Teacher Resource

National Park Service
U.S. Department of the Interior

Fossil Butte National Monument
Kemmerer, Wyoming

Radiometric Dating Game

Life Skills:
· Thinking & Reasoning
· Communication

Time Frame:
30 Minutes

Group Size:
Entire Class

Summary:

The *Radiometric Dating Game* demonstrates the basic concepts associated with **radiometric dating** methods by using a variant of musical chairs.

National Science Education Standards:

Content Standard D: Earth and Space Science
The Origin and Evolution of the Earth System (9-12)

Main Curriculum Tie:

Idaho
Standard 2—Physical Science
Describe the characteristics of isotopes (8-9.PS.2.4.3)
Standard 4—Earth and Space Systems
Identify methods used to estimate geologic time (8-9.ES.4.1.2)

Wyoming
Concepts and Processes—Earth, Space, and Physical Systems
Origin and Evolution of the Earth System (9-12)

Intended Learning Outcomes:

· Use science process and thinking skills.
· Manifest scientific attitudes and interests.
· Communicate effectively using science language and reasoning.

Materials:

· CD player with speakers
· Music CD (preferably instrumental)
· 15 chairs
· Stopwatch
· Easel with graphing pad
· Colored marking pens

Background For Teachers:

Certain **elements** have **isotopes** that are **radioactive** and decay at known rates. Their decay produces stable isotopes of a different element. The unstable radioactive isotope is referred to as the **parent**, and the stable isotope produced by decay is called the **daughter**. The time necessary for one half of the parent to decay to the daughter is known as a **half-life.**

Some rock-forming minerals commonly incorporate radioactive isotopes into their crystal strucutre. Once these minerals have crystalized, the clock begins ticking as the parent isotopes within starts decaying into the stable daughter isotopes; both must remain trapped in the mineral. Using special equipment like mass spectrometers, scientists are able to measure the amount of the parent and daughter isotopes currently present in the whole rock, or in its individual mineral grains. Given this information and the **decay constant**, the age of the rock can be determined.
The accuracy of these dating techniques is dependent on the validity of a number of assumptions. The most important of these include:

1. Since the time of its formation, the rock or mineral sample must have remained a **closed system** (See Note 1 in the left margin).

Note 1—If the teacher wishes to explain open and closed systems during the *Radiometric Dating Game* he or she can tell students that the walls of the classroom represent the system, and that as long as the door is shut the system is closed (no one can enter or leave), but if the door is opened and someone enters or leaves then the system is open. A closed systems implies no change, while an open system means it has changed.

2. The **decay constant** of the parent isotope must be known accurately and cannot have changed over time for any reason.
3. No atoms of the daughter isotope can be present in the rock at its time of formation (initial daughter).

Open system or "leaky" behavior, a violation of assumption 1, can occur due to **weathering** and **alteration**, or by heating, burial, and uplift of a rock subsequent to its formation. Elimination of these factors by careful sample selection is essential. Assumption 2 is thought to be operative within the Earth system and therefore is never violated. Violations of assumption 3 are not uncommon and make accurate dating difficult, but not impossible. There are well-established methods for calculating the amount of initial daughter present and applying a correction.

Note 2—The age of the Earth is considered to be equivalent to the age of the solar system, which has been calculated from the oldest meteorites at about 4.6 billion years. The oldest dated Earth material is a single zircon crystal from meta-sedimentary rocks in Australia dated at 4.404 billion years old. The oldest rock is the meta-igneous Acasta Gneiss of Canada that is dated at 4.04 billion years old.

The usefulness of a particular isotope pair is dependent upon the natural abundance of the parent element, and whether the sample contains the parent and daughter isotopes in measurable quantities. Modern mass spectrometers are capable of detecting quantities down to the several parts per billion (ppb) range. The minumum age limit reflects the time necessary for the amount of daughter isotope in the sample to reach this level. A maximum age limit is reached when the remaining parent isotope has fallen below the minimum detection levels. In the case of most long-lived radioisotopes, the maximum detectable age is 4.6 billion years or the age of the Earth (See Note 2 in the left margin).

Ultimately the choice of an isotope pair in dating an object is predicated on the incorporation of the parent element at its time of formation. Thus carbon-14 is useful for dating bones, wood and other artifacts that naturally contain carbon. The remaining isotopes are useful for dating igneous and metamorphic rocks, and individual mineral grains from sedimentary rocks. Only the dating of **pristine** igneous rocks or mineral grains yield an actual "birth date." In the case of metamorphic rocks, the age represents the time of the most recent **metamorphism**. Given that most sedimentary rocks are made of fragments of pre-existing rocks, datable mineral grains in them indicate the age of the original source rock, not the sedimentary rock itself. Table 1 (page 2) lists the most commonly used isotopes.

