5) Cancel terms and rewrite the equation:

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

6) Perform the operations and solve:

$$\frac{3.372}{0.477} = x$$
$$7.068 = x$$

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

$$2356 = 3^{7.068}$$

d. 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 taking the natural log of e reduces to 1. For example:

$$125 = 1000e^n$$

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

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

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

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

$$-2.0794 = n$$

III.   **SUMMARY**

      A. Review major topics

          1.   Fractions

          2.   Decimals

          3.   Percent

          4.   Signed Numbers

          5.   Exponents

          6.   Square Roots

          7.   Scientific Notation

          8.   Order of Mathematical Operations

          9.   Algebra

          10. Logarithms

      B. Review learning objectives

IV.   **EVALUATION**

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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.

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.

Instructional Aids:

1.   Overheads
2.   Overhead projector/screen
3.   Chalkboard/whiteboard
4.   Lessons Learned

I. MODULE INTRODUCTION

A. Self Introduction

   1. Name

   2. Phone number

   3. Background

   4. Emergency procedure review

B. Motivation

   A knowledge of the unit analysis and conversion process is a necessity for the RCT. It is useful for air and water sample activity calculations, contamination calculations, and many other applications.

C. Overview of Lesson

   1. Units

   2. Unit systems

   3. Unit analysis and conversions including use of conversion factor tables

O.H.: Objectives

D. Introduce Objectives

II. LESSON OUTLINE

A. Units and Measurements

   1. Units are used to express 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. A number--expresses the magnitude.

      b. A unit--expresses the dimension.

   2. A number and a unit must both be present to define a measurement.

   3. Measurements are algebraic quantities and as such may be mathematically manipulated subject to algebraic rules.

4. 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:

a. Length (L)

b. Mass (M) (not the same as weight)

c. Time (T)

5. 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:

a. Area is the product of length times length (width), which is L × L, or L2.

b. Volume is area times length, which is length times length times length, or L3.

c. Velocity is expressed in length per unit time, or L/T.

d. Density is expressed in mass per unit volume, or M/L3.

B. Systems of Units

1. 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.

2. English System

Margin notes:

See Fig. 1 in the Study Guide - "Fundamental Units"

Objective 1.02.01

See Table 1 of the Study Guide - "English System Base Units"

a. 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.

b. 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.

3. International System of Units (SI)

a. 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.

b. In 1960, the International System of Units (abbreviated SI from the French name Le Système Internationale d'Unites) was adopted by the 11th General Conference of Weights and Measures (CGPM).

c. 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.

4. SI Prefixes

Objective 1.02.02

a. 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 cm3.

b. 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.

c. 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.

d. Prior to the adoption of the SI system, two groups of units were commonly used for the quantities length, mass, and time: MKS and CGS.

5. SI Units

a. 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 only one SI unit for each physical quantity. The SI system base units are those in the metric MKS system. Table 4 in the Study Guide 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.

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

6. 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 equivalent dose is the sievert, which has units of joule per kilogram. These quantities and their applications will be discussed in detail in Lesson 1.06.

7. Other units

There are several other SI derived units that are not listed in Table 4 of the Study Guide. 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.

C. Unit Analysis and Conversion Process   Objective 1.02.03

1. Units and the Rules of Algebra

a. 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.

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

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

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

b. 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.

    c. 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.

2. Steps for Unit Analysis and Conversion

    a. Determine given units and desired units.

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

       1) 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.

       2) Examples of conversion factors are:

$$\frac{365\,days}{1\,year}$$

$$\frac{12\,inches}{1\,foot}$$

$$\frac{1\,foot^3}{2.832E4\,cm^3}$$

       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.

       4) 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-3

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

5)   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:

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

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

    1)   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.

    2)   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:

3. 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; 1 hour = 3600 seconds

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

    $$\left(\frac{3 years}{}\right)\left(\frac{365.25 days}{year}\right)\left(\frac{24 hours}{day}\right)\left(\frac{3600 sec}{hour}\right) = 94,672,800 sec$$

4. 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.

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

Objective 1.02.04

D. Temperature Measurements and Conversions

See Fig. 2 in the Study Guide - "Comparison of Kelvin, Celsius and Fahrenheit scales"

1. 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.

2. 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.

3. About thirty years after the Fahrenheit scale was developed, 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.

4. 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.

5. 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.

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

See Table 5 in the Study Guide - "Equations for Temperature Conversions"

1) $^{o}C = \dfrac{\left(^{o}F - 32\right)}{1.8}$

or

$^{o}C = \left(^{o}F - 32\right)\left(\dfrac{5}{9}\right)$

2) $^{o}F = 1.8\left(^{o}C\right) + 32$

or

$^{o}F = \left(\dfrac{9}{5}\right)\left(^{o}C\right) + 32$

3) $K = {}^{o}C + 273.15$

7. Example 3: Convert 65° Fahrenheit to Celsius:

$$^oC = \frac{\left(65^oF - 32\right)}{1.8}$$

$$^oC = \frac{33}{1.8}$$

$$^oC = 18.3\,^oC$$

III. SUMMARY

A.   Review major topics

    1.   Units

    2.   Unit systems

    3.   Unit analysis and conversions including use of conversion factor tables

B.   Review learning objectives

IV.   EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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

References:

1.   "Chart of the Nuclides"; Sixteenth Edition, Knolls Atomic; 2003.
2.   "Modern Physics"; Holt, Rinehart and Winston, Publishers; 1976.
3.   "Chemistry: An Investigative Approach"; Houghton Mifflin Co., Boston; 1976.
4.   "Chemical Principles with Qualitative Analysis"; Sixth ed.; Saunders College Pub.; 1986.
5.   "Introduction to Chemistry" sixth ed., Dickson, T. R., John Wiley & Sons, Inc.; 1991.
6.   "Matter"; Lapp, Ralph E., Life Science Library, Time Life Books; 1965.
7.   "Physics"; Giancoli, Douglas C., second ed., Prentice Hall, Inc.; 1985.
8.   DOE/HDBK-1015 "Chemistry: Volume 1 of 2"; DOE Fundamentals Handbook Series;
          January 1993.

Instructional Aids:

1.   Overheads
2.   Overhead projector/screen
3.   Chalkboard/whiteboard
4.   Chart of the Nuclides
5.   Periodic Table of the Elements
6.   Lessons Learned

I.   MODULE INTRODUCTION

   A. Self-Introduction

      1. Name

      2. Phone number

      3. Background

      4. Emergency procedure review

   B. Motivation

     It is important to a RCT that they have a basic understanding of physics because they may work in an environments where materials can undergo changes in state, resulting in changes in the work environment.

   C. Overview of Lesson

      1. Physics definitions

      2. Law of Conservation of Energy

      3. The Atom

      4. Periodic Table

      5. Valence Electrons

                                        O.H.: Objectives

   D. Introduce Objectives

II.   MODULE OUTLINE

   A. Work and Energy

     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. A general definition of matter is anything that has mass and occupies space. Energy can be understood by relating it to another physical concept - work.

1. Work and Force   Objective 1.03.01

     a. Work is defined in physics as a force acting through a distance.

     b. A force is a push or a pull. A more technical definition of force is any action on an object that causes the object to change speed or direction.

     c. Units

         (1) Force is derived as the product of mass and acceleration.

         (2) The SI derived unit is expressed in terms of newtons, (N)

$$N = \frac{Kg \times m}{S^2}$$

         (3) Mathematically, work is expressed as:

            W = F x d

            where:

            W = Work

            F = Force (newtons)

            d = Distance (meters)

         (4) The SI unit of work is the joule

         (5) One joule of work is performed when a force of one newton is exerted through a distance of one meter.

         (6) Thus:

$$J = N \times m$$

B. Energy   Objective 1.03.02

     1. Energy is defined as the ability to do work.

a. 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

b. Potential energy 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

c. Thermal energy describes the energy that results from the random motion of molecules. For example, steam possesses heat energy.

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

2. Law of Conservation of Energy   Objective 1.03.03

a. 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.

b. 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 vehicle moving, giving it kinetic energy.

c. Units

    (1) Thermal energy is often measured in units of calories (CGS)
        or British Thermal Units or BTUs (English).

        (a) 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.

        (b) 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.

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

        (a) 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.

        (b) It takes about 15.8 eV of energy to remove an electron
            from an atom of argon.

        (c) Superunits such as kiloelectron volt (keV) and
            megaelectron volt (MeV) are used to indicate the
            energies of various ionizing radiations.

d. Work-Energy Relationship

    (1) When work is done by a system or object, it expends energy.
        For example, when gaseous combustion products 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.

(2) When work is done on a system or object, it acquires energy.

(3) The work done on the car by the combustion of the gasoline causes the car to move, giving it more kinetic energy.

(4) 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.

See Fig. 1 - "Energy Conversion in an Automobile"

(5) Consider the example of the automobile. 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 and 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.

e.   Energy-mass relationship

Energy can also be converted into mass and mass converted into energy. This topic will be discussed further in Section 1.04 Nuclear Physics.

C. Energy and Change of State

Objective 1.03.04

1.   Matter is anything that has mass and takes up space.

2.   There are three states of matter solid, liquid and gas.

See Table 1 - "State of Matter Compared" and Fig. 2 - "States of Matter"

3. Solid State

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

        (1) The molecules or ions of a solid are held in place by strong
             attractive forces.

        (2) The molecules still have thermal energy, but the energy is
             not sufficient to overcome the attractive forces.

        (3) The molecules of a solid are arranged in an orderly, fixed
             pattern.

4. Liquid State

    (a) 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.

    (b) 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.

    (c) 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.

5. Gaseous State

    (a) 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.

(b) 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.

D. The Atom   Objective 1.03.05

1. The Bohr Model was described by Ernest Rutherford and Niels Bohr – 1911

   See Fig. 3 - Atomic Model

   a. Made of protons, neutrons, and electrons

   b. Central core called the nucleus

   c. Contains protons and neutrons

   d. Nuclear forces hold nucleus together

2. Protons

   a. Positively charged (+1)

   b. Mass = 1.6726×10^{-24} gm or 1.007276470 amu

   c. Each element is determined by the number of protons in its nucleus. All atoms of the same element have the same number of protons.

3. Neutrons

   a. Neutrally charged (0)

   b. Mass = 1.6749×10^{-24} gm or 1.008665012 amu

   c. Determines the isotope of an element. Same number of protons (therefore, of the same element) but different number of neutrons. Does not affect chemical property of element.

4. Electrons

   a. Negatively charged (-1)

   b. Small mass = 9.1085×10^{-28} or 0.00054858026 amu (1/1840 of a proton)

   c. 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.

     d.   Number of electrons is normally equal to the number of protons (atom is electrically neutral)

     e.   The number of electrons in the outermost shell determines the chemical behavior or properties of the atom.

E.   The Elements

   1.   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.

   2.   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.

   3.   Chemical Names   See Table 2 - "List of Elements by Name"

     a.   Currently, there are more than 110 named elements. 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.

     b.   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.

4.   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. 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."

F.   Nomenclature

1.   Atomic Number

a.   The number of protons in the nucleus of an atom.

b.   All atoms of a particular element have the same atomic number.

c.   Atomic numbers are integers.

d.   Atomic number for hydrogen is 1.

e.   A helium atom has two protons in the nucleus, which means that
its atomic number is 2.

f.   Uranium has 92 protons in the nucleus, and has an atomic
number of 92.

2.   Mass Number

a.   The total number of protons plus neutrons in the nucleus of an
isotope of an element is called the mass number.

b.   Since a proton has a mass of 1.0073 amu, we will give it a mass
number of 1.

c.   The mass number for a neutron is also 1, since its mass is 1.0087
amu.

d.   By adding the number of protons and neutrons we can determine
the mass number of the atom of concern.

Right margin notes:

See Table 2 - "List
of Elements by
Name"

Objective 1.03.06

      (1) A normal hydrogen atom has 1 proton, but no neutrons. Therefore, its mass number is 1.

      (2) A helium atom has 2 protons and 2 neutrons, which means it has a mass number of 4.

      (3) If a uranium isotope has 146 neutrons, then it has a mass number of 238 (92 + 146). If it only has 143 neutrons its mass number would be 235.

   e. The mass number can be used with the name of the element to identify to which isotope of an element we are referring, such as Uranium-235, Uranium-238 (often shortened to U-235 and U-238).

3. Atomic Mass

   a. The actual mass of a particular isotope.

   b. The units are expressed in Atomic Mass Units (AMU)

      (1) AMUs are based on 1/12 of the mass of a carbon-12 atom, which has an atomic mass of 12 amu.

      (2) The mass of a hydrogen atom is 1.007825 amu (1 proton + 1 electron)

      (3) The mass of a Uranium-238 atom is 238.0508 and the mass of a U-235 atom is 235.0439.

4. Atomic Weight

   a. Average weight of an element based on the percent abundance of its naturally occurring isotopes

   (1) using $^{13}_{6}C$ and $^{12}_{6}C$

      (2) 12.00 (0.989) + 13.00 (0.011) = 11.868 + 0.143 = 12.011 amu.

   b. Units are expressed in AMU

   c. Used in calculations of chemical reactions

G. Nuclide Notation　　　　　　　　　　　　　　　　　　　　　　Objective 1.03.07

　　1.　$_Z^A x$ format where:

　　　　a.　X is the symbol for the element.

　　　　b.　Z is the atomic number - the number of protons.

　　　　c.　A is the mass number - number of protons (Z) plus the number
　　　　　　of neutrons (N); therefore, A=Z+N

　　2.　Uranium-238 would be written $_{92}^{238}U$

H. Modern Periodic Table　　　　　　　　　　　　　　　　　　　See Fig. 5 -
　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　"Periodic Table of
　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　The Elements"

　　1.　The modern Periodic Table is an arrangement of the elements in
　　　　order of increasing atomic number. A comparison of the properties　　Objective 1.03.08
　　　　for selected elements will illustrate that there is a predictable,
　　　　recurring pattern (periodicity). This observation is summarized in
　　　　the Periodic Law - the properties of the elements are repetitive or
　　　　recurring functions of their atomic numbers.

　　2.　Data about each element in the Periodic Table are present in a
　　　　column and row format. The rows or horizontal sections in the
　　　　Periodic Table are called periods. The columns or vertical sections　　Objective 1.03.09
　　　　in the Periodic Table are called groups or families.

　　3.　The structure of the Periodic Table is directly related to the
　　　　arrangement of electrons in the atoms.

　　4.　Electrons orbit around the nucleus in structured shells, designated　　See Table 3 -
　　　　sequentially as 1 through 7 (K through Q) from inside out. Shells　　"Electron
　　　　represent groups of energy states called orbitals. The higher the　　Configuration of
　　　　energy of the orbital the greater the distance from the nucleus. The　　the Elements"
　　　　lowest energy state is in the innermost shell (K).　　　　　　　　See Fig. 4 -
　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　"Electron Shells"

　　5.　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: $n = 2 \rightarrow 2(2^2) = 8$

6. 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.

7. 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.

   Objective 1.03.10

8. 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 - table salt

9. Note the right most column in the Periodic Table. These elements are known as the noble or inert gases because they all have a full valence shell. 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.

10. The Quantum Mechanical Model

a. 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.

b. The quantum mechanical model further states that the energy levels are subdivided into sublevels, referred to by the letters *s*, *p*, *d* and *f*. An energy level can contain 1 to 4 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.

III. SUMMARY

A. Review major topics

    1. Physics definitions

    2. Law of Conservation of Energy

    3. The Atom

    4. Periodic Table

    5. Valence Electrons

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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

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.

Instructional Aids:
1.   Overheads
2.   Overhead projector and screen
3.   Chalkboard/whiteboard
4.   Lessons Learned

I.   MODULE INTRODUCTION

   A. Self-Introduction

      1. Name

      2. Phone number

      3. Background

      4. Emergency procedure review

   B. Motivation

      This lesson is designed to provide an understanding of the forces present within an atom.

   C. Overview of Lesson

      1. Nucleon

      2. Nuclide

      3. Isotope

      4. Mass-Energy Equivalence

      5. Mass Defect

      6. Binding Energy

      7. Fission

      8. Criticality

      9. Fusion

   D. Introduce Objectives

                  O.H.: Objectives

II. MODULE OUTLINE

   A. Nuclear Terminology

                  Objective 1.04.01

      1. Nucleon - a constituent particle of the nucleus, either a proton or a neutron

      2. Nuclide

    a. Atoms with a specific combination of neutrons and protons

    b. Nuclides have individual blocks on the Chart of the Nuclides

3. Isotope

    a. Have the same number of protons but different number of neutrons

    b. Same atomic number but different atomic mass number

    c. Isotopes of Hydrogen have one proton; however, the atomic mass number is different

    d. Protium (^{1}H) has A=1, deuterium (^{2}H) has A=2, tritium (^{3}H) has A=3

B. Mass - Energy Equivalence

Objective 1.04.02

1. Theory on Relativity developed by Albert Einstein in 1905

2. Equation: Write equation on board

    E   =   mc^{2}

    where:

    E   =   Energy

    m   =   mass

    c   =   speed of light

3. Mass may be transformed to energy and vice versa

4. Mass and energy are interchangeable

5. The mass of an object depends on its speed

6. Matter contains energy by virtue of its mass

7. Energy/Mass cannot be created or destroyed, only converted

Information only

8. Pair Annihilation (Mass to Energy example)

    a. When a positron and electron collide, both particles
    are annihilated and their mass is converted to energy

    b. Mass of electron/positron is 0.00054858026 amu,
    annihilation energy will be:

(1 amu = 931.478 MeV)

$$\frac{2(0.00054858026\,amu)}{1} \times \frac{931.478\,MeV}{amu} = 1.022\,MeV$$

C. Mass Defect/Binding Energy   Objective 1.04.03

  1. Mass Defect   See Fig. 1 "Atomic Scale"

    a. Difference between the sum of the protons and
    neutrons and the actual mass of a nuclide

    b. 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)

    c. Example for $^{2}_{3}$Li :   Work example on board

      1)   A   =   7
                Z   =   3
                M   =   7.01600 amu

      2) Therefore:

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

2. Binding energy

    a. The energy equivalent of mass defect

    b. Example for $_3^7\text{Li}$:

Work example on board
(1 amu = 931.478 MeV)

$$BE = \frac{0.042164\,amu}{1} \times \frac{931.478\,MeV}{amu} = 39.72\,MeV$$

3. Binding energy of a neutron

    a. Energy added to a nucleus by adding the mass of a single neutron

    b. Must be calculated for each isotope to determine value

    c. Example for ^{235}U:

Work example on board

$$\Delta m = (m_n + m_{U235}) - m_{U236}$$
$$\Delta m = (1.00867 + 235.0439) - 236.0456$$
$$\Delta m = 0.0070\ amu$$
$$0.0070\ amu \times 931.5\ MeV/amu = 6.52\ MeV$$

4. Binding energy per nucleon

See Fig. 2 "Binding Energy vs. Mass Number"

    a. Calculated by dividing the total binding energy of an isotope by its mass number

    b. Example for $_3^7\text{Li}$:

Work example on board

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

    c. Peaks at about 8.5 MeV for mass numbers 40 – 120

5. Nuclear Transformation Equations (Q Value)

Example alpha decay for ^{226}Ra:

$$_{88}^{226}\text{Ra} \longrightarrow {}_{86}^{222}\text{Rn} + {}_2^4\alpha + Q$$
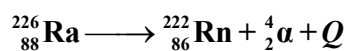
D. Terminology

Objective 1.04.04

1. Fission

a. Splitting of a nucleus into at least two other nuclei
    with the release of energy

b. Two or three neutrons are generally released

c. Liquid drop model

    1) Equates the nucleus with a drop of water   See Fig. 3 "Liquid Drop Model of
                                                   Fission"

    2) Each contains cohesive forces

    3) When forces are overcome, the water drop/atom
        will split/fission

d. Fissile nuclei

    1) Neutron binding energy must exceed critical
        energy for fission

    2) Critical energy for fission (E_c): The energy
        required to drive the nucleus to the point of
        separation.