Most Commonly Used Isotope Pairs			
Parent Isotope	Daughter Isotope	Half-life (years)	Usefulness (years)
^{14}C (carbon-14)	^{14}N (nitrogen-14)	5,730	500-60,000
^{40}K (potassium-40)	^{40}Ar (argon-40)	1.25 billion	100,000-4.6 billion
^{87}Rb (rubidium-87)	^{87}Sr (strontium-87)	48.8 billion	10 million-4.6 billion
^{232}Th (thorium-232)	^{208}Pb (lead-208)	14 billion	10 million-4.6 billion
^{235}U (uranium-235)	^{207}Pb (lead-207)	703.8 million	10 million-4.6 billion
^{238}U (uranium-238)	^{206}Pb (lead-206)	4.47 billion	10 million-4.6 billion

Table1

Note 3—**Sanidine** (potassium feldspar) crystals from various volcanic ash layers found in the Green River Formation at Fossil Butte National Monument have been dated using the Potassium-40/Argon-40 method and the Argon-40/Argon-39 method (a variation of the Potassium-40/Argon-40 method) yielding dates of 50.2 million years old, and 51.7 and 52.2 million years old respectively. The most recent published date (2008) from the **K-spar tuff**, a volcanic ash layer near the middle of the Green River Formation is 51.66 +/- 0.09 million years.

Fossil Butte National Monument preserves a small portion of an ancient lake known as Fossil Lake. The **carbonate** mud deposited in the lake has become the **limestone** and **dolomite** of the Green River Formation. The age of these sedimentary rocks cannot be determined by **radiometric dating** techniques.

Fortunately, there are volcanic ash layers known as **tuffs** interbedded with the limestone and dolomite (See Note 3 in the left margin).

Instructional Procedures:

Review concepts: element, isotope, **radioactivity**, parent, daughter, half-life, and the assumptions of radiometric dating (closed system, constant decay rate, no daughter isotope present at time of formation).

You will need a timekeeper/DJ (1), counter/graphers (2), isotopes (16), and chair handlers (4).

Use the following steps to play the radiometric dating game:

1. Before the game begins the chair handlers will place eight chairs in a single row alternating the facing of each chair. Once the chairs are in place, the 16 isotopes will arrange themselves in a circle around the chairs and remain standing. The counter/graphers will verify that the number of daughter (seated=0), and parent (standing=16) isotopes, and record the information in the game table and plot it on the graphs for time (in half-lives)=0. Once this is completed, signal the timekeeper/DJ to start the stopwatch and music. The isotopes will start to walk around the chairs in a clockwise direction. When the stopwatch reaches one minute the timekeeper/DJ will stop the music, and each parent isotope will attempt to take a seat in the chair nearest them. By rule there can only be one isotope per chair. The timekeeper/DJ will reset the stopwatch.
2. At this point one half-life has passed. Time is suspended while the counter/graphers verify the number of daughter (8 seated) and parent (8 standing) isotopes, and transfer the information to the table and graphs for time (in half-lives)=1. Chair handlers will place four additional chairs (See Note 4 in the left margin), two at each end of row facing them in alternate directions. When these tasks are completed, signal the timekeeper/DJ to start the stopwatch and music. Those in chairs will remain seated, those standing will begin to move. After one minute the music will stop and the circling parents will try to find an empty chair. The timekeeper/DJ will reset the stopwatch.
3. At this point a second half-life has passed and time is suspended. Repeat step 2 for time (in half-lives)=2. Now their are 12 daughters (seated) and 4 parents (standing). Have the chair handlers place two additional chairs, one at opposite ends of the row.
4. At this point a third half-life has passed and time is suspended. Repeat step 2 for time (in half-lives)=3. Now there are 14 daughters (seated) and 2 parents (standing). Have a chair handler place one additional chair at the one end of the row.
5. At this point a fourth half-life has passed and the game is at an end. Have the counter/graphers verify the number of daughter (15 seated) and parent (1 standing) isotopes, and transfer the information to the table and graphs for time (in half-lives)=4.