    3) No kinetic energy required by the neutron

    4) Fissile nuclei: ^{235}U, ^{233}U, ^{239}Pu

                                        See Fig. 4 "^{235}U Fission Process"

e. Fissionable nuclei

                                        Fertile material is a term used to

    1) Neutron binding energy not enough to exceed   describe nuclides which generally
        critical energy for fission   themselves do not undergo induced
                                          fission (fissionable by thermal

    2) Kinetic energy required to cause fission   neutrons) but from which fissile
                                          material is generated by neutron

    3) ^{238}U, ^{232}Th   absorption and subsequent nuclei
                                          conversions. Fertile materials can

f. Energy released   occur naturally and can be converted
                                          into a fissile material by irradiation

    1) Makes two smaller nuclei from one large   in a reactor.
        nucleus

    2) Binding energy per nucleon increases

    3) Approximately 200 Mev released per fission (for
        ^{235}U)

g. Fission product

        1) Created during fission

        2) Normally unstable - N/P ratio too high

        3) Will undergo radioactive decay until stable - May take less than a second to several hundred years to reach stability

  2. Criticality

    a. Criticality is the condition in which the number of neutrons produced by fission is equal to the number of neutrons produced in the previous generation   See Fig. 5 "Chain Reaction"

    b. The effective multiplication constant or 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.   See Table 1 - "The Effective Multiplication Constant"

        1) Subcritical - $K_{eff} < 1$

        2) Critical - $K_{eff} = 1$

        3) Supercritical - $K_{eff} > 1$

  3. Fusion

    a. Fusion builds atoms

    b. The process of fusing nuclei into a larger nucleus with an accompanying release of energy

    c. Change of mass

    d. Energy released

III. SUMMARY

  A. Review major topics

    1. Nucleon

    2. Nuclide

    3. Isotope

    4. Mass-Energy Equivalence

     5.   Mass Defect

     6.   Binding Energy

     7.   Fission

     8.   Criticality

     9.   Fusion

   B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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

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. 160 "Ionizing Radiation Exposure of the Population of the United States".

Instructional Aids:

1.   Overheads
2.   Overhead projector/screen
3.   Chalkboard/whiteboard
4.   Lessons Learned

I. MODULE INTRODUCTION

     A. Self-Introduction

         1. Name

         2. Phone number

         3. Background

         4. Emergency procedure review

B. Motivation

    1. Radiation sources are not limited to nuclear facilities. The study of sources provides data for:

        a. Basis for occupational exposures

        b. Effects from high source exposures

        c. Assesses impact from nuclear facilities

        d. Determines use of building materials

C. Overview of Lesson

    1. Terrestrial radiation

    2. Cosmic radiation

    3. Internally emitted radiation

    4. Radon

    5. Nuclear fallout

    6. Medical exposures

    7. Consumer products

    8. Nuclear facilities

                                                    O.H.: Objectives

D. Introduce Objectives

II. MODULE OUTLINE

A. Natural Background Radiation Sources

    1. Terrestrial Radiation

Objective
1.05.01 a.

        a. Earth

Explain: Different books will use other dose rates. The references used here are NCRP reports.

           1) Source - small amounts of radioactive material found in rock and soil

           2) Major isotopes: Uranium and Thorium

           3) Exposure dependent on location

               Atlantic and Gulf coastal = 15-35 mrem/yr
               Greater U.S. = 35-75 mrem/yr
               Colorado Plateau = 75-140 mrem/yr

           4) Exposure dependent on type of soil

               Volcanic - 125 mrem/yr
               Sandstone - 50 mrem/yr
               Limestone - 25 mrem/yr

           5) U.S. average: 1 sq mile 1 ft deep contains 1 ton K-40, 3 tons U-238, 6 tons Th-232

           6) Extremely high locations - due to high concentrations of monazite:

Monazite: a Thorium Mineral

         Kerala India - Population is 70K
            16K receive >500 mrem/yr
          500 receive >2,000 mrem/yr
           Highest: 5,865 mrem/yr
             Minas Garais Brazil
           Average: 1,160 mrem/yr
            Max: 12,000 mrem/yr

        b. Radioactivity in Water

           1) All water contains some radioactivity

2) Examples

Sea water contains K-40
Natural springs contain U and Th
Rainwater picks up radioactivity from the air
Ground water picks up radioactivity from the soil Contributor
to internal doses

c. U.S. average of alpha emitters in water is <1 pCi/l

1) Colorado – 40-50 pCi/l

2) Brazil – 240 pCi/l (bottled water)

d. U.S. national average from terrestrial (NCRP Report No. 95) is
28 mrem/yr

2. Cosmic Radiation   Objective
                                                                     1.05.01 b.

a. Natural radiation originating from outside of our atmosphere

b. Discovered during early terrestrial experiments with weather
balloons

c. Primary

1) Galactic Cosmic Rays

From outside the solar system

Positively charged particles

•   87% protons
•   11% alpha
•   2% misc.

High energies - up to 10^{20} eV

2) Geomagnetically Trapped

When galactic rays approach earth, they must have enough
energy to pass through magnetic fields

If they lack enough energy, they become trapped in two
energy bands

- 1K - 3K meters
- 12K - 15K meters

3) Solar Cosmic Rays

   Produced by severe solar flares

   Consist mainly of protons

   High energy - detected on ground

   Low energy - detected at high alt.

   Measurements

   - 30,000 ft - 100 mr/hr
   - 80,000 ft - 10 R/hr

   Concern for high altitude space travel

d. Secondary

   1) Results from the interaction of primaries with the earth's atmosphere

   2) Cascade effect: one primary ionization = 100 million secondary ionizations

   3) Products produced: pions, muons, electrons, photons, protons, neutrons

   4) Primaries absorbed within the upper 10% of the atmosphere

   5) Dominant components at ground level are penetrating muons and the electrons they produce.

   6) Latitude contributes a small factor due to the earth's magnetic field

   7) Exposures increase with altitude, decrease with latitude (Denver 50 mr/yr cosmic)

   8) U.S. average = 27 mrem/yr

3. Internal Emitters (Food Chain)   Objective
                                                                     1.05.01 c.

   a. Results from the transfer of natural radiation from the food chain to man

    b.   Deposited internally from trace amounts found in soil, water and air

    c.   Isotopes: Primary - K-40
others - Rb-87, Ra-226, U-238, Po-210, C-14

    d.   U.S. national average is 39 mrem/yr from Internal Emitters

4.   Radon

    a.   Due mostly to Radon and thoron gas

    b.   Radon is a product of the U-238 Series

        U-238 6 Th-234 6 Pa-234 6 U-234 6 Th-230 6
Ra-226 6 Rn

    c.   Thoron is a product of the Th-232 series

        Th-232 6 Ra-228 6 Ac-228 6 Th-228 6 Ra-224 6
Rn-220

    d.   U and Th are present all over. Daughter products diffuse to the surface. These gases attach themselves to dusts and aerosols which are inhaled.

    e.   Radon concentrations are based on amounts of U and Th in the area

    f.   Factors:

- Weather (inversions)
- Indoor insulation
- Ventilation rate

    g.   High Areas:

- Colorado (Grand Junction) – mine tailings
- Pennsylvania – High radium concentration
- Underground mines, caves, caverns, etc.
- Helsinki – 240 rem to lung from radon

Most has been removed

    h.   U.S. national average for inhaled radionuclides is 200 mrem/yr.

Objective
B. Man Made Background Radiation Sources   1.05.02 a.

  1. Nuclear Fallout

    a. Refers to the debris that settles as a result of weapons testing

    b. Contains over 200 fission products, bomb parts and all near-blast matter

    c. Dispersement is a function of:

      1) Bomb yield

          Kiloton Range - troposphere, 9,000 - 17,000 meters - easily washed down

          Megaton Range - Stratosphere, may stay aloft for five years

      2) Types of blast

          Surface burst
          Above ground

      3) Meteorological Factors - (weather)

    d. Weapons test ban treaty of 1962-63 limited testing

    e. U.S. average from nuclear fallout is <1 mrem/yr (NCRP #93)

  2. Medical Exposures

                                                                              Objective
    a. Diagnostic X-rays   1.05.02 b.

      1) Over 300,000 X-ray units in the U.S., about 67% of adult population is exposed each year

      2) X-ray machines consist of:

        a) X-ray tube

        b) HV Supply

        c) Filament

        d) Shielding

      3) Three general types:

       a)   Radiography - X-ray tube and a photographic plate (Chest, Dental)

       b)   Fluoroscope - Uses an image intensifier, observes internal processes

       c)   Photofluorographic - Fluorescent screen and camera, large amounts of people

   b.   Medical Radionuclides (Two Types)

     1)   Nuclear Medicine

       Used to diagnose medical problems

       Attaches a radionuclide to a pharmaceutical that will seek a particular organ

- Radionuclide selection:
- Photon emitter
- Short lived

       Tc-99m, In-113m

     2)   Radiation Oncology

       Uses high energy power source to treat tumors

       Typical 6,000 Curie Co-60 source delivers 100 Rad/min

     3)   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)

3.   Consumer Products (NCRP Report 56)   Objective 1.05.02 c.

   a.   Television (Example)

     1)   Source -- X-rays from High Voltage a few.

     2)   Limit (1960) -- 0.5 mr/hr at 5 cm

     3)   1967 - 149 big screen TVs were recalled, 2 emitted greater than 100 mRad/hr

4) U.S. average -- 0.5 to 1.5 mr/yr

b. Shoe fitting fluoroscopes (Example)

1) Source - X-ray tube

2) 1953 - 10,000 in use

3) Exposures - 7 to 14 R per 20 sec exposure GSD - 30 to 170 mr

c. Radioluminous Watches (Example)

1) Source - Ra-226 "Glow in the Dark"

2) 10,000,000 still in use

3) Pr-147 and H-3 used today

d. Hundreds of other products contribute

1) U.S. national average from all consumer products is
10 mrem/yr

4. Nuclear Facilities

a. Public exposures from

1) Mining (several hundred) and milling (20 mills)

2) Fuel Fabrication (21 facilities)

Objective
1.05.02 d.

3) Reactors (~90 power, 300 non-power)

b. U.S. national average - <1 mrem/yr

C. 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.

III. SUMMARY

A. Review major topics

1. Terrestrial radiation

2. Cosmic radiation

3. Internally emitted

    4. Radon

    5. Nuclear fallout

    6. Medical exposures

    7. Consumer products

    8. Nuclear facilities

  B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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
                 c.
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

References:

1.   "Training Publication 89n, Training Publication 30n"; GPO
         Division of Radiological Health.
2.   ANL-88-26 (1988) "Operational Health Physics Training"; Moe,
         Harold; Argonne National Laboratory, Chicago.
3.   "Health Physics and Radiological Health Handbook"; Shleien;
         1992.
4.   "Chart of the Nuclides"; Sixteenth Edition, Knolls Atomic; 2003.
5.   "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th
         ed.; Pacific Radiation Corporation; 2008.
6.   DOE/HDBK-1019 (January 1993) "Nuclear Physics and Reactor
         Theory" Volume 1 of 2; DOE Fundamentals Handbook Series.

Instructional Aids:

1.   Overheads
2.   Overhead projector/screen
3.   Chalkboard/whiteboard
4.   Lessons learned

I. MODULE INTRODUCTION

A. Self Introduction

     1. Name

     2. Phone number

     3. Background

     4. Emergency procedure review

B. Motivation

Atoms consist of protons, neutrons, and electrons and only certain combinations of protons and neutrons exist in nature. Specific combinations of protons and neutrons within the nucleus determine whether nuclei are stable or unstable. Stable nuclei have no excess energy, while unstable nuclei, due to their surplus energy, transform themselves into stable nuclei by giving up energy. The emission of this extra energy to achieve stability is the phenomenon of *radioactivity*.

C. Overview of Lesson

     1. Neutron to proton ratio

     2. Radioactivity and radioactive decay

     3. Radiation characteristics

     4. Decay modes

     5. Natural/artificial radioactivity

     6. Fission product stability

     7. Chart of the nuclides

     8. Units of activity

     9. Activity calculation

     10. Measurement terminology

D. Introduce Objectives   O.H.: Objectives

II. MODULE OUTLINE   Objective 1.06.01

  A. Nuclear Stability   See Table 1 - "Forces Acting in the Nucleus"

    1. Forces in the Nucleus

      a. Gravitational Force: very weak attractive force between all nucleons; acts over a relatively long range.

      b. Electrostatic Force: a strong repulsive force between like charged particles (protons); acts over a relatively long range.

      c. Nuclear Force: a strong attractive force between all nucleons; acts over an extremely short range.

      d. In stable atoms the attractive and repulsive forces balance (are equal). If forces are not balanced the nucleus will be unstable.

    2. Neutron/Proton Ratio

      a. Only certain combinations or ratios of neutrons and protons will result in a balance of these forces (stable).

      b. For atomic numbers less than 20, the neutron to proton ratio (n:p) is about 1:1.

      c. As number of protons is increased, the electrostatic force increases. The numbers of neutrons must increase more rapidly in order for the nuclear force to balance with electrostatic force.

      d. As Z increases above 20 the n:p ratio gradually increases until Z = 83, where stable ratio is about 1.5:1.

      e. There are no completely stable nuclei with Z > 83.

      f. By graphing the numbers of neutrons against the number of protons for stable isotopes, a "line of stability" is depicted.

    3. Stability Ranges

      a. Nuclear stability is governed by the particular combination of neutrons and protons in a given nucleus.   See Fig.1 - "Neutron:Proton Ratios for Stable Nuclides"

b. Because many elements have several stable isotopes, there is a range for numbers of neutrons that will be stable in a nucleus with a certain number of protons.

c. A nuclear arrangement outside of this range will be unstable. An unstable nucleus will attempt to become stable by changing its nuclear configuration.

d. Nuclear configuration is changed by eliminating excess neutrons or protons, thereby changing the n:p ratio becoming more stable.

Objective 1.06.02

B. Radioactivity

1. Definitions

a. Nuclear configuration changes occur through transformations. This is done by changing neutrons to protons, or vice versa and then ejecting the surplus mass or energy from the nucleus.

b. Particles or energy emitted from the nucleus is called radiation. Radiation can be in the form of particles or waves.

c. The property of certain radionuclides 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 term radionuclide has been coined to refer to these "radioactive nuclides."

d. The emission of a particle or electromagnetic radiation in order to reach a more stable configuration produces a change or transformation.

e. 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.

f. 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.

g. 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.

h. The nucleus before the decay (or transformation) is called the parent and the nucleus after the decay is called the daughter.

i. 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.

j. 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 endproduct.

2. Nature of Radioactivity

a. 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.

b. 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.

c. 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.

d. After a long and complicated series of investigations, to which many outstanding physicists contributed, a better understanding of natural radioactivity was available.

e. 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.

C. Modes of Decay and Types of Radioactive Emissions

1. 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.

    Objective 1.06.03

2. 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.

3. 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.

4. Alpha Decay

    a. With a few exceptions, only relatively heavy radioactive nuclides decay by alpha emission.

        Objective 1.06.04 a.

    b. An alpha particle is essentially a helium nucleus. It consists of two protons and two neutrons, giving it a mass of 4 amu.

    c. Because of the two protons it has an electric charge of +2.

    d. The symbol α is used to designate alpha particles.

    e. 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:

    $$\, _{Z}^{A}X \rightarrow \, _{Z-2}^{A-4}Y + \, _{2}^{4}\alpha$$

    f. For example, Radium-226 decays by alpha emission to produce Radon-222 as follows:

    $$\, _{88}^{226}Ra \rightarrow \, _{86}^{222}Rn + \, _{2}^{4}\alpha$$

    g.   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.

5.   Beta Decay   Objective 1.06.04 b.

    a.   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.

    b.   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.

    c.   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).

    d.   Beta particles originate in the nucleus, in contrast with ordinary electrons, which exist in orbits around the nucleus.

    e.   The symbol β^- is used to designate beta particles.

    f.   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.

    g.   In order to conserve energy and momentum between the parent and the daughter plus beta particle there is also the emission of an antineutrino, symbolized by the Greek letter nu with a bar above it $\left(\bar{v}\right)$.

    h.   The standard notation for beta decay is:

$$_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + \beta^- + \bar{v}$$

     i.   For example, Lead-210 decays by beta-minus emission to produce Bismuth-210 as follows:

     j.   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 $1/3 E_{max}$.

     k.   They travel several hundred times the distance of alpha particles in air and require a few millimeters of aluminum to stop them.

     1.   Neutrinos (ν) and anti-neutrinos $\left(\bar{v} \right)$ 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.

6.   Positron Decay   Objective 1.06.04 c.

     a.   A nuclide that has a low n : p ratio (too many protons) will tend to decay by positron emission.

     b.   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.

     c.   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.

     d.   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."

     e.   The symbol β^+ is used to designate positrons.

     f.   With positron emitters, the parent nucleus changes a proton into a neutron and gives off a positively charged particle.

    g. 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.

    h. The emission of a neutrino (symbolized by ν) also occurs in conjunction with the positron emission.

   i. Positron decay is illustrated by the following notation:

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z-1}Y + \beta^+ + \nu$$
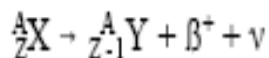
    j. For example, Nickel-57 decays by positron emission:

$$^{57}_{28}Ni \rightarrow \, ^{57}_{27}Co + \beta^+ + \nu$$
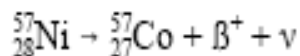
7. Electron Capture

    a. For radionuclides having a low n : p ratio, another mode of decay can occur known as orbital electron capture (EC).

    b. 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. This mode of decay is frequently referred to as K-capture. The nucleus might conceivably capture an L shell electron, but K electron capture is much more probable.

The nucleus might conceivably capture an L shell electron, but K electron capture is much more probable.

    c. The transmutation resembles that of positron emission, as follows:
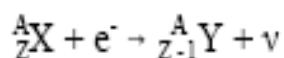
$$^{A}_{Z}X + e^- \rightarrow \, ^{A}_{Z-1}Y + \nu$$

    d. The electron combines with a proton to form a neutron, followed by the emission of a neutrino.

    e. 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.

    f. Either positron emission or electron capture can be expected in nuclides with a low n : p ratio.

    g. The intranuclear effect of either mode of decay would be to change a proton into a neutron, thus increasing the n : p ratio.

h. Note that ^{57}Ni has two modes of decay. This is an example of branching which is explained in the section DECAY PHENOMENA.

$$^{57}_{28}\text{Ni} + e^- \rightarrow {}^{57}_{27}\text{Co} + \nu$$
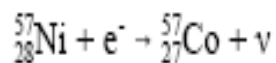
8. Gamma Emission

a. 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.

b. 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.

c. The symbol γ is used to designate gamma radiation.

d. Since the gamma decay doesn't involve the gain or loss or protons or neutrons, the general equation is slightly different from the other decay equations.

$$^{A}_{Z}\text{X}^* \rightarrow {}^{A}_{Z}\text{X} + \gamma$$

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.

e. 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.	See Table 2 - "Types of Radioactive Emissions" and Table 3 - "Modes of Decay"

9. Other Types of Transformations

    a. Internal conversion

        1) This phenomenon 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.

        2) The photon is said to have undergone internal conversion.

        3) The conversion electron is ejected from the atom with kinetic energy equal to the gamma energy minus the binding energy of the orbital electron.

        4) This process usually takes place in the K-shell. There will then follow emission of characteristic X-rays as with electron capture.

In principle, internal conversion is similar to the photoelectric effect (to be discussed in Lesson 1.07).

    b. Isomeric transition

        1) 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.

        2) 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.

        3) The metastable or excited state, is usually represented by a small m following the mass number, A, in the standard nuclide notation.

        4) For example, Technetium-99m and Technetium- 99 are isomers. $^{99m}_{43}Tc$ will decay $^{99}_{43}Tc$ with the emission of a 140.5 keV gamma.

Generally, the isomer achieves ground state by emitting delayed (usually greater than 10^{-9} seconds) gamma radiation.

Further radioactive decay can still occur from the ground
state. In this case, ^{99}Tc decays to ^{99}Ru, which is stable.

D. Decay Phenomena   Objective 1.06.05

1. Each radionuclide, artificial and natural, has its own characteristic
    pattern of decay. There are several aspects associated with this
    pattern:

    a. Modes of decay

    b. Types of emissions

    c. Energies of the emissions involved

    d. Rate of decay

2. Mode of Decay

    a. All nuclei of a given radionuclide seeking stability by ^{226}Ra decays by
        radioactive decay do so in a specific manner.   alpha emission
                                                                           which is
    b. There are some radioactive nuclides which may decay with   accompanied by a
        branching, whereby a choice of decay modes exists. In such   gamma photon.
        case, a definite branching ratio exists.   This represents the
                                                                           only mode of decay
        A case in point is the decay of ^{57}Ni, mentioned previously.   open to ^{226}Ra.
        This isotope of nickel decays 50% by K-capture and 50% by
        β^+ emission. The branching ratio would be:

        $$\frac{\beta^+}{EC} = 1$$

3. Types and energies of Emissions

    a. 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.

    b.   The energies associated with radiations are given in terms of "million electron volts" (MeV).

        1)   Beta emissions may occur with energies to about 5 MeV

        2)   Alpha particles to about 10 MeV

        3)   Gamma photons to about 3 MeV.

    c.   The energy of the particulate radiations is manifested as kinetic energy--the higher the energy the greater the velocity of the particle.

    d.   The velocity of photons is constant (c = speed of light) and energy differences are manifested by varying wavelengths and frequencies.

4.   Rate of Decay

    a.   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.

    b.   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.

    c.   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.

5.   Singly-occurring Natural Radionuclides

    a.   Careful measurements show that almost all materials contain traces of radioactivity.

    b.   One might suspect that these traces might be due to contamination with some of the heavy radionuclides belonging to one of the radioactive series described. However, some of the lighter elements are themselves weakly radioactive.

See Table 4 - "Naturally occurring Radionuclides"

c. 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:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

6. Artificial Radioactivity   Objective 1.06.06

a. 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.

b. As implied in the nomenclature, natural and artificial radioactivity differ in origin. There are other distinctions between the two types which will be discussed.

c. 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.

d. A brief account of the discovery of artificial radioactivity will be given before further discussing its similarities and dissimilarities to natural radioactivity.

7. Induced Transmutations

a. 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.

b. 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.

$$^{14}_{7}N + ^{4}_{2}\alpha \rightarrow \rightarrow \rightarrow ^{17}_{8}O + ^{1}_{1}H$$
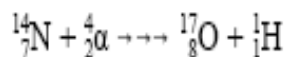
    c.   Since the discovery of the transmutation of nitrogen, many hundreds of artificial or induced transmutations have been found. Until 1932, most induced transmutations were performed utilizing naturally occurring alpha emitters as sources of incident particles.

    d.   With the development of particle accelerators, other bombarding particles have been successfully used. No attempt will be made here to catalog the many kinds of possible transmutations, nor will any attempt be made to discuss the theory and quantitative data regarding nuclear reactions.

8.   Induced Radioactivity

    a.   During the first 15 years of experimental work with nuclear reactions, the transmutation products (insofar as could be observed) were not radioactive.

    b.   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.

    c.   It was determined in 1934 that induced transmutations could produce nuclei which were residually unstable in somewhat the same manner as naturally occurring radionuclides.

    d.   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.

        1)   The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of induced or artificial radioactivity:

$$^{27}_{13}Al + ^{4}_{2}\alpha \rightarrow \rightarrow \rightarrow ^{30}_{15}P + ^{1}_{0}n$$
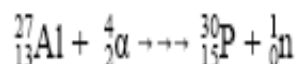
2) The resultant nucleus $^{30}_{15}$P was observed to be radioactive,

emitting a small charged particle and reaching stability within minutes.

e. 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

9. Natural vs. Artificial

a. Heavy radionuclides (natural, and artificial) generally decay by a long series of alpha and beta emissions.

b. Lighter, artificial radionuclides, such as activation and fission products, usually decay by beta or positron emission or by orbital electron capture.

c. In contrast to natural radioactivity, lighter artificially-produced radionuclides generally revert to stability in only a few decay steps.

10. Fission Products

a. 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.

b. For example, take a thermal fission of ^{235}U:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{55}Cs + ^{90}_{37}Rb + 2(^{1}_{0}n)$$

1) 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.

2) The stable ratio for Rubidium (^{85}Rb) is 1.3:1, while the product above has a ratio of about 1.5:1.

3) As can be seen, the fission products in the above equation have too many neutrons.

c. Each fission fragment initiates a radioactive series, called a fission decay chain, involving several successive beta decay transformations.

    d.   Fission product beta emission, as with other beta emitters, generally is accompanied by gamma emission.

  i. Predicting Mode of Decay

    a.   Radioactive nuclides tend to decay in a way that results in a daughter nuclide that lies closer to the line of stability.

    b.   Nuclides below the line of stability will usually undergo beta-minus decay.

    c.   Nuclides above the line of stability will usually undergo positron decay or electron capture.

    d.   Nuclides at the upper end of the line of stability will usually undergo alpha decay.

    e.   Figure 2 illustrates the type of decay nuclides in different regions will typically undergo.

> These are general rules that have many exceptions, especially in the region of heavy nuclides.

E. Radioactive Families

> Objective 1.06.08

  1. The transmutations associated with naturally-occurring radionuclides frequently yield a daughter which is also radioactive.

  2. To date, about 70 different naturally occurring radionuclides have been identified, each with its own characteristic pattern of radioactivity.

  3. Most of these yield radioactive daughters and are now known to be intimately interrelated in radioactive series or families.

  4. Three Natural Decay Series

    a.   It has been established that most isolated radioactive species with $Z > 82$ belong to one of three independent groups or families.

> See Fig. 3 - "Natural Decay Series"

    b.   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.

c. One family starts with Uranium-238 ($_{92}^{238}$U) and is called the Uranium series.

d. Another starts with Thorium-232 ($_{90}^{232}$Th) and is called the Thorium series.

e. A third starts with Uranium-235 ($_{92}^{235}$Th) and is called the Actinium series.

f. In each series, there is a "seesawing" in the transmutation chain between decreasing the atomic number by two with α emission and increasing it by one with β- emission.

g. Each series has an isotope of Radon [historically known as Radon ($_{86}^{222}$Rn), Thoron ($_{86}^{222}$Rn), and Actinon ($_{86}^{219}$Rn) respectively] as a member of the series. All isotopes of Radon are radioactive and are gases at standard temperature and pressure.

h. Each series ends in a different stable isotope of Lead ($_{82}^{206}$Pb , $_{82}^{208}$Pb , $_{82}^{207}$Pb and respectively).

i. Figure 3 shows the three natural decay series.

5. Artificial Series

a. 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.

b. The longest-lived radionuclide in the series is $_{93}^{237}$Pb with a half-life of 2.2E06 years.

c. Assuming the age of the earth is 2.2E09 years, this would indicate that, from the time of creation, ^{237}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}.

The historical name of ^{235}U was "Actinouranium." Note its third daughter.

It is obvious, therefore, why it would be difficult to find traces of neptunium and its descendants in nature.

F.   Chart of the Nuclides   Objectives 1.06.09
                                                                       and 1.06.10

   a.   General Arrangement

      a.   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

      b.   Such a plot at once reveals the continuity in composition in
           progressing from the lighter to the heavier elements. Post Chart
           in classroom or provide books for students to use during
           discussion.

      c.   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 book.

   b.   Specific Nuclide Representation

      a.   Each specific nuclide is represented in the Chart of the Nuclides
           by a block.

      b.   The coloring and labeling of each block specifies certain
           information concerning the properties of the nuclide.

      c.   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.

                                                                       Refer students to
                                                                       block for ^{23}Na.
      d.   A grey block denotes a stable nuclide. A typical example is   Discuss block color
                                                                       and values, such as
           stable sodium ($^{23}_{11}Na$).   percent abundance,
                                                                       activation cross-
      e.   Unlike sodium, most elements have more than one stable   section and atomic
           isotope. For example, magnesium (Mg) has three stable isotopes.   mass.

                                                                       Refer students to
                                                                       blocks for ^{24}Mg,
                                                                       ^{25}Mg and ^{26}Mg.
                                                                       Discuss and
                                                                       compare values.

f. A white block denotes an artificially produced radioactive nuclide. A typical example is $_{26}^{59}\text{Fe}$.	Refer students to block for ^{59}Fe. Discuss half-life, emissions and energies, etc.
g. 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).	
h. A grey block with a black bar across the top denotes a long-lived, naturally- occurring radioactive isotope. $_{92}^{238}\text{U}$ is a good example.	Refer students to block for ^{90}Sr. Discuss values. Refer students to block for ^{238}U. Discuss block colors and values.

c.   Depicting Nuclear Processes

a.   As a result of decay, radionuclides shift from block to block within the Chart of the Nuclides. The diagram shows the relative locations of the products of various nuclear processes.

> Refer students to diagram in Study Guide

b.   As can be seen, the relative locations (displacements) of the primary modes of decay are:

> These changes are depicted in the "Guide for using the Chart of the Nuclides."

1)   Alpha (α):
down 2, left 2 ($\downarrow\downarrow, \leftarrow\leftarrow$)

2)   Beta (β-):
up 1, left 1 ($\uparrow\leftarrow$)

3)   Positron (β+)/EC:
down 1, right 1 ($\downarrow\rightarrow$)

c.   Displacements can also occur as a result of nuclear reactions brought about through bombarding given nuclides with various nuclear particles or gamma photons.

d.   Chart of the Nuclides Summary

a.   The Chart of the Nuclides provides considerable information about the behavior of nuclides. There is continuity in composition of the nuclides.

b. 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.

c. Nuclides below this line are characterized by having an excess of neutrons and will, in general, be beta particle emitters.

d. Nuclides above this line are characterized by having an excess of protons and will, in general, decay by positron emission or electron capture.

e. Nuclides lying beyond the line of stability will, in general, demonstrate a tendency to seesaw between alpha decay and beta decay.

f. All nuclides, if followed through their various decay schemes will eventually end in a gray box (stable isotope).

g. 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) Energies of emissions

        c) Half-life   Objective 1.06.11

G. Units of Activity

    1. The rate of decay of a radioactive substance constitutes the quantity of radioactivity, or activity, in that substance.

        a. The definition of activity refers to the number of transformations (disintegrations) per unit time.

        b. 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.

c.   The SI unit of activity is the becquerel, while the historical unit is the curie. Each will be discussed below.

2.   The Curie   Objective 1.06.11 a.

a.   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.

1)   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.

2)   If permitted to attain this equilibrium, one gram of radium will produce about 0.66 mm^3 of radon.

3)   In this quantity of radon, about 37 billion atoms disintegrate each second.

b.   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.

c.   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.

d.   Current regulations define the curie (Ci) as 3.7E10 disintegrations per second (2.22E12 dpm).

e. Since the curie represents a very large amount of activity, often smaller, and more convenient subunits are used.	See Table 5 - "Curie Subunits"
3. The Becquerel	Objective 1.06.11 b.
a. 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).	1 dps = 1 Bq
b. Since the becquerel is a rather small unit, metric prefixes are often applied to aid in designating larger amounts of activity.	See Table 6 - "Becquerel Superunits"

c. The relationship between the becquerel and curie is:

1) 1Bq = 1 dps = 2.7E-11 Ci

2) 1 Ci = 3.7E10 dps = 3.7E10 Bq

4. Using unit analysis and conversion, activity measurements given in dps, dpm or curies can be converted to becquerels.

H. Specific Activity	Objective 1.06.12

1. Specific activity is defined as the activity per unit mass of a radioactive substance.

2. Reported in units such as curies per gram (Ci/g) or becquerels per kilogram (Bq/kg).

3. Recall that the curie originated from the number of emanations from one gram of radium every second.

4. 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.

5. 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 ($T_{\frac{1}{2}}$ = 5.27 years) would have a mass less than 0.9 milligrams, whereas a curie of natural ^{238}U ($T_{\frac{1}{2}}$ = 4.5E9 years) would require over two metric tons of the metal.

6. Obviously, the shorter the half-life of a radionuclide, the greater its specific activity.

I. The Radioactive Decay Law

1. The activity of any sample of radioactive material decreases or decays at a fixed rate which is a characteristic of that particular radionuclide.

2. No known physical or chemical agents (such as temperature, pressure, dissolution, or combination) may be made to influence this rate.

3. The rate may be characterized by observing the fraction of activity that remains after successive time intervals.

4. For convenience we choose a fraction that is easy to work with, one-half (½).

5. 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.

6. This time that is required for the activity present to be reduced to one-half we call the half-life.   Objective 1.06.13

7. 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.

   a. One half-life reduces to $(\frac{1}{2})^1$

   b. Two half-lives reduces to $\frac{1}{2} \times \frac{1}{2} = (\frac{1}{2})^2$ or ¼

   c. Three half-lives will reduce to $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = (\frac{1}{2})^3$ or c

8. In the general case the fraction of activity remaining after any number of half lives will be $(\frac{1}{2})^n$, where n is the number of half-lives that have elapsed.

9. To put it still another way, the reduction in activity occurs at an exponential rate, which we have expressed as the power of ½.

10. In Figure 4 it can be seen that as time passes, radioactive decay
    occurs at an exponential rate.

    a. In using the half-life for our time value, we express this
        exponential function as $(\frac{1}{2})_n$.

    b. 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 ($n = 0$).

    c. If we use t to represent time, at this point, then, t = 0.

11. If we let T½ represent the half-life, then, after one half-life, t = T½,
    and n = 1. This demonstrates that n represents the ratio of time
    versus the half-life.

12. Mathematically, this is expressed as:

$$n = \frac{t}{T_{\frac{1}{2}}}$$

    where:

    n = number of half-lives
    t = time elapsed
    $T_{\frac{1}{2}}$ = half-life

13. Obviously, the units of t must be the same as the time units of T½ in
    order to determine the value of n.

    a. 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.

    b. The fraction remaining at that instant where $t = 4$ hours would
        be:

$$\left(\frac{1}{2}\right)^{\frac{4}{10}} = \left(\frac{1}{2}\right)^{0.4} = 0.7578$$

14. The activity at the instant where $t = 0$ is the initial or original
    activity, represented as A_0.

15. The activity at any time t after 0 we will denote as A_t.

16. 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.

17. Using a proportion we can see the relationship between the two activities:

$$\frac{A_0}{A_t} = \frac{1}{(\frac{1}{2})^n}$$

18. By cross-multiplying we obtain the equation for determining the remaining activity:

$$A_t = A_0(\tfrac{1}{2})_n$$

For example, if the initial activity of the radionuclide mentioned above was 52 μCi, then the activity after 4 hours would be:

$$A_t = 52\,\mu Ci \left(\frac{1}{2}\right)^{\frac{4}{10}}$$
$$A_t = 52\,(0.7578)$$
$$A_t = 39.4\,\mu Ci$$

19. Remember that we stated earlier that radioactive decay is an exponential process. Recall also that a logarithm is, by definition, an exponent.