Note 4—In the *Radiometric Dating Game* chairs are added to the game of "musical chairs" to provide additional seating for newly forming daughter isotopes during each successive half-life. The idea is that being seated is a more stable position(daughter=stable) than either standing or moving (parent=unstable=radioactive).

See examples of the *Radiometric Dating Game* table and graphs on page

Extensions:

Internet Assignment—Research the age of the Earth online. Have students report on the ages and radiometric dating methods used for a variety of samples (meteorites, Moon rocks, Earth rocks and minerals). Which class of samples yields the oldest ages? If more than one method was used to date a particular sample, and the dates determined are different have them speculate why this might be, and whether the difference is significant.

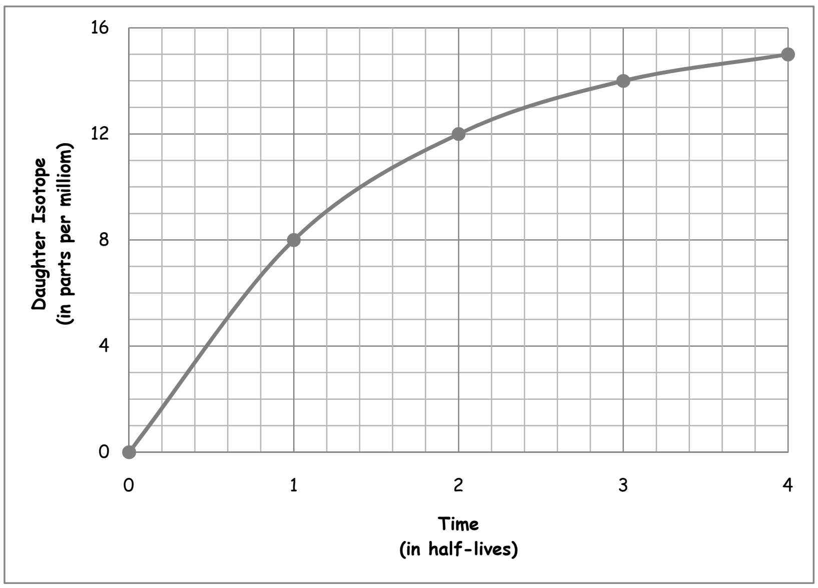
Assessment Plan:

The teacher may select from one of the following assessments, or allow the student to chose the one he or she will complete:

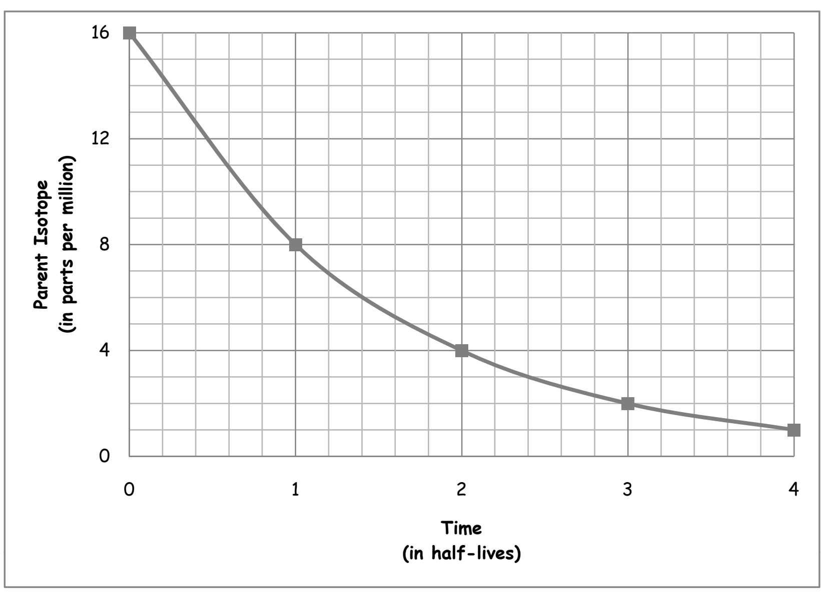
1. *Radiometric Dating Game Student Worksheet*—A student master is provided on pages 5-8 and a teacher answer key on pages 9-12.
2. *Radiometric Dating Game Comic Strip, Graphic Organizer, Song, or Story*—A student master is provided on page 13 and a grading rubric on page 14.