20. 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.

21. This graph shows us that the rate of decay does in fact occur at a constant rate.

22. 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 λ (pronounced "lambda").

23. In FIGURE 5 the reduction of activity is now a logarithmic (exponential) function of $(\frac{1}{2})^n$.

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.

See Fig. 5 - "Radioactive Decay (Semi-log Scale)"

24. Since *n* is the ratio of t versus $T_{1/2}$, 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.

25. The fraction remaining will be a function of the decay constant (λ) and the time (*t*).

26. If we then relate the decay constant to the half-life, λ will be a composite of the natural log of 2 and the half-life.

27. Since the process leads to a decrease in activity, the exponent will be represented by $-\lambda t$.

28. Therefore, the decay constant itself will represent:

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

29. Thus, the decay constant is the fraction that disintegrates per unit time (reciprocal time).

   - If, for example, the half-life is in seconds, λ will be in sec^{-1}.

30. The equation for activity using the decay constant will be:

$$A_t = A_0\, e^{-\lambda t}$$

   a. Note that in this equation the base of the natural log is raised to a power which includes the -ln 2.

> Objective 1.06.14

   b. The result of this equation is exactly the same at that which results from the equation using (½)^n.

   c. It is simply a different way of expressing the decrease in activity with the passage of time as a result of radioactive decay.

31. Using the data in the prior example, the equation would be:

$$A_t = 52\, e^{\left(\frac{-\ln 2}{10}\right)4}$$
$$A_t = 52\, e^{-0.277}$$
$$A_t = 52\,(0.7578)$$
$$A_t = 39.4\ \mu Ci$$

32. Example: Given 10 mCi of 32P, which has a half-life of 14.2 days, find the quantity remaining after 60 days.

$$A_t = 10\,e^{\left(\frac{-\ln 2}{14.2}\right)60}$$
$$A_t = 10\,e^{-2.93}$$
$$A_t = 10(0.0534)$$
$$A_t = 0.534\,mCi$$

Work example problem with students.

33. 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.

Have students work practice problems in Study Guide.

J. Series Decay

1. Concerns the mathematical relationship of quantities of activity present when two or more radionuclides exist in a decay chain.

2. Examples of a decay chain are the natural decay series, or a two-step fission product decay series such as:

    $$Sr^{90} \rightarrow \beta^- + Y^{90} \rightarrow \beta^- + Zr^{90}\,(stable)$$
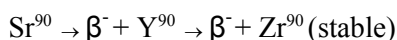
3. The relationship between three or more radionuclides is described by Bateman. The solution, while straight forward, is quite involved. A two-step relationship (parent-daughter) can be readily derived and is reasonably easy to work with.

K. Parent-daughter Relationships

1. In a radioactive decay series, the decay of the parent nuclide produces a daughter product and radiation is emitted.

2. 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.

3. 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.

4. When the number of atoms being produced is the same as the number of atoms that are decaying, a state of equilibrium is said to exist.

5. There are several types of equilibrium, depending on how the half-life of the daughter compares to the half-life of the parent.

    a. Secular Equilibrium

        1) 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.

        2) Initially, the majority of the activity will be contributed by the parent.

        3) As more and more of the parent nuclide decays, the amount of activity contributed by the daughter will increase.

    b. Transient Equilibrium

        1) In transient equilibrium the half-life of the parent is longer than that of the daughter, but not very long.

        2) In a freshly purified parent fraction, the daughter activity builds up, then decays with the same rate of decay as the parent.

    c. No Equilibrium - When the half-life of the parent is shorter than that of the daughter, the two never reach a state of equilibrium.   See Fig. 6 - "No Equilibrium"

L. Radiation Dosimetry Terminology

                                                                         Objectives 1.06.15

1. During the early days of radiological experience there was no precise   and 1.06.16
    unit of radiation dose that was suitable either for radiation protection
    or for radiation therapy.

a. For example, one early unit devised was the "skin erythema unit," where allowable dose was the amount required to produce skin reddening.

b. 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.

c. 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.

2. Exposure (X)   Objective 1.06.15 a.

a. Exposure is a measure of the ability of photons (X and gamma) to produce ionization in air.   Objective 1.06.16 a.

b. 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 C/kg of air

c. There is no SI unit defined for exposure. This was done intentionally to discourage further use of the quantity.

d. 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.

e. Another unit must be used to describe the amount of ionization caused by any radiation in any material.

3. Absorbed Dose (D)   Objective 1.06.15 b

a. Units of dose measure the amount of radiation energy absorbed or deposited per unit of mass.

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.

b. The "energy deposited" by radiation is an expression for the "amount of ionization caused" and both expressions mean the same thing.

c. 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.

d. 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.

e. The Rad   Objective 1.06.16 b.

   1) The old (CGS) unit of absorbed dose is the rad, which is an acronym for Radiation Absorbed Dose.

   2) 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.

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.

f. The Gray

   1) 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).

   2) The relationship between the gray and the rad is that 1 Gy = 100 rad:

$$1\ Gy = \frac{1\ J}{kg} \times \frac{1E7\ ergs}{1\ J} \times \frac{1\ kg}{1E3\ g} \times \frac{1\ rad}{100\ ergs/g} = 100\ rad$$

g. 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.

h. 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.

i. 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.

4. Radiation Weighting Factor (W_R)

Objective 1.06.15 c.

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.

See Table 7 - "Comparison of Dosimetric Terms"

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 terms as compared in Table 7 to be equivalent.

a. 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.

See Table 8 - "Radiation Weighting Factors"

b. 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.

c. 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.

d. The radiation weighting factor is a conversion factor used to derive the equivalent dose from the absorbed dose, expressed as:

$$H_T = D \; W_R$$

where: H = equivalent dose
        D = absorbed dose averaged over the tissue or organ
        W_R = radiation weighting factor

e. 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.

f. 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.

g. For example an absorbed dose of 100 millirad thermal neutron would be converted to an equivalent dose as follows:

100 mrad (n_t) x 5 = 500 mrem

h. The radiation weighting factor can also be applied to an absorbed dose rate (rad/hr) in order to obtain equivalent dose rate (rem/hr).

5. Equivalent Dose (H_T)

    a. 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.

    b. The Rem

        1) A unit of equivalent dose is the rem, which is an acronym   Objective 1.06.15 d.
            for Roentgen Equivalent Man.

        2) 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.

        3) The equivalent dose in rem is numerically equal to the
            absorbed dose in rad multiplied by the radiation weighting
            factor:

            $\text{rem} = \text{rad} \times W_R$

    c. The Sievert
                                                                              Objective 1.06.16 c.
        1) The SI Derived unit of equivalent dose is the sievert (Sv).

        2) The equivalent dose in sieverts is equal to the absorbed dose
            in grays multiplied by the radiation weighting factor:

            $\text{sievert} = \text{gray} \times W_R$

        3) Since, one gray is equal to 100 rad, it follows that for
            $W_R = 1$:

            $1 \text{ Sv} = 100 \text{ rem}$

d. 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.

e. 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.

f. Table 9 provides a summary of these dosimetry units and their associated values.

III. SUMMARY

A. Review major topics

1. Neutron to proton ratio

2. Radioactivity and radioactive decay

3. Radiation characteristics

4. Decay modes

5. Natural/artificial radioactivity

6. Fission product stability

7. Chart of the nuclides

8. Units of activity

9. Activity calculation

10. Measurement terminology

B. Review learning objectives

See Table 9 - "Dosimetry Terminology Summary"

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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

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.

Instructional Aids:

       1.   Overheads
       2.   Overhead projector/screen
       3.   Chalkboard/whiteboard
       4.   Lessons learned

V. MODULE INTRODUCTION

   E. Self-Introduction

      5. Name

      6. Phone number

      7. Background

      8. Emergency procedure review

   F. Motivation

   The understanding of how radiation interacts with matter is fundamental when providing radiological protection. You as an RCT should be particularly interested in how radiation is absorbed by the body for three reasons.

      1. Absorption in body tissues may result in physiological injury

      2. Absorption is the principle upon which detection is based.

      3. The degree of absorption and type of interaction is a primary factor in determining shielding requirements

   G. Overview of Lesson

      1. Definitions of terminology used in the lesson

      2. Mechanisms of Energy transfer for each type of ionizing radiation

      3. Shielding characteristics

      4. Interactions of radiation with our bodies

   H. Introduce Objectives   O.H.: Objectives

VI. MODULE OUTLINE   Objective 1.07.01

    i.   Transfer of Energy Mechanisms (absorption) for radiations include:

                   See Fig. 1 -
     1. Ionization   "Ionization"

        a. Any process which results in the removal of an electron (with negative one charge) from an electrically neutral atom or molecule

        b. Whenever this happens it creates an ion pair made up of the negative electron and the positive atom or molecule. Some examples of the energy required to produce one ion pair:

           He = 42.7 eV
           Ar = 26.4 eV
           N_2 = 36.5 eV
           Air = 33.9 eV

     2. Excitation   See Fig. 2 -
                                             "Excitation"

        a. Transfer of energy to (absorption by) the electrons or nucleus of an atom or molecule. This energy is less than that required for ionization. The process raises an electron from one energy level to a higher energy level within the atom and the atom remains electrically neutral.

        b. It is also important to remember that all of the particles or ray produced by primary interactions lose their energy the same way, ionization and excitation, in secondary interactions.

     3. Bremsstrahlung

        a. Bremsstrahlung is the radiative energy loss of moving charged particles as they interact with the matter through which they are moving.

        b. Bremsstrahlung radiation results from the interaction of a high speed particle near a heavy (high Z) atom. The particle is deflected from its course by the electrostatic force of the positively charged nucleus. The kinetic energy the electron loses is emitted as X-ray radiation.   The photon emitted is an X-ray because it originated outside the nucleus.

ii.   Direct Ionizing Radiation

   1.   Charged particles do not require contact to interact because the "Coulomb force" (force from the charge) will act over a distance to cause ionization and excitation in the absorber medium. This force is dependent on:

Objective 1.07.02
See Table 1 -
"Summary of Energy
Loss Terms and Units"

      a.   energy (speed) of particle

      b.   charge of particle

      c.   density and number of absorber

   2.   Interaction concepts

      a.   Specific Ionization (S.I.)

         1)   Number of ion pairs formed by a charged particle per unit path length (ion pairs/cm). This is dependent on the material type of ionizing particle and the material being ionized.

      b.   Linear Energy Transfer (LET)

         1)   Average energy locally deposited in an absorber by a charged particle per unit distance of travel (keV/cm)

      c.   Stopping Power (S)

         1)   Average energy lost by a charged particle per unit distance of travel (keV/cm)

      d.   Range (R)

         1)   Average depth of penetration of a charged particle into an absorber before it loses all of its kinetic energy and stops (cm)

         2)   Inversely related to stopping power

            high range = low stopping power
            low range = high stopping power

e. W-value (W)

1) Average amount of energy needed to produce an ion pair in a given medium

(W)(S.I.) = S or (eV/ion pair)(ion pairs/cm) = eV/cm

2) Allows one to relate Specific Ionization to Range or Stopping Power

See Fig. 3 - "Ionization by an Alpha Particle"

3. Alpha Absorption

Objective 1.07.03

a. Large charge +2

b. Large mass 4 AMU's

c. Interactions

1) Ionization

2) Excitation

d. Interaction concepts

1) Spec. ionization - very high

2) LET ------------ very high

3) Stopping power - very high

4) Range----------- very low

4. Beta particles

Objective 1.07.04

a. Charge –

b. Mass 5.49 E-04 AMU

c. Interactions

1) Ionization

2) Excitation

3) Bremsstrahlung

See Fig. 4 - "Bremsstrahlung Radiation"

    d. Interaction concepts

       1) Specific ionization - high

       2) LET-------------------high

       3) Stopping power----- high

       4) Range-------------   low

iii.   Indirect Ionizing Radiation

   1. Indirect ionizing radiations, having no charge, do not readily interact with matter.

   2. When they do, they may produce direct ionizing radiation particles (charged particles) which will produce many secondary ions

   3. Probability of interaction is dependent on

      a. Density and Z number of the absorber

      b. Energy of the radiation

   4. Photon Interactions   Objective 1.07.05

      a. Photoelectric Effect   See Fig. 5 - "Photoelectric Effect"

         1) The photon transfers all of its energy to an electron; ejecting the electron from the atom

         2) The photon disappears

         3) Almost always a "K" shell electron (inner shell - lowest energy level)

         4) Generally low energy gamma (eV range)

      b. Compton Scattering   See Fig. 6 - "Compton Scattering"

         1) Photon transfers a part of its energy to an electron (binding energy + kinetic energy = beta particle + lesser energy photon)

2) The less energetic photon (Compton photon) has its direction of travel changed and may undergo further Compton scatter or photoelectric effect interactions in the absorber

3) Any electrons except "K" shell (outer shells - higher energy levels)

4) Generally occurs with middle energy gamma (low MeV range)

5) Optional Note:

The mechanism of Compton Scattering was first fully explained in 1923 by physicist A. H. Compton. He correctly suggested that the photons could be thought of as carrying a bundle of energy like a billiard ball, and that the resulting angles and energies of the electron and residual photon could be computed using the classical laws of physics i.e. conservation of energy and momentum. This explanation was initially rejected by others because it was felt that photons and other forms of electromagnetic energy were really waves which could not exhibit particle-like properties. Compton received the Nobel Prize in physics in 1927 for this discovery.

c. Pair Production

1) In an interaction between the electromagnetic field of a high Z number nucleus and a photon - all of the energy of the photon is transformed into an electron and a positron (two charged particles) each having some kinetic energy.

2) Very high energy gamma required because a minimum energy is required (1.022 MeV to make the mass of the two particles) in fact, it may take energy levels greater than 2 or 3 MeV and then only a very small part of all interactions will cause pair production

See Fig. 7 - "Pair Production and Annihilation"

3) What happens to the two particles?

   a) Ionization, excitation, and bremsstrahlung occurs for both particles. When the positron loses almost all of its energy, it will then be attracted to an electron and will annihilate releasing two photons of equal energy (511 keV each).

4) This process demonstrates Einstein's mass-energy relationship $E = mc^2$ works in both directions

d. Photon interaction review

   1) photoelectric effect: low energy = eV range

   2) compton scattering: med energy = Low MeV

   3) pair production: very high energy = High MeV

4. Neutron Interactions

a. Classified by:

   1) Kinetic energy of the neutron   Objective 1.07.06
                                                        See Table 2 - "Neutron
      a) Thermal: (< 0.5 eV)   Energy Categories"

      b) Intermediate: (0.5 eV - 100 keV)

      c) Fast: (100 keV - 20 MeV)

      d) Relativistic: (> 20 MeV)

   2) Z number of target

      a) Lower Z numbers absorb more energy per each interaction or collision

   3) Absorption cross section of target

      a) Some elements absorb neutrons more readily than others i.e. cadmium, boron, and hafnium

    b.   Slow Neutron Interactions (Capture)   Objective 1.07.07

        1) Radiative Capture: neutron is absorbed into nucleus and a gamma is emitted. This is also called gamma emission or neutron activation.

        2) Charged Particle Emission: neutron is absorbed into nucleus and a charged particle is emitted

        3) Fission: neutron is absorbed into nucleus then the nucleus splits into fission fragments.

    c.   Fast Neutron Interactions (Scatter)

        1) Elastic Scattering: kinetic energy is the only form of energy involved.   Objective 1.07.08

See Fig. 8 - "Elastic Scattering"

        2) Inelastic Scattering: some kinetic energy is changed to excitation energy of the nucleus which then emits a photon (gamma ray) to remove this excitation energy.   See Fig. 9 - "Inelastic Scattering"

    d.   Remember neutrons are not charged particles but neutron interactions do produce charged particles and photons, which will cause large amounts of secondary ionization and excitation

  iv.   Shielding

    1. Equations

      a. $I = I_o \, e^{-ux}$

      b. $I = I_o \, (\frac{1}{2}^n = $ thickness divided by the Half Value Layer (HVL)

    2. Cautions

      a.   In thick shielding you have to account for buildup factor which is due to the scattering of radiation in the absorber

      b.   "Sky Shine" is radiation reflected back to earth by the atmosphere.

      c.   Scattering can cause radiation to go around corners or edges of shielding

      d.   High beta dose rate shielded with high Z absorber may increase dose rate due to bremsstrahlung production

3. Typical shielding materials

   a. alpha   paper

   b. beta   low Z (rubber, aluminum, plastic)

   c. gamma   lead, steel

   d. neutron   low Z (Hydrogenous Materials)

      1) The use of materials with a high Hydrogen concentration will moderate (slow down) the neutron intensity.

      2) Lower energy neutrons are easily captured by materials with a high cross section for absorption. (Boron, Cadmium)

      3) When shielding for neutron radiation consideration must be given for gamma production from activation of shielding material and bremsstrahlung X rays.

III. SUMMARY

A. Review major topics

   1. Definitions of terminology used in the lesson.

   2. Mechanisms of Energy transfer for each type of ionizing radiation.

   3. Shielding characteristics

   4. Interactions of radiation with our bodies.

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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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.

References:

1. "Radiation Biology"; Casarett, Alison; Prentice-Hall, Inc.; 1968.
2. "A Catalog of Risks"; Cohen, Bernard; Health Physics, Volume 36, pg. 707-722; 1979.
3. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.
4. "The Effects on Population of Exposure to Low Levels of Ionizing Radiation"; National Academy of Sciences; 1972.
5. "Ionizing Radiation Levels and Effects"; United Nations, Volume II - Effects; New York; 1972.
6. "Health Effects of Exposure to Low Levels of Ionizing Radiation"; Biological Effects of Ionizing Radiation (BEIR) Report V; National Research Council; 1990.
7. Health Impacts from Acute Radiation Exposure, Pacific Northwest National Laboratory, PNNL-14424, Dan Strom, September 2003.

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned.

I. MODULE INTRODUCTION

    A. Self-Introduction

        1. Name

        2. Phone number

        3. Background

        4. Emergency procedure review

    B. Motivation

The biological effects radiation has on the human body has led to current radiation control programs. An RCT must have some basic understanding of the methods in which radiation may cause biological damage to protect themselves and the workers from unnecessary exposure to ionizing radiation.

    C. Overview of Lesson

        1. Cellular structure and damage

        2. Radiosensitivity

        3. Stochastic/deterministic effects

        4. Chronic effects

        5. Acute effects

        6. Embryological effects

        7. Heritable effects

    D. Introduce Objectives

O.H.: Objectives

II. MODULE OUTLINE

    A. Cell Structure

        1. Basic unit of life

See Fig. 1 – "Basic Cell Structure"

          a. Made up of protoplasm

            1) Carbohydrates

Objective 1.08.01

2) Lipids

3) Inorganic salts

4) Proteins

5) Nucleic acids

6) Gases

b. Consists of 70-80% water

c. Primary constituents:

1) Membrane

2) Cytoplasm

3) Nucleus

2. Cell Membrane

a.   Encloses the cell

b.   100 angstroms thick

c.   Regulates the concentration of water, salts, and organic matter

d.   Capable of "active transport"

e.   All waste products or secretions pass through the membrane

3. Cytoplasm

a.   Jelly-like substance in which the nucleus is suspended

b.   Aqueous solution of proteins and salts

4. Mitochondria

a.   Power plant of the cell

b.   Contains a special energy storing molecule called Adenosine Tri-Phosphate (ATP)

c.   Supplies the energy for all cell activities.

     5. Lysosome

        a.   Contains digestive enzymes which break down large molecules

     6. Cell Nucleus

See Fig. 2 - "Double Helix"

        a.   Directs all cell activity

        b.   Contains all the genetic material

     7. DNA/Chromosomes

See Fig. 3 - "DNA Base Pairs"

        a.   DNA (deoxyribonucleic acid) - master blueprint

        b.   When the cell divides chromatic coils form chromosomes

        c.   The number of chromosomes is fixed for a given species (Humans - 46)

        d.   Chromosomes contain several hundred genes which are responsible for traits

  B. Radiation Damage to Cell Constituents

Objective 1.08.0

    1. Cell Membrane

        a.   It takes about 3,000 - 5,000 rad (30 - 50 gray) to rupture

        b.   Results in leakage of beneficial material and introduction of potentially harmful fluids

        c.   At lower doses, radiation increases the permeability and some leakage occurs

    2. Cytoplasm

        a.   Negligible effect

    3. Mitochondria

        a.   A "few thousand" rad will disrupt the function

        b.   Interrupts the storage of energy via Adenosine Tri-Phosphate (ATP).

   c. If the cell has a large reserve of stored food, it can repair itself

   d. The greater the dose, the greater the damage, the longer the repair time

   e. If the repair time is too long and the food reserve fails, the cell dies from starvation

4. Lysosome

   a. Ruptures between 500 and 1,000 rad (5 - 10 gray)

   b. Digestive enzymes are released and begin to digest the rest of the cell

5. Nucleus

   a. Difficult to affix a dose because the nucleus is the most radiosensitive part of the cell

   b. Inhibits the ability of the cell to divide by affecting the DNA and RNA

   c. Without normal DNA the cell cannot produce a duplicate set of chromosomes

   d. The longer division is delayed the greater chance it will die; as the dose increases, the delay time lengthens

C. Radiosensitivity   Objective 1.08.03

   1. The relative susceptibility of cells, tissues and organisms to the injurious action of radiation

   2. Law of Bergonie and Tribondeau (1906):

       a. "The radiosensitivity of a tissue is directly proportional to its reproductive capacity and inversely proportional to its degree of differentiation"

   3. Factors which affect a cells sensitivity to radiation   Objective 1.08.04

       a. Cells are more sensitive if they have a high division rate.

    b.   The higher the metabolic rate in a cell, the lower its resistance to radiation

    c.   Cells tend to be more sensitive if they are non-specialized

    d.   Well nourished cells, or cells with a high level of oxygenation are more sensitive

4. Radiosensitive Tissues:

    a.   Germinal (reproductive) cells of the ovary and testis e.g., spermatogonia

    b.   Hematopoietic (bloodforming) tissues: red bone marrow, spleen, lymph nodes, thymus

    c.   Basal cells of the skin

    d.   Epithelium of the gastrointestinal tract (interstitial crypt cells)

Note: They do not follow the four general rules

5. Radioresistant Tissues:

    a.   Bone

    b.   Liver

    c.   Kidney

    d.   Cartilage

    e.   Muscle

    f.   Nervous tissue

A whole body exposure of 600-700 R will kill most animals; however, even higher doses have been delivered to the brain for cancer treatment.

6. Radiosensitivity not only differs from one cell or tissue to another but also between individuals and genders

D. Primary and Secondary Effects of Radiation

Objective 1.08.06

   1. Primary Effect

      a. Ionization & Excitation of atoms making up the cell

      b. Produced when the primary (initial) interaction of radiation is with the target atoms in the cell such as those in the DNA

   2. Secondary Effects

      a. Formation of free radicals which are very reactive and can chemically attack target molecules, such as DNA

      b. Occurs with the disassociation of water

Water makes up 70 - 80% of the cell

        Three possible reactions:

        1) H interacting with H = H_2

        2) OH combining with H = H_2O

        3) H_2 + OH = H_2O_2

      c. Formation of H_2O_2 (hydrogen peroxide) can lead to cell death. H_2O_2 is a harmful oxidizer which poisons the cell

E. Stochastic and Deterministic Effects

Objective 1.08.07

   1. Stochastic Effects

      a. An effect in which the probability of the effect occurring increases with the dose.

      b. The effects have no established threshold, they can occur from the irradiation of only one cell; any exposure, however low, has some chance of causing the effect.

      c. Two examples of stochastic effects: cancer and genetic mutations.

2. Deterministic (Non-Stochastic) Effects

    a.   Effects in which the severity of the effect increases as the dose increases

    b.   It is generally assumed that a threshold exists; and if doses received are below the threshold dose, no effects will occur

    c.   Effects typically result from the collective injury of many cells

    d.   Effects include: cataracts, skin burns, lowering of blood cell counts, etc.

F. LD-50/30   Objective 1.08.08

1. Implies that 50% of a population will die within 30 days with NO medical treatment

2. LD-50/30 for humans is 300 - 500 rads (3 - 5 gray) in a short period of time, and is typically stated as 450 rad (4.5 gray)

                                                                                    Objective 1.08.09

G. Effects of Chronic Exposures to Ionizing Radiation

1. Chronic exposure

    a.   Typically refers to smaller exposures over a long time period

    b.   No unique disease associated with radiation exposure, but there is a statistical increase in the risk of developing disease

    c.   Radium dial painters, early radiologists, atomic bomb survivors provide evidence of induced effects in humans

2. Cancer

    a.   Radiation induced cancers are justification for today's protection standards

    b.   Possibility of inducing tumors

    c.   Radiation may cause cancer but also be used to treat cancer

Analogy: a knife can be use to heal (by a surgeon) or to inflict injury.

3. Cataracts

    a.   A cataract is opacity of the lens of the eye

    b.   A chronic exposure of 600 rad (6 gray) may produce a cataract for high LET radiation

    c.   Generally symptoms will not appear for years after the exposure

    d.   Effects may be cumulative

    e.   Neutrons and gamma are primary hazards

    f.   Exposures at younger ages increase susceptibility

4. Life Span (Shortening or Lengthening)

    a.   Data is uncertain and firm conclusions are difficult to estimate.

    b.   Aging is the progressive deterioration of tissues along with declining functional capacities

    c.   Irradiated animals under lab conditions showed some cellular changes that can be associated with aging

    d.   Low doses of 0.1 R/day or 100-400 R over a lifetime has indicated an increase in rat lifetime, and also a lower incidence of disease. This effect is known as Radiation Hormesis. No firm conclusions of this have been universally accepted.

H. Effects of Acute Radiation Exposures   Objective 1.08.10

Acute exposures are those exposures which involve relatively large doses of radiation received over a relatively short period of time.

1. Stages

    a.   Prodromal

    b.   Latent

    c.   Illness

       d.   Recovery/death

2. Three syndromes

    a.   Hematopoietic Syndrome

        1) Also called "Therapeutic Range" because treatment can play a large role

        2) Dose level - Between 200 to 1,000 rads (2 -10 gray) - (Some blood changes can be seen at lower doses)

        3) Critical organs are the blood forming organs

        4) Affects the production of white blood cells - Leukopenia- decreased ability to fight infection

        5) Lowered platelet count causes hemorrhaging and slowing of the healing process

        6) Symptoms:

            Nausea and vomiting

            Epilation

        7) Treatment - antibiotics to fight infection–bone marrow transplants to replace damaged cells, (uncertain if this works)

        8) If death does occur it will be due to infection and hemorrhaging

    b.   Gastrointestinal Syndrome

        1) Dose level - Between 1,000 - 5,000 rads (10 -50 gray)

        2) Affects the GI tract

        3) Stops the production of new epithelial cells which line the wall of the intestines and are responsible for absorption of nutrients and control body fluid metabolism.

        4) Symptoms:

            a) appear in a few hours

            b) nausea and vomiting

            c) dehydration from diarrhea and low nutrient absorption

            d) electrolyte imbalance

        5) Cause of death: circulatory collapse from loss of fluids

c.   Central Nervous System (CNS) Syndrome

        1) Dose level:

            >5,000 rad (>50 gray)

        2) Critical Organ:

            Central Nervous System

        3) Symptoms:

            Convulsions

            tremors

            ataxia

            lethargy

        4) Cause of death:

            Respiratory failure and/or brain edema

> See Table 1 in the Student Guide for a summary of effects from extreme to low doses. Remind students that the dose ranges for effects might vary by reference.

3.   In the event an individual survives an acute exposure of high dose, they run an increase risk of latent effects

I.   Effects on the Embryo/Fetus   Objective 1.08.11

1.   According to the law of Bergonie and Tribondeau, children are more radiosensitive than adults, fetuses more than children, and embryos are the most radiosensitive.

2.   Radiation doses may cause death or abnormalities.

3. Most critical period 2 to 6 weeks gestation – most organs formed

4. Doses as low as 25 rad (0.25 gray) may cause defects.

5. Reported effects include blindness, cataracts, mental deficiency, coordination defects, deformed arms legs, and general mental/physical subnormality

6. An exposure of 400 - 600 rad (4 - 6 gray) during the first trimester (excluding the first week) of pregnancy is sufficient to cause fetal death and spontaneous abortion

J. Heritable Effects

1. Differences in the genetic structure of somatic and germ cells

Objective 1.08.12

2. Mutations can be produced in genes by radiation

3. Dominant genes will generally determine characteristics when the 23 chromosome pairs are matched

4. In order for a recessive gene to determine a characteristic it must be paired with another recessive gene

5. This indicates mutations may not appear for several generations

6. Doubling Dose - double natural mutation rate –estimated to be greater than 100 rem (1 Sv)

Reference: BEIR V

7. Radiation damage in humans can result in both somatic and heritable effects

1) Somatic effects - Effects which occur in the exposed individual.

2) Heritable effects - effects which occur in the future generations of the exposed individual.

III. SUMMARY

    A. Review major topics

        Cellular structure and damage

        Radiosensitivity

        Stochastic/Deterministic effects

        Chronic effects

        Acute effects

        Embryological effects

        Heritable effects

    B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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 the 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".

Instructional Aids:

1. Overheads

2. Overhead projector/screen

3. Chalkboard/whiteboard

4. Lessons learned.

I. MODULE INTRODUCTION

    A. Self-Introduction

        1. Name

        2. Phone Number

        3. Background

        4. Emergency procedure review

    B. Motivation

        To understand why there are limits to exposure the RCT must understand the history of the development of the limits. The RCT has to be aware of the current CFRs and DOE Orders that may effect them at the work place.

    C. Overview of Lesson

        1. History of standards

        2. Advisory agencies

        3. Federal policy on radiation matters

        4. Regulating agencies

        5. Radiological Control Standard

        6. 10 CFR Part 835

    D. Introduce Objectives   O.H.: Objectives

II. MODULE OUTLINE

    A. History of Standards

        1. Setting exposure limits is vital and difficult.

            a. Vital: Workers must be protected from the harmful effects.

            b. Difficult: many factors enter into the effects which radiation produces.

2. Concept of an "acceptable risk"

    a. The benefits are weighed against the potential damage.

    b. Then limits are set at some level at which the most benefit to mankind.

3. Limits are revised as new knowledge is gained.

4. Early use of radiation led to large exposures.

5. As early as 1897, cases of skin damage began to appear.

6. Erythema Dose

    a. Early efforts at control were hampered by a lack of quantitative methods.

    b. There were no units by which one could assess the amount of radiation.

    c. As a result of the use of radiation by doctors in treating patients, a unit called the erythema dose came into use.

    d. Highly qualitative unit; defined in terms of the amount of radiation which would produce a well-defined reddening of the skin.

    e. Not a satisfactory unit.

    f. It varied not only with the type of radiation and the dose rate, but also with the response of different parts of the body.

B. ICRU, ICRP, AND NCRP   Objective 1.09.01

1. 1925, International Commission on Radiological Units and Measurements (ICRU).

    a. 1928, adopted the Roentgen.

    b. ICRU has been the main force in defining and adopting units for use on an international basis.

2. 1928, International Commission on Radiological Protection (ICRP).

    a. This group discusses and reviews basic protection principles.

    b. Recommendations serve as a guide from which regulations can be drawn up by each country.

    c. 1934, recommended a tolerance level of exposure: 0.2 R/day. This limit remained in force until 1950.

3. 1929, National Committee on Radiation Protection and Measurements (NCRP).

    a. Coordinated by the National Bureau of Standards.

    b. Recommendations of the Committee appeared in the National Bureau of Standards Handbooks.

    c. 1946 reorganized

    d. 1964 replaced by a non-profit corporation chartered by Congress National Council on Radiation Protection and Measurements.

    e. The Council is made up of the members and the participants who serve on a number of committees.

    f. 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.

4. Radiation exposure concerns

    a. Initially, concerns resulted from patients and medical personnel exposure to external radiation from the use of x-rays for diagnosis and therapy.

b. 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.

c. Potential genetic effects of radiation and the impact of long-term exposure at low dose rates emerged.

d. 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.

e. Efforts have been directed toward quantifying the risk associated with a certain level of exposure.

f. Non-threshold relationship, any dose carries some risk of producing damage therefore all exposure should be kept at the lowest practical levels. Several factors need to be considered.

    1) Information available for the quantification of risks is imperfect.

    2) The assumptions of a risk by an individual, in general, presumes a willingness to chance the risk in exchange for some resultant benefit.

    3) The resultant benefit which accrues justifies the risk.

    4) The balancing of risk versus benefit in order to obtain a net benefit is not easily accomplished.

    5) The prudent approach, adopted by both the ICRP and the NCRP is to keep exposures as low as reasonably achievable (ALARA).

g.   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.

   1)   This group consists of a large number of scientists throughout the country.

   2)   The group functions as an advisory body.

   3)   Purpose is to supply technical information as a basis from which regulations can be developed

h.   The results of continuing reviews of biological data have revealed two types of radiation effects.

   1)   Those for which a practical threshold dose for occurrence can be demonstrated, deterministic (nonstochastic) effects.

   2)   Those for which there is apparently no threshold, stochastic effects.

   3)   Deterministic effects can be prevented by limiting the dose to the individual to a value below the threshold dose for occurrence of the effects.

   4)   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.

   5)   Stochastic effects, limit the probability of occurrence to some level (deemed acceptable) by limiting the radiation exposure.

C.   ICRP Basic Recommendations

   1.   In its current reports, the ICRP recommends a basic system of dose limitation which includes these three interrelated aspects:

   a.   No practice shall be adopted unless its introduction produces a positive net benefit.

   b.   All exposures shall be kept ALARA, economic and social factors being taken into account.

c. The equivalent dose to individuals shall not exceed the recommended limits.

D. Federal Policy on Radiation Matters

1. 1959, Federal Radiation Council (FRC) was formed (Public Law 86-373).

    a. Advised the President concerning radiation matters

    b. Provided guidance for all Federal agencies in setting standards and in working with the States.

    c. The recommendations of the FRC were approved in 1960 and formed the basis of the Federal radiation protection guidance.

    d. The FRC was abolished by Reorganization Plan No. 3 in 1970.

2. Environmental Protection Agency (EPA) took over. The Office of Radiation Programs (ORP) of the EPA took over the activities of the FRC.

    a. 1981, the EPA drafted proposed revised recommendations in the Federal Register regarding occupational exposure, and solicited comments.

    b. 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.

    c. The revised EPA guidance was approved and issued in January 1987.

3. The Bureau of Radiological Health of the U.S. Department of Health and Human Services has developed a set of recommendations for protection from diagnostic x-rays.

E. Regulating Agencies   Objective 1.09.02

1. 1954, Atomic Energy Act, the United States Atomic Energy commission (AEC) was given the responsibility of regulating the atomic energy industry.

    a. The Act authorized the AEC to set up a licensing program to be augmented by whatever rules or regulations are deemed appropriate.

    b. The bases for these rules are: to protect the public health and safety, and provide for national defense and security.

2. 1974, Energy Reorganization Act, abolished the AEC and established two agencies to perform the functions of the AEC, Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA).

3. NRC

    a. The regulations of the NRC are set forth in the Code of Federal Regulations (CFR), Title 10.

    b. Part 20, Standards for Protection Against Radiation, deals specifically with the regulations for control of radiation hazards by the licensee.

    c. Other parts of Title 10 deal with licensing and regulatory requirements associated with the use of source, special nuclear material and by-product material.

    d. The NRC is charged with the task of seeing that these measures prevail. This aspect requires inspection and review in order to assure this.

        1) This function is carried out by NRC personnel (inspectors) at regular intervals.

        2) 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.

    e.   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.

4.   ERDA

    a.   In 1977, the U.S. Department of Energy (DOE) replaced ERDA.

5.   DOE

    a.   The DOE activities relate to energy research and development.

    b.   The DOE has issued occupational radiation protection standards which pertain to its own activities as well as to those of its contractors.

> Insert site-specific information addressing DOE orders/standards applicable to radiological control at the site, based on contracts.
>
> Objective 1.09.03

        1)   These standards appear in 10 CFR Part 835.

        2)   These standards are based upon the recommendations of the ICRP, NCRP and the guidance of the EPA.

        3)   Rule 10 CFR 835: The scope of 10 CFR 835 establishes radiation protection standards, limits and program requirements for protecting individuals from radiation resulting from the conduct of DOE activities.

            a)   Implemented by the Price-Anderson Amendments Act

            b)   Civil penalties may be assessed

            c)   Requires DOE activities be conducted with a written radiation protection program.

            d)   Some sites may still contractually be obligated to adhere to provisions of the DOE RCS.

    c.   Similar to the NRC, the DOE is charged with the inspection of its contractors to see that they are in compliance with DOE requirements.

  6.   Department of Transportation (DOT)

    a.   Safety in the shipment of radioactive substances

    b.   Title 49 Transportation, of the CFRs, deals with hazardous shipments including radioactive materials.

  7.   Other Agencies

    a.   Interstate Commerce Commission,

    b.   Coast Guard,

    c.   Federal Aviation Agency,

    d.   Postal Service,

    e.   International Atomic Energy Agency.

F. DOE Radiological Control Standard (RCS)

  1.   Radiological Control Policy

    a.   The fundamental principle underlying the RCS is:

      1)   "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."

    b.   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.

    c.   ALARA

      1)   Personal radiation exposure shall be maintained ALARA.

      2)   Exposure shall be controlled below regulatory limits and there is no exposure without commensurate benefit.

      d.   Ownership

          1)   Each person involved in radiological work is expected to demonstrate responsibility and accountability through an informed, disciplined and cautious attitude toward radiation and radioactivity.

      e.   Excellence

          1)   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.

          2)   Continuing improvement is essential to excellence in radiological control.

2.   Standard Applicability and Control

      a.   Recommends practices for the conduct of radiological control activities.

      b.   Best courses of action currently available and should be viewed by contractors as an acceptable technique.

      c.   Not a substitute for regulations.

      d.   Following the course of action will achieve and surpass requirements, but RCS is not sufficient to ensure compliance with all of 10 CFR 835.

      e.   Revision

          1)   The RCS is a living document.

          2)   Revision will be made to incorporate lessons learning and suggestions.

          3)   The Chief, Health, Safety and Security Officer is responsible for this task.

          4)   Recommendations are requested.

      f.   Use of the RCS is recommended to conduct DOE-funded radiological activities at DOE and non-DOE sites.

      g.   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.

      h.   The RCS should be kept current and should be entered into the contractor document control system.

      i.   The RCS does not apply to the Naval Nuclear Propulsion Program.

3.   Compliance

   The RCS is a guidance document and compliance is not mandatory, unless the contractor is contractually obligated to follow provisions of the RCS.

4.   Site-Specific Manual

      a.   A Site-Specific RCM should be issued and endorsed by the contractor senior site executive.

      b.   DOE-HSS approval is not required.

      c.   Management policies, requirements, expectations and objectives for the site Radiological Control Program should be clearly and unambiguously stated..

      d.   The Site-Specific Manual should be kept current and entered into the contractor document control system.

      e.   Subcontractors should comply with the Site-Specific RCM.

5.   Application of Requirements

      a.   It is not the intent of the RCS to unnecessarily create new or separate organizations if those functions can be incorporated into existing ones.

      b.   Existing charters may need to be revised to address RCS recommendations.

      c.   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.

III. SUMMARY

    A. Review major topics

        1. History of standards

        2. Advisory agencies

        3. Federal policy on radiation matters

        4. Regulating agencies

        5. Radiological Control Standard

    B. Review of learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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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.

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".

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned

I. MODULE INTRODUCTION

A. Self-Introduction

  1. Name

  2. Phone Number

  3. Background

  4. Emergency procedure review

B. Motivation

  All personnel at a facility must be committed to ALARA.
  The RCT can play a major role in establishing and
  maintaining that commitment.

C. Overview of Lesson

  1. ALARA Philosophy

  2. Objectives of ALARA Programs

  3. ALARA Concerns

  4. Collective Dose Philosophy

  5. Scope of ALARA Program

  6. ALARA Reviews

  7. RCT Responsibilities

D. Introduce Objectives   O.H.: Objectives

II. MODULE OUTLINE

A. ALARA Philosophy   Objective 1.10.01

  1. 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.

  2. The effects of low-level doses over extended periods of
      time are not definitively characterized and the risk is
      difficult to quantify.

3. Studies of atomic bomb survivors and individuals involved in Nuclear incidents show the relationship between dose and effects is well known only at high doses.

4. The benefit of completing a task must be compared to the risk of the exposure received.

B. Objectives of ALARA Programs

1. 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.

2. Personal radiation exposure shall be maintained As-Low-As- Reasonably Achievable (ALARA).

3. 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.

C. ALARA Concerns

1. Implementation of ALARA concepts should be carried out through all phases of a facilities lifetime.

2. ALARA Program concerns include:

    a. Engineering features

        1) Discharge of radioactive liquid to the environment

        2) Control of contamination

        3) Efficiency of maintenance, decontamination and operations should be maximized

        4) Components should be selected to minimize the buildup of radioactivity

        5) Support facilities should be provided for donning and removal of protective clothing and for personnel monitoring

        6) Shielding requirements

        7) Ergonomics consideration

        8) Access control designed for hazard level.

    9) Surfaces that can be decontaminated or removed

    10) Equipment that can be decontaminated

b. Area arrangement

    1) Traffic patterns to allow access yet prevent unnecessary exposure

    2) Equipment separation

    3) Valve locations

    4) Component laydown/storage areas

c. Operations

    1) Inspection tour - access, mirrors, visibility

    2) Inservice Inspections - use of remote control equipment, TV, Snap on insulation, platforms, etc.

    3) Remote readout instrumentation

    4) Remote valve/equipment operators

    5) Sampling stations, piping, valving, hoods, sinks

d. Maintenance needs

    1) Adequate lighting, electric outlets, other utilities

    2) Removal and storage areas for insulation/shrouding

    3) Relocation of components to low dose areas

    4) Workspace for maintenance personnel

    5) Lifting equipment

    6) 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.

    e.   Radiological control needs

        1)   Access control

        2)   Shielding adequacy and access plugs

        3)   Temporary shielding and support structures

        4)   Adequate ventilation

        5)   Breathing air

        6)   Contamination control - drip pans, curbs, drains, and routing

        7)   Decontamination facilities

        8)   Radiation monitoring equipment

        9)   Communications

D. Collective Dose Philosophy

    1.   Control of the collective dose to the work force.

    2.   Collective dose is defined as the total individual doses in a group or a population.

    3.   Spreading dose among more workers versus higher individual exposures for fewer workers is an ALARA issue.

        a.   Spreading dose

           1)   The linear model states that the less exposure a worker receive the less chance they will receive harmful biological effects.

           2)   Lower collective dose is a good indicator of an effective ALARA Program

        b.   Higher Individual Exposure

           1)   Exposure to fewer individuals means that the risk to the rest of the work force has been minimized.

           2)   Merely controlling maximum dose to individuals is not sufficient, collective dose must be controlled as well.

Objective 1.10.02

4. Reducing radiological risks should not result in higher risks for other hazards.

5. Reduction in radiological risk should be reasonably achievable based on the current state of technology, economic factors, and social conditions

E. Scope of ALARA Program   Objective 1.10.03

1. Establish a program to maintain exposures ALARA.

2. Design and modify facilities and select equipment with ALARA concepts integrated into the processes.

3. Establish radiological control programs, plans and procedures.

4. Make available equipment, instrumentation and facilities necessary for ALARA program implementation.

5. Train facility workers and management as well as radiological control personnel in ALARA programs and reduction techniques.

6. Applies equally to the reduction of external and internal exposure.

7. The ALARA program must be incorporated in everyday, routine functions as well as non-routine, higher risk tasks.

8. The involvement and commitment of all facility personnel, not just radiological control personnel, is necessary to achieve the reduction of external and internal exposure.

9. To justify activities that could result in exposure to ionizing radiation, the following conditions should be satisfied:

    a. The risks associated with projected radiation exposures should be small when compared to the benefit derived.

    b. Further reduction in projected exposure is evaluated against the effort required to accomplish such reduction and is not reasonable

    c. The risks from occupational exposure or to the public should not exceed everyday or accepted risks.

10. Ownership - each individual involved in radiological work must demonstrate responsibility and accountability through an informed, disciplined and cautious attitude toward radiation and radioactivity.

   a.   Management responsibilities:

   1)   Design and implement ALARA program

   2)   Provide resources such as tools, equipment, adequate personnel

   3)   Create and support ALARA Review Committee

   4)   Approve ALARA goals

   5)   Design and implement worker training

   b.   Radiological Control Technician Responsibilities:

   1)   Perform the functions of assisting and guiding workers in the radiological aspects of the job

   2)   Knowledge of conditions at the work site

   3)   Knowledge of work activities to be performed

   4)   Identification of protective clothing and equipment requirements

   5)   Identification of dose reduction techniques

   6)   During work conduct, maintaining awareness of conditions

   7)   Correction of worker mistakes

   8)   Response to abnormal events

   c.   ALARA "group" - including facility/RC supervision/management:

   1)   Evaluate worker suggestions and provide feedback in a timely manner

   2)   Participate in pre-and post-work meetings

   3)   Keep abreast of ALARA techniques pertinent to operations on site.

   4)   Track facility performance in comparison to stated goals

F. ALARA Reviews

   1. Pre-job ALARA Reviews   Objective 1.10.04

      a. For every task involving radiological work, sufficient radiation protection controls should be specified in procedures and work plans to define and meet requirements.

      b. 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 in ways that ensure that the employee is able to maintain their exposure ALARA.

      c. Proposed ALARA protective measures shall be evaluated to ensure the costs are justified.

   2. Pre-Job Briefing

      a. Pre-job briefings are held with employees who will be involved in work activities involving unusual radiological conditions.

      b. Identify effective dose reduction measures.

      c. RC needs are communicated to workers. Worker needs are communicated to RC.

      d. Procedures are verified.

      e. Worker qualifications are verified.

      f. Emergency procedures are discussed.

      g. At 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.

      h. ALARA pre-job briefing checklists

         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

3. Post-Job ALARA Reviews

    a. Jobs determined to require a ALARA review shall undergo a post-job review to ensure the overall effectiveness of job planning and implementation.

    b. Unusual exposure events are investigated to determine the root cause. Recommendations are made and corrective actions are then taken to prevent future reoccurrences of these events.

4. Post-Job Debriefing

    a. The opportunity to critique the work performance.

    b. Although, they will not affect the dose already received for a particular job, they can be effective in reducing the doses received the next time that job is performed.

    c. Information discussed at post-work meetings include discussions of what went wrong and what could have been done differently to reduce the exposures received.

    d. Post-work meeting rely heavily on the input of each radiation worker for information on how best to reduce exposure the next time that job is performed.

    e. Typical questions asked could include:

        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?

G. Radiological Control Technicians

    1. The responsibilities of the Radiological Control   Objective 1.10.05
Technician:

       a. Pre-job ALARA reviews

       b. Pre-job briefings

       c. Radiation hold points identified

       d. Tool and equipment requirements/need for special
tools

           1) Pre-fabrication of temporary shielding

           2) Removal of component to low dose areas

           3) Previous job evolutions, previous survey
conditions

       e. Area Set-up

           1) Access to and from work area

           2) Service lines available - air, electric,
ventilation, lighting

           3) Staging areas - low radiation areas, tool
preparation and personnel waiting areas

           4) Communications - equipment, lines, TV
monitoring.

           5) Radiological controls - anticipation of
conditions during job with identification of
controls required, surveys completed, high and
low dose areas identified, contamination
control requirements, airborne

       f. Worker preparation

           1) Experienced workers

           2) Specialized training - mock ups, photographs,
rehearsals, etc.

           3) Briefings - conditions, needs of RC personnel,
what to expect, abnormal conditions

           4) Pre-work check off packages

g. Conduct of the job

1) The technician is tasked with assisting other workers in maintaining their exposures ALARA.

2) The technician can not lose sight of his own exposure reduction needs.

3) 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.

4) If the technician notices the worker not following good radiological work practices, on the spot corrections should be made.

5) Stop work authority is granted to all employees and all radiological control personnel should exercise this authority when:

   a) Inadequate radiological control

   b) Radiological controls not being implemented

   c) Radiological controls hold point not being satisfied.

III. SUMMARY

A. Review major topics

1. ALARA Philosophy

2. Objectives of ALARA Programs

3. ALARA Concerns

4. Collective Dose Philosophy

5. Scope of ALARA Program

6. ALARA Reviews

7. RCT Responsibilities

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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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 dose equivalent 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.

References:

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.

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned

I.   MODULE INTRODUCTION

A. Self-Introduction

  1. Name

  2. Phone number

  3. Background

  4. Emergency procedure review

B. Motivation

  1. The goal of any radiation safety program is to reduce exposure, whether internal or external, to a minimum. The external exposure reduction and control measures available are of primary importance to the everyday tasks performed by the RCT.

C. Overview of Lesson

  1. Minimizing Personal exposure

  2. "Source reduction" techniques and calculations

  3. "Time-saving" techniques and calculations

  4. "Distance to radiation source" techniques and calculations

  5. Skin density thickness

  6. Shielding calculations

D. Introduce Objectives

O.H.: Objectives

II. MODULE OUTLINE

A. Basic Methods for Exposure Reduction

Objective 1.11.01

  1. 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.

2. There are four basic methods available to reduce external exposure to personnel:

    a. Reduce the amount of source material (or reduce emission rate for electronically-generated radiation).

    b. Reduce the amount of time of exposure to the source of radiation.

    c. Increase the distance from the source of radiation.

    d. Reduce the radiation intensity by using shielding between the source and personnel.

3. In order to use the basic methods for controlling exposure, the worker must be able to determine the intensity of the radiation fields. The following equations are used to make this determination.

    a. A "rule-of-thumb" method to determine the radiation field intensity for simple sources of radioactive material is the "curie/meter/rem" rule. (Co-60)

        1 Ci @ 1 meter = 1 R/hr

    b. To determine the gamma radiation field intensity for a radioactive point source

        $I_{1ft} = 6CEN$

        where:

        I_{1ft} = Exposure rate in R/hr 1 ft.
        C = Activity of the source in Ci
        E = The gamma energy in MeV
        N = The number of gammas per disintegration

        1) This equation is accurate to within $\pm20\%$ 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.:

            $[(\gamma_1)(\%_1) + (\gamma_2)(\%_2) + \cdots + (\gamma_n)(\%_n)]$

Not very accurate, valid only for certain photon energies

Objective 1.11.02

c.   For distances in meters:

$I_{1m} = 0.5CEN$

d.   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:

$$I = \frac{(6CEN)(1^2)}{d^2}$$

where: d = distance in feet;

e.   For metric distances the equation becomes:

$$I = \frac{(0.5CEN)(1^2)}{d^2}$$

where: d = distance in meters

f.   Example: Determine the exposure rate at 10 ft for a 8 Ci point source of Co^{60} that emits a 1.173 and 1.332 MeV gamma, both at 100% of the disintegrations.

$$I at 10\,ft = \frac{[(6)(8)(\sum 1.173(1) + 1.332(1))][1^2]}{(10\,ft)^2} = 1.2\ \text{R/hr}$$

g.   Example: To determine the exposure rate at 1 ft for a 1Ci point source of ^{137}Cs that emits a 662 keV (0.662 MeV) gamma in 85% of the disintegrations:

$I_{1ft} = 6(1Ci)(0.662\ \text{MeV})(0.85)$

$I_{1ft} = 3.38\ \text{R/hr}$

h.   Example: Calculate the exposure rate at 2 meters for 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 1.11-1
Examples are not completed in student study guide. Have students work example and then work on board.

Sample Problem 1.11-2

$I = [(.5)(1.8\text{Ci})(2.505\text{ MeV})(1.00)] \div (2)^2$

$I = 0.564$ R/hr @ 2 meters

   i. Example: Calculate the exposure rate at 1 ft., 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%).

Sample Problem 1.11-3
Note: Ir-192 emits other gammas at lower percentages, but these are not included

$I_{1ft} =$

$6(0.4\text{Ci})[(0.316)(.87) + (0.486)(.52) + (0.308)(.32) + (0.295)(.3)]$

$I_{1ft} = 6 (0.4\text{Ci})(0.7147)$

$I_{1ft} = 1.715$ R/hr

$I_{1ft} = 1,715$ mR/hr

Objective 1.11.03

B. Source Reduction

   1. 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.

   2. Various techniques are employed to accomplish external exposure reduction using source reduction.

      a. Allow natural decay to reduce source strength

         1) If the radioisotopes involved are short-lived, then waiting to perform the task may significantly reduce the hazard.

Sample Problem 1.11-4

         2) For example, 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 radio-nuclides contained in the pump has an effective half-life of 40 days. In 80 days the activity in the pump will be reduced to one fourth of original activity:

$A = A_o \, 2^{-n}$

$$\frac{A}{A_o} = 2^{-2}$$

$$\frac{A}{A_o} = \frac{1}{4}$$

By waiting for natural decay to reduce the source strength, a considerable savings in external exposure can be achieved.

b. Move the source material to another location

   1) 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.

   2) 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.

   3) Discharge or remove the resin or filtering media prior to working in the area or on the system.

   4) Move the radioactive source (e.g., a drum, barrel or calibration source) to another location prior to starting work.

C. Time Savings

   1. 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.

   2. 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.

   3. 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.

Objective 1.11.04

4. Various techniques are employed to reduce personnel external exposure by reducing the amount of time spent in radiation fields.

    a. Analyze and train using mock-ups of the work site

        1) 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.

        2) 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.

        3) By determining the most efficient method and rehearsing the task, the amount of time, and therefore the exposure, can be reduced.

    b. Use of pre-job briefings is an important part of any good ALARA program

        1) Discussions at the pre-job briefing with the individuals assigned to the task can identify any potential problems not previously identified.

        2) 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.

    c. 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.

    d. 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.

    e. Pre-assemble equipment and tools outside the area

        1) Equipment that can be preassembled should be preassembled prior to any entry into the radiation field.

    2) Tools that require assembly, pre-testing, and/or calibration should be performed outside the radiation field.

  f. 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.

  g. Use communication devices such as walkie-talkies

    1) Poor communication can lead to incorrect or poor quality work and prolonged waiting in the radiation field while supervisors or experts are contacted.

    2) 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.

  h. Use a team of workers instead of allowing one individual to receive all of the exposure

    1) Even if the task requires a minimum amount of time, if it causes one individual to receive an exposure greater than allowable, a team of workers should be used to reduce the individual exposures.

    2) If a team of workers is used, good communications are necessary to ensure the total exposure for the job does not increase significantly.

  i. Use experienced personnel

    1) The total time required to perform a job is reduced if experts are used instead of inexperienced personnel.

    2) Inexperienced personnel should not be trained in significant radiation fields.

5. The exposure received by personnel will increase as the time spent in the radiation field increases.

a. The exposure received is equal to the radiation field
    intensity times the exposure time

$$X = (\frac{R}{t})T$$

where: X = exposure

$\frac{R}{t}$ = *exposure rate*

T = period of time exposed

b. Example: 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?

$$X = (\frac{120mR}{hr})(90\min)(\frac{1hr}{60\min})$$

X=180 mR

6. 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."

a. Stay time is calculated as follows:

$$Stay\ Time = \frac{H_{allowable} - H_{receivable}}{}$$

where:

$H_{allowable}$ = Allowable equivalent dose

$H_{received}$ = Equivalent dose already accumulated in the
            time period

b. Example: 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?

Since the conversion from gamma exposure rate to equivalent dose is essentially 1:1, then 2.5 R/hr = 2.5 rem/hr

$$Stay\ time = (\frac{600mrem - 120mrem}{2.5rem/hr})(\frac{1rem}{1000mrem})$$

$$Stay\ time = 0.192hr(\frac{60\min}{1hr}) = 11.5\min$$

c. Example: An individual must enter a mixed gamma/neutron radiation field for emergency repair work. The radiation field consists of 2500 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 1.11-7

$$H_{total} = (\frac{2500mR}{hr})(1) + (\frac{500mrad}{hr})(3)$$

H_{total} = 4000 mrem/hr

$$Stay\ Time = (\frac{600mrem - 340mrem}{4000mrem/hr})$$

$$Stay\ Time = 0.065\ hr(\frac{60\min}{hr})$$

Stay Time = 3.9 min

Sample Problem 1.11-8

d. Example: Assume the work that must be completed will take 35 min. and a group of workers, with no previous exposure for the month, is available. How many additional workers are needed to complete the emergency task if no one individual exceeds the ALARA monthly guideline?

$$Stay\ Time = \frac{600\ mrem}{4000\ mrem/hr}$$

$$Stay\ Time = 0.15\ hr\ \frac{60\ \min}{hr}$$

$$Stay\ Time = 9\ \min\ per\ individual$$

$$Number\ of\ workers = \frac{35 - 3.9\ \min}{9\ \min/man}$$

$$Number\ of\ workers = 3.46$$

Therefore, four additional workers are required.

D. Distance Objective 1.11.06

   1. 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, increasing the distance from the source is more effective than decreasing the time spent in the radiation field.

      a. 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.

      b. 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).

    c. For a point source, if the distance is doubled, the radiation intensity will be reduced by a factor of (2)2 or 4.

    d. Calculations to show this relationship will be used later in this section.

2. Various techniques are employed to accomplish external exposure reduction by increasing the distance.

    a. Remote handling tools/remote control devices

        1) Tools, such as tongs or long-handled tools, are an effective means of increasing the distance from a point source to a worker.

        2) For very high radiation fields, remote control devices may be appropriate, especially if the task is performed frequently.

    b. Remote observation by cameras or indicators

        1) Gauges or meters can be moved to a location remote from the source of radiation.

        2) 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.

    c. Move work to another location

        1) If the source of radiation can not be reduced, then possibly the work can be moved to a low exposure area.

        2) 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.

    d. Maximize the distance during work from the source when possible

        1) 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.

2) Identifying "low dose rate waiting areas" can notify workers of the location of the lowest exposure rate in an area or room.

3) Be aware of the location of radiation sources at the worksite and locate the worker at a point farthest from the source.

4) Work at arm's length and do not lie on or hug radioactive components.

e. 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.

f. Extendable Instruments

Extendable radiation survey instruments, such as the Eberline Teletector, can reduce the exposure to the surveyor by increasing the distance.

3. Point source calculations Objective 1.11.07

a. As previously mentioned, the exposure rate is inversely proportional to the square of the distance from the source. The mathematical equation is:

$$(I_2)(d_2)^2 = (I_1)(d_1)^2$$

where:

I_1 = Exposure rate at distance (d_1)

I_2 = Exposure rate at distance (d_2)

d_1 = First distance from the source

d_2 = Second distance source

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.

b. 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.

c. For example: a 1 Ci point source of Cs-137 has a gamma exposure rate of 3.38 R/hr at 1 ft. What would the exposure rate be at 3 ft?

Sample Problem 1.11-9

$$I_2 = I_1(\frac{d_1^2}{d_2^2})$$

$$I_2 = (3.38R/hr)(\frac{(1)^2}{(3)^2})$$

$$I_2 = 0.376R/hr = 376mR/hr$$

d. Example: 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?

Sample Problem 1.11-10

$$(d_2)^2 = \frac{I_1 d_1^2}{I_2}$$

$$(d_2)^2 = \frac{15.03R/hr - (1ft)^2}{0.1R/hr}$$

$$d_2 = 12.26ft.$$

e. 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.

f. Some sources, such as a pipe or tank, can not be treated as a point source. These sources must be treated as line sources or large surface sources.

Objective 1.11.08

4. Line source calculations   Objective 1.11.08

    a. 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.

    b. If the line source is treated in this manner, the relationship between distance and exposure rate can be written mathematically as:

$$I_1d_1 = I_2d_2$$

        1) The exposure rate is inversely proportional to the distance from the source

        3) Assuming the source material is distributed evenly along the line

        4) Assuming the point at which the exposure rate is calculated is on a line perpendicular to the center of the line source

        5) Assuming the width or diameter of the line is small compared to the length

        6) 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

    c. For example: 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 feet?   Sample Problem 1.11-11

$$I_1d_1 = I_2d_2$$

$$I_2 (5R/hr)(\frac{1\,ft}{4\,ft})$$

$$I_2 = 1.25R/hr$$

    d. Example: What would the exposure rate be at 15 feet for the same small diameter pipe?   Sample Problem 1.11-12.1

$I_1d_1 = I_2d_2$

Determine rate at L/2.

$$I_2 = (5R/hr)(\frac{1\,ft}{5\,ft})$$

Determine rate at 15 ft.

$$I_2 = \frac{(1R/hr)(5\,ft^2)}{(15\,ft^2)}$$

$$I_2 = 111 mR/hr$$

5. Planar or surface sources   Objective 1.11.09

   a. 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.

   b. 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.

   c. When the distance to the plane source is small compared to the longest dimension, then the exposure rate falls off a little slower than

$$\frac{1}{d}$$

    (i.e. not as quickly as a line source).

   d. As the distance from the plane source increases, then the exposure rate drops off at a rate approaching:

$$\frac{1}{d^2}$$

6. The exposure rate versus distance calculations can be used to make an estimate of the radiation intensity at various distances.

7. These estimates are valuable tools to estimate and verify the readings obtained from exposure rate meters.

E. Mass Attenuation Coefficient

Objective 1.11.10

1. The probability of a photon interaction per path length and therefore has units of (length)$^{-1}$ (typically cm^{-1}).

2. Mathematically:

$\mu_m = \mu_l/\rho$

where:

μ_m = mass attenuation coefficient

μ_l = linear attenuation coefficient

ρ = physical density

F. Density-Thickness

1. The value equal to the product of the density of the material times its thickness which then becomes the thickness of the material measured in mass/(length)^2 (typically mg/cm^2)

Objective 1.11.11

2. Density Thickness values:

a. Skin (shallow dose) - 7 mg/cm^2

b. Lens of the eye - 300 mg/cm^2

c. Whole body (deep dose) - 1000 mg/cm^2

Objective 1.11.12
See Table 1 - "Density Thickness"

G. Shielding Calculations

1. 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).

Objective 1.11.13

2. 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.

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$$

3. 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.

$$TVL = \frac{\ln(10)}{\mu} = \frac{2.3026}{\mu}$$

4. 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.

$$HVL = \frac{0.693}{\mu_{mass}^{xP}}$$

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.

Density & μ_{mass} values from RH handbook See Table 2 - "HVL"

6. The basic equation for using the HVL concept is:

$$I = I_o (\frac{1}{2})^n$$

Where :

$I = shielded\ exposure\ rate$

$I_o = unshielded\ exposure\ rate$

$$n = HVL = \frac{shield\ thickness\,(cm)}{HVL(cm)}$$

7. The basic equation for using the TVL concept is:

$$I = I_0 (\frac{1}{10})^n$$

$I = I_0$ *shielded exposure rate*

I_0 = *unshielded exposure rate*

$$n = \#TVL = \frac{shield\ thickness\,(cm)}{TVL\ thickness\,(cm)}$$

8. For example calculate the shielded exposure rate from a   Sample Problem 1.11-13
   500 mR/hr Cs-137 source with 5 cm of lead shielding. The
   HVL for Cs-137 and lead is 0.65 cm.

   $$n = \#\,HVL = \frac{5cm}{0.65} = 7.7\,HVL$$

   $$I = (\frac{500mR}{hr})(\frac{1}{2})^{7.7}$$

   $$I = 2.4 mR\,/\,hr$$

9. For example, calculate the shielded exposure rate from a   Sample Problem 1.11-14
   7.4 R/hr Cs-137 source with 4 cm of lead shielding. The
   HVL for Cs-137 and lead is 0.65 cm.

   $$n = \#\,HVL = \frac{4cm}{0.65} = 6.15\,HVL$$

   $$I = (\frac{7.4R}{hr})(\frac{1}{2})^{6.15}$$

   $$I = 0.104R\,/\,hr = 104mR\,/\,hr$$

10. For example, calculate the #TVL and the thickness of lead   Sample Problem 1.11-15
    required to reduce the exposure rate from a 7.5R/hr Co-60
    source to less than 100 mR/hr. One TVL for Co-60 and
    lead is 4.0 cm.

    $$\frac{100mR}{hr} = (\frac{7.5R}{hr})(\frac{1}{10})^n$$

    $$\log(\frac{100}{7500}) = \log(\frac{1}{10})^n$$

    $$n = \#TVL = 1.88$$

$$1.88 = \frac{shield\ thickness\ in\ cm}{4.0cm}$$

$$shield\ thickness = (1.88)(4.0\ cm)$$

$$shield\ thickness = 7.5\ cm$$

Sample Problem
1.11-16

11. For example, calculate the #TVL and the thickness of lead required to reduce the exposure rate from a 450 mR/hr Co-60 source to less than 5 mR/hr. One TVL for Co-60 and lead is 4.0 cm.

$$\frac{5mR}{hr} = (\frac{450mR}{hr})(\frac{1}{10})^n$$

$$\log(\frac{4}{450}) = \log(\frac{1}{10})^n$$

$$n = \#TVL = 1.95$$

$$1.95 = \frac{shield\ thickness\ in\ cm}{4.0cm}$$

$$shield\ thickness = (1.95)(4.0cm)$$

$$shield\ thickness = 7.8cm$$

III. SUMMARY

A. Review major topics

2. Minimizing Personal exposure

3. "Source reduction" techniques and calculations

4. "Time-saving" techniques and calculations

5. "Distance to radiation source" techniques and calculations

6. Skin density thickness

7. Shielding calculations

B. Review learning objectives.

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the passing criteria for the examination.

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.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; 5th ed.; Pacific Radiation Corporation; 2008.

2. DOE-STD-1098-2008, "Radiological Control Standard".

3. 10 CFR Part 835 (2007) "Occupational Radiation Protection".

4. "Health Physics and Radiological Health Handbook"; Shleien; 1992.

Instructional Aids:

1. Overheads

2. Overhead projector/screen

3. Chalkboard/whiteboard

4. Lessons learned

I. MODULE INTRODUCTION

   A. Self-Introduction

      1. Name

      2. Phone Number

      3. Background

      4. Emergency procedure review

   B. Motivation

      The tasks that make up the responsibilities of the RCT include those actions used to minimize the potential exposure of workers from internal exposures.

      This class is designed to familiarize the technician with those actions necessary as a result of the entry of radioactive materials into the body and the basis for those actions.

   C. Overview of Lesson

      1. Modes of entry into the body

      2. Preventive measures, their use, and their basis

      3. Metabolism of materials and elimination processes

      4. Assessment methods

      5. Definitions

   D. Introduce Objectives   O.H.: Objectives

II. MODULE OUTLINE

   A. Entry of Radioactive Materials into the Body

      2. Knowledge of the ways in which radioactive materials enter the body is essential for two reasons.

         a. How radioactive material gets into the body must be known in order to design and implement measures to prevent entry.

    b.   The mode of entry by which particular materials get into the body can influence the behavior of the materials.

2.   Modes of entry

    a.   Inhalation - materials enter the body in the air that is breathed.

    b.   Ingestion - materials enter the body through the mouth.

    c.   Absorption - material enters the body through intact skin.

    d.   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.

3.   Preventive measures

    a.   Inhalation - assessment of conditions, use of engineering controls (e.g. ventilation systems), respiratory protection equipment.

    b.   Ingestion - proper radiological controls and work practices (e.g. no eating, drinking, or chewing in a contamination area).

    c.   Absorption - assessment of conditions and protective clothing.

    d.   Entry through wounds - not allowing contamination near a wound by work restriction or proper radiological controls if an injury occurs in a contaminated area.

    e.   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

Objective 1.12.01

Objective 1.12.02

    2) Block the pathway from the source of radioactive materials into the body.

B. Annual Limit on Intake and Derived Air Concentration

    1. 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.

    2. 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.

    3. These limiting values are:

        a. Annual Limit on Intake (ALI) - 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.

        b. Derived Air Concentration (DAC) - Quantity obtained by dividing the ALI for any given radionuclide by the volume of air breathed by an average worker during a working year.

    4. The derivation of the Annual Limit on Intake is based on known metabolic processes for the nuclides involved and reference man.

    5. Reference Man

        a. Reference man defines the physiological makeup of an average man in terms of factors required for dose calculations and includes such items as:

            1) Height and other dimensions

            2) Mass

            3) Size and mass of organs

        b. 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.

Objective 1.12.03

5 rem/year whole body (stochastic)

50 rem/year organ (deterministic)

Objective 1.12.04

Objective 1.12.05

    c. 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.

    d. The resulting quantities are the values that are listed for Annual Limits on Intake.

6. 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:

$$\frac{0.02\text{m}^3}{\text{min}} \times \frac{60\,\text{min}}{\text{hr}} \times \frac{8\text{hrs.}}{\text{day}} \times \frac{5\text{days}}{\text{week}} \times \frac{50\text{weeks}}{\text{year}} = 2400\text{m3}$$

7. The DAC is equal to the ALI divided by the volume of air breathed by the average worker during a working year:

$$DAC = \frac{ALI}{2400m^3}$$

8. 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.

    b. The ALARA process is utilized for personnel exposures to ionizing radiation.

9. Subpart E (835.403 "Air 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.

Objective 1.12.06

10. 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.

a. 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.

1) 10 CFR 835 states that an Airborne Radioactivity Area is any area where the concentration of airborne radioactivity, above natural background, exceeds or is likely to exceed the DAC values listed in Appendix A or Appendix C of Part 835, or where an individual present in the area without respiratory protection could receive an intake exceeding 12 DAC-hours in a week.

2) Posting of airborne radioactivity areas controls access to minimize exposure.

b. Minimize the stay time of workers in airborne areas to short periods of time.

c. Augment installed engineering controls with respiratory protection equipment to further reduce the concentration of contaminants in the air the workers are actually breathing.

11. 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.

    a. 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.

    b. Engineering controls are augmented with respiratory protection equipment when airborne contaminants exceed or potentially exceed DAC values.

C. Movement of Radioactive Materials Through the Body

    1. 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.

    2. 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.

Objective 1.12.07

    3. 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.

    a. Chemical form - solubility

    b. Location - pathways

    c. Body's need - intake and incorporation vs. elimination

    4. Intake and Uptake

    a. 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.

       1) Intake: the amount of radionuclide taken into the body.

        2)   Uptake: the amount of radionuclide deposited in the body which makes its way into the body fluids or systemic system (i.e., blood)

    b.   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. (Intake is defined in the 10 CFR 835 Implementation Guide).

D. Normal Metabolic Pathways for Materials in the Body

    1. Inhaled radioactive materials

        a.   General pathways

See Fig. 1 - "Metabolic Pathways".

            1)   Exhalation

            2)   Deposition in lungs with eventual transfer to GI tract or retention

            3)   Transport to body fluids

            4)   Transfer to lymph nodes with eventual movement to body fluids

            5)   Retention in lymph nodes

        b.   Once in the bodily fluids, possibilities include:

            1)   Transfer to specific organ

            2)   Filtration and elimination by kidneys

            3)   Transport and removal from body fluids through circulatory systems (perspiration)

        c.   Insoluble particulates

            1)   Lung retention time based on particle size and density

            2)   Removal in mucous to digestive tract

            3)   Elimination in fecal was

        d.   Soluble particulate materials

       1) Retention in lungs based on size and density – some exhalation

       2) Some removed to GI tract for elimination or to body fluids

       3) Transfer to body fluids via lymph nodes or directly from lungs

       4) Some retention in lymph nodes

       5) Body fluids to tissue or organ of interest

       6) Excretion

2. Ingested Radioactive Materials   e.g., <1% of Pu is absorbed

   a. For elements not used by the body, absorption by ingestion is poor, and most materials will pass straight through the body.

   b. Materials pass through stomach to small intestine where transport of soluble materials to body fluids will occur.

   c. From body fluids, materials go to the organs and/or are removed through normal biological elimination processes.

   d. Soluble materials

       1) Transfer to body fluids in intestines

       2) Circulation, absorption, incorporation in tissues and organs

       3) Elimination in urine

   e. Insoluble materials

       1) Passes straight through

       2) Elimination in feces

3. Absorbed Radioactive Materials

   a. 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.

b. The most important of these is tritium as water vapor. Once absorbed into the body, tritium exchanges freely with hydrogen, disperses throughout the body almost immediately, and irradiates bodily tissues throughout the body.

4. Target Organs

a. Some elements are collected in target organs. As an example, iodine is collected by the thyroid gland.

b. Major dose to the thyroid could be expected as a result of gamma and beta interactions emitted by iodine collected in the thyroid gland.

c. 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.

d. 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.

5. Other elements are processed differently.

a. Some are distributed freely throughout body fluids.

b. Some are collected in specific organs such as the kidneys, spleen or bone.

c. 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.

d. Knowledge of material behavior is critical to assessing parts of the body affected and subsequent impact to the health of the individual involved.

Example: If surrounded by a cloud of tritium existing as water vapor, the ratio of exposure of absorption through the skin vs. inhalation is 1:2. (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.)

Example: ^{3}H, ^{137}Cs

Example: Sr, U, and Pu are concentrated in the bone

E.   Elimination Processes

   1.   Once radioactive materials enter the body, there are two mechanisms which result in reduction of the quantities present.

        a.   Normal biological elimination

             Objective 1.12.08

             1)   Radioactive materials incorporated into body tissues and organs are eliminated from the body as are their non-radioactive counterparts.

             2)   Eliminated through exhalation, perspiration, urination, and defecation.

             3)   Each element has a measurable biological half-life - the time required to reduce the amount of material in the body to one-half of its original value.

             4)   If body functions are saturated, the elimination rate may be vastly different and the concept of a biological half-life is not applicable.

             5)   The biological half-life is independent of the physical or radiological half-life.

             6)   Examples include:

                  a) ^{3}H - 10 days

                  b) ^{60}Co - 9.5 days

        b.   Radioactive decay

             1)   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 physical half life.

             2)   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.

$$T_e < T_b, T_p$$

3) 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.

2. Effective half-life

   a. 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:

   b. The removal rate as a result of the combined processes is measured as an effective half-life and is calculated using the following formula:

   c. 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.

   Objective 1.12.09

   $$\lambda_e = \lambda_b + \lambda_p$$

   Objective 1.12.10

   d. Example calculations:

   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.

   $$T_e = \frac{(10\,\text{days}) \times (12.3\,\text{years} \times 365.25\,\text{days}/\,\text{year})}{(10\,\text{days}) + (12.3\,\text{years} \times 365.25\,\text{days}/\,\text{year})}$$

   $$T_e = 9.9778\,\text{days}$$

   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.

   $$T_e = \frac{(2000\,\text{days}) \times (44.56\,\text{days})}{(2000\,\text{days}) + (44.56\,\text{days})}$$

   $$T_e = 43.589\,\text{days}$$

F. Medical Elimination - Rate Increase Methods   Objective 1.12.11

   1. 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.

   2. Blocking agents

      a. 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.

      b. 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.

      c. 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.

   3. Diluting agents

      a. 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 H^3 exposure.

      b. 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.

    c. The compound used must be as readily absorbed and metabolized as the compound that contains the radioisotope.

4. Mobilizing agents

    a. A mobilizing agent is a compound that increases the natural turnover process, thus releasing some forms of radioisotopes from body tissues.

    b. Usually most effective within 2 weeks after exposure; however, use for extended periods may produce less dramatic reductions.

5. Chelating agents

    a. 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.

    b. Commonly used to enhance elimination of transuranics and other metals.

    c. 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.

    d. Common chelating agents include EDTA and DTPA

       1) $CaNa^2$ EDTA - commonly used in cases of lead poisoning. It is also effective against zinc, copper, cadmium, chromium, manganese, and nickel.

       2) $CaNa^3$ DTPA - transuranics such as plutonium and americium.

6. Diuretics

    a. Diuretics increase urinary excretion of sodium and water.

    b. Used to reduce internal exposure, however its use has been limited. Applications could include ^{3}H, ^{42}K, ^{38}Cl and others.

      c. Can lead to dehydration and other complications if not performed properly.

  7. Expectorants and inhalants

      a. Used to increase flow of respiratory tract excretions.

      b. Thus far this type of therapy has not been proven successful in removing radioactive particles from all areas of lungs.

  8. Lung lavage

      a. Involves multiple flushing of lungs with appropriate fluid to remove radioactive materials in the lungs.

      b. Usually limited to applications where resulting exposures would result in appearance of acute or subacute radiation effects.

III. SUMMARY

  A. Review major topics

    1. Modes of entry into the body

    2. Preventive measures, their use, and their basis

    3. Metabolism of materials and elimination processes

    4. Assessment methods

    5. Definitions

  B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a questions examination comprised of multiple choice. 80% should be the minimum passing criteria for the examination.

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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.

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.

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned

I. **MODULE INTRODUCTION**

   A. Self-Introduction

      1. Name

      2. Phone number

      3. Background

      4. Emergency procedure review

   B. Motivation

      It is necessary for an RCT to have a good theoretical understanding of radiological instrumentation. This will help them to understand the data obtained by that instrumentation.

   C. Overview of Lesson

      1. Sources of Electrical Energy

      2. Basic Electrical Quantities

      3. Measurement systems

      4. Detectors

      5. Readout Circuitry

      6. Detector yield

      7. Various detectors

   D. Introduce Objectives

II. **MODULE OUTLINE**

   A. Sources of Electrical Energy

      1. All matter composed of atoms

         a. Protons

            1) Positive charge

            2) In nucleus

O.H.: Objectives

    b. Electrons

      1) Negative charge

      2) Orbit nucleus

2. Fundamental laws for electrical charges   Objective 1.13.01

    a. Opposite electrical charges of equal value cancel each other out.

    b. Opposite electrical charges attract each other.

    c. Like electrical charges repel each other.

3. Electric current is movement of electrons

    a. Energy required to remove from orbit

    b. If low, conductor

4. Seven sources of energy

    a. Friction: Static electricity - 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.

    b. Heat: Thermocouples - 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.

    c. Pressure: Piezoelectric effect - 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.

    d. Light: Photoelectric effect - In some materials, light can cause atoms to release electrons, when this happens, current flows through the material.

e. Chemical action: Batteries - Certain types of chemical reactions create electricity by separating the positive and negative charges in atoms. Batteries depend on chemical reactions to produce electricity.

f. Magnetism: Generators - 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.

g. Ionizing Radiation: Radiation can remove electrons from atoms and thereby create a flow of electrons or current.

1) Alpha radiation

2) Beta radiation

3) Gamma radiation

B. Basic Electrical Quantities

1. Current

   Objective 1.13.02

a. A measure of the movement or flow of electrons past a point in a circuit

b. 1 amp = 6.24 x 10^{18} electrons/second

= 1 coulomb/second

c. DC = one way

d. AC = alternating

2. Voltage

a. A measure of electrical potential energy force that causes current flow

b. Measured in volts

3. Resistance

a. Measure of the opposition to electron flow in a circuit

b. Measured in ohms.

      c. Very high in insulators

      d. Very low in conductors

   4. Ohm's Law

      a. $I = E/R$

      b. $E = IR$

      c. $R = E/I$

   where:

   E = voltage (volts)

   I = current (amps)

   R = resistance (ohms)

C. Measurement Systems   Objective 1.13.03

   1. Measurement/Detection   See Fig. 1 - "Basic Radiation
Measurement System"

      a. Radiation type

      b. Radiation intensity

      c. Applications

   2. Detector function - The incident radiation interacts with
the detector material to produce an observable effect,
be it a chemical change or an electrical signal.

   3. Readout circuitry function - measures and analyzes the
produced effect in the detector and provides a usable
output signal and/or indication.

D. Detectors

   1. Detection process

   2. Types

      a. Ionization Detectors - In ionization detectors, the
incident radiation creates ion pairs in the detector.

        1) Gas-filled

        2) Solid

    b. 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.

    c. Chemical detectors - In chemical detectors, the incident radiation causes ionization or excitation of the detector media thereby causing chemical changes which can be analyzed.

    d. Other detectors - Some detectors use other methods of detection, e.g., Cerenkov, Activation Foils, or Biological.

E. Readout Circuitry

  1. Measurement process

  2. Types

    a. Ratemeter

        1) Electric Pulse Output measures the effect of single events in a system. The output consists of several signals resolved in time.

        2) Current Output measures the average effect due to a large number of interactions in the system.

    b. Counter

F. Detector Yield

  1. As all detectors measure radiation as a function of its observed effects, a correlation must be made between the effect and the incident radiation.

  2. Factors

    a. Detector size and shape

    b. Detector material characteristics.

c. Radiation energy

d. Probability of ionization

G. Gas-Filled Detectors

1. Basic construction

a. Detector gas - The gas used in the detector can be almost any gaseous mixture which 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.

b. Electrodes - 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.

c. H.V. supply - Could be either batteries or alternating current.

2. Basic theory

a. Ion pair production - Created when ionizing radiation interacts with the detector gas.

b. Ion pair collection - When a voltage potential is established across the two electrodes the ion pairs will be attracted to the respective electrode with the opposite charge.

c. Analysis - 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.

d. Ion pair production factors

1) Type of radiation - 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.

See Fig. 2 - "Basic Gas-filled Detector"

Objective 1.13.04

2) Energy of the radiation - 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.

See Table 1 - "Specific Ionization in Air at STP"

3) 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.

4) Detector size and shape - A larger detector volume offers more "targets" for the incident radiation, resulting in a larger number of ion pairs.

5) Type of detector gas - The ionization potential is expressed in units of electron volts per ion pair and is called the W-Value. Typical gases have values of 25-50 eV, with an average of about 34 eV per ion pair.

6) Detector gas pressure and composition – Instead of increasing detector size to increase the number of "target" atoms, increasing the pressure of the gas will accomplish the same goal.

7) Voltage potential across the electrodes - If left undisturbed, the ion pairs will recombine, and not be collected. If a field is created in the detector by applying a voltage potential across the electrodes, the ion pairs will be accelerated towards the electrodes.

Objective 1.13.05

See Fig. 3 - "Six-region Curve for Gas-filled Detectors"

8) Effect of voltage potential on detector processes –If the applied voltage potential is varied from 0 to a high value and the pulse size is recorded and graphed, a response curve will be observed. The ion chamber region, the proportional region, and the Geiger-Mueller region are useful for detector designs used in radiological control. Other regions, the recombination region, the limited proportional region, and the continuous discharge region, are not useful.

9) Materials

3. Ion chamber detectors

   a. Operation/design Objective 1.13.06

      1) All primary ions created are collected before they can recombine, called Saturation Current.

      2) No secondary ions created, no gas amplification occurs.

   b. Advantages

      1) Less regulated power supplies

      2) Response proportional to dose rate

   c. Disadvantages

      1) Sensitivity poor

         a) Small output current

         b) 2 E-14 amps per mR/hr

      2) Affected by humidity

         a) High impedance

         b) Leakage paths

      3) Affected by temp/at pressure

         a) Typically 2% for 10 °F

         b) 4.6% per psig

   d. Typical applications

      1) Dose rate instruments

      2) Installed monitors

         a) ARMS

         b) PRMS

4. Proportional detectors

   a. Operation/design

      1) Secondary ionization - such output is still proportional to input.   Objective 1.13.06

      2) Primary ions cause amplification of signal due to secondary ionization of gas.

         a) 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.

         b) 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.

      3) Large output pulses - The large number of events, known as an avalanche, create a single, large electrical pulse.

      4) Discrimination - 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).   Objective 1.13.07

         a) Resolving time - the total time from a measurable detector response before another pulse can be measured.

   b. Detector construction

      1) Cylindrical detectors

         a) Portable survey instrument

         b) BF_3 or P-10 gas.

    2) Window, 2pi gas flow

      a) P-10 gas

    3) Windowless, 2pi gas flow

    4) 4pi gas flow

    5) Gas flow, flat

  c. Advantages

    1) Good discrimination

    2) Good sensitivity

    3) Useful for dose rates

  d. Disadvantages

    1) Requires highly regulated power supplies

5. Geiger-Mueller detectors

  a. Operation/design

    1) 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 package.

    2) Dead time is the time from the initial pulse until another pulse can be produced.

    3) Recovery time is the time from the initial full size pulse to the next full size pulse, not including the dead time.

    4) Sequence of events

      a) Ion pair (IP) produced

      b) IP acceleration toward electrode

      c) Secondary ionization

Right column notes:

See Fig. 4 - "Basic 2 Proportional Detector w/Window"

Objective 1.13.07

See Fig. 5 - "Dead Time of a G-M Tube"

        d) Avalanche

        e) Negative ions collected at center electrode, start of dead time

        f) Positive ion cloud drifts toward shell

        g) Voltage potential increases

        h) End of dead time, start of recovery time

        i) Amplification/ pulse size increases

        j) End of recovery and resolving time

    b. Effects of long resolving time

      1) Reduced accuracy

      2) Unusable in high flux rates

    c. GM detector construction

    d. Advantages of GM

      1) Not affected by temp/press - Not vented to the atmosphere and also due to the magnitude of the output pulse.

      2) Less regulated power supplies.

      3) More sensitive (for same size) - 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.

      4) Simple electronics package.

    e. Disadvantages of GM

      1) Does not measure true dose - Detector response is not related to the energy deposited.

2)　Typically large dead time - Activity present but undetected during dead time, resulting in a reduction of detector efficiency.

3)　Cannot discriminate - The instrument will respond with a very large pulse regardless of the type or energy of radiation.

f.　Typical applications (Insert site specific applications)

6.　Discrimination

Objective 1.13.08

a.　Purpose

1)　Physical discrimination

a)　Shielding is primary method of physical discrimination.

b)　Shield has greater effect on lower energy gammas.

c)　Shields can stop all alpha and beta.

2)　Detector gas fill

a)　Each type of radiation has a specific ionization factor in a particular gas.

b)　In addition, each different detector gas has a different response to various radiation energies.

c)　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.

3)　Electronic discrimination

a)　Discriminator low level

- Input sensitivity

- Rejects low level pulses.

    b) Pulse height is used to discriminate between types and energy of radiation.

    c) A GM detector cannot be used to electronically discriminate between types of radiation because all output pulses are of the same height.

H. Scintillation Detectors

    1. Scintillation process

      a. Scintillation detector materials

        1) The scintillation material converts radiation energy to a visible light output by excitation of the material.

        2) Phosphors and fluors

          a) Organic Crystals - 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.

          b) Organic Liquids - The incident radiation will interact with the molecules of the liquid solvent, exciting those molecules. The molecules transfer their energy to the organic solute molecules suspended in the solvent. The molecules of the solute return to the ground state by emission of a light photon.

          c) Inorganic Crystals - 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.

Objective 1.13.09

- 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.

    d) Inorganic Powders - Operate with a mechanism similar to that of inorganic crystals.

  b. Photomultiplier Tubes/Photocathode

    1) The photocathode converts light output to photo electrons

    2) The photomultiplier tube converts photoelectrons to an amplified electrical signal

See Fig. 6 -"Photomultiplier Detector" Construction

2. Applications

  a. NaI(TI) - Commonly used in applications where high gamma sensitivity and a high energy resolution is desired.

  b. Liquid scintillator - Used in applications where it is desired to measure radiation of low energy or low penetrating ability.

3. Advantages

  a. Discrimination - Ability to discriminate between alpha, beta, gamma radiations and between different radiation energies with a moderate resolution.

  b. High Gamma Sensitivity (NaI(TI))

  c. Low energy response (liquid)

  d. Alpha detection (ZnS(Ag))

4. Disadvantages

  a. Poor low energy gamma response it has no alpha or beta response.(NaI(Tl))

  b. Cumbersome and solution is one time use only (liquid).

  c. Regulate power supply for pulse height analysis

  d. Fragile (NaI(Tl)), (ZnS(Ag))

I. Neutron Detection   Objective 1.13.10

 1. Slow neutrons

  a. Boron activation

   1) The neutron is absorbed by a B-10 atom which decays to a Li -9 atom and an alpha particle.

   2) The alpha causes ionization; gas amplification provides a usable electrical signal.

  b. Fission Chamber - 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 in 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.

  c. 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.

  d. Thermoluminescence - Thermoluminescent dosimeters can be designed to detect slow neutrons by incorporating lithium-6 in the crystal.

  e. 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.

 2. Fast neutrons

  a. 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.

b. Thermalization - One technique for measuring fast neutrons is to convert them to slow neutrons. In this technique, a sheet of cadmium is placed on the outside of the detector to absorb any slow neutrons. A thickness of paraffin, or another good moderator, is placed under the cadmium to convert the fast neutrons into slow ones. One of the slow neutron detectors is positioned inside the paraffin to measure the slow neutrons, thereby measuring the original fast neutrons.

c. Application - BF$_3$ neutron detector   See Table 2 - "Neutron Flux/Dose Relationship"

   1) Neutron flux/dose relationship

   2) Neutron detector energy response curve

J. Semi-Conductor

  1. Principles of operation

    a. Rely on the collection of electron-hole pairs from   Objective 1.13.11
      the detector to produce a usable electrical signal.   See Figs. 7 - 11

  2. GeLi system

    a. Advantages

      1) high resolution

      2) shorter response time and more linear response than NaI (Tl) detector

      3) small crystals offer best resolution

    b. Disadvantages

      1) only used for photon detection

      2) must be cooled at all times.

        3) lower efficiency than NaI

        4) long counting times for environmental samples

    3. Intrinsic (HP) germanium detectors

      a. Differences between GeLi and HPGe

        1) Principles of operation

      b. Advantages of HPGe's

        1) Stored at room temperature (with no voltage applied)

        2) More portable

      c. Disadvantages of HPGe's

        1) Operation needs liquid nitrogen

        2) Expense

      d. Applications

        1) Portable MCA's

        2) Same as GeLi

    4. Applications (MCA) - Gamma Spectroscopy System

K. Condenser R-Meter/Chamber

    1. Method of detection - The condenser chamber is an integrating, air wall tissue equivalent ionization chamber used to measure exposure to X or gamma radiation.

      a. Two Functions - 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.

    2. Range - Condenser chambers vary in size. The total measured exposure in a chamber decreases as the volume increases. Chambers are generally available which enable us to cover exposure ranges from several mR up to 250 R.

3. Energy response - Condenser chambers vary in material and thickness as well as in size. The choice of wall material and thickness off-sets the energy dependence of the chambers.

4. Applications - 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.

III. SUMMARY

A. Review major topics

1. Sources of Electrical Energy

2. Basic Electrical Quantities

3. Measurement systems

4. Detectors

5. Readout Circuitry

6. Detector yield

7. Various detectors

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.