		Time (in half-lives) 0	1	2	3	4
Row 1	Daughter Isotope (in parts per million)	0	8	12	14	15
Row 2	Parent Isotope (in parts per million)	16	8	4	2	1
Row 3	Sum (Row 1 + Row 2)	16	16	16	16	16

Table 2—*Radiometric Dating Game* data table



Graph 1—*Radiometric Dating Game* daughter isotope abundance graph



Graph 2—*Radiometric Dating Game* parent isotope abundance graph

Radiometric Dating Game Student Worksheet

Name:________________________________ **Date:**_____________

1. Copy the data from the *Radiometric Dating Game* data table into Rows 1-3 of the blank table below. Fill in the empty spaces in Rows 1-3 (Time (in half-lives)=5 and 6) based on your knowledge of the behavior of parent and daughter isotopes, and the definition of a half-life. To complete the remainder of the table follow the instructions below.

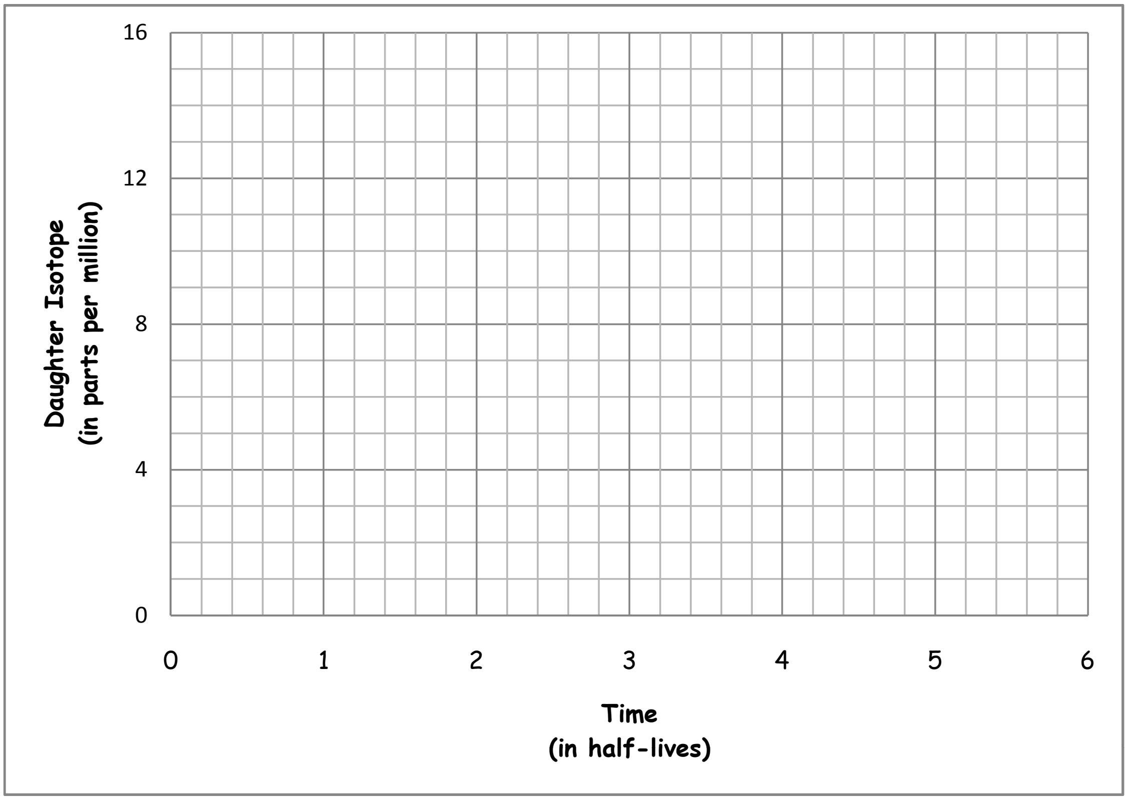
		Time (in half-lives)						
		0	1	2	3	4	5	6
Row 1	Daughter Isotope (in parts per million)							
Row 2	Parent Isotope (in parts per million)							
Row 3	Sum of Isotopes (Row 1 + Row2)							
Row 4	Parent Isotope (fraction remaining)							
Row 5	Parent Isotope (percentage remaining)							
Row 6	Daughter-to-Parent Ratio							

Row 4—determine the fraction of parent isotope remaining at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by placing the amount of the parent isotope (*Row 2*) at time=x in the numerator, and the sum of isotopes (*Row 3*) at time=x, which is equivalent to the initial abundance of the parent isotope, in the denominator. Simplify your fractions. Show your work.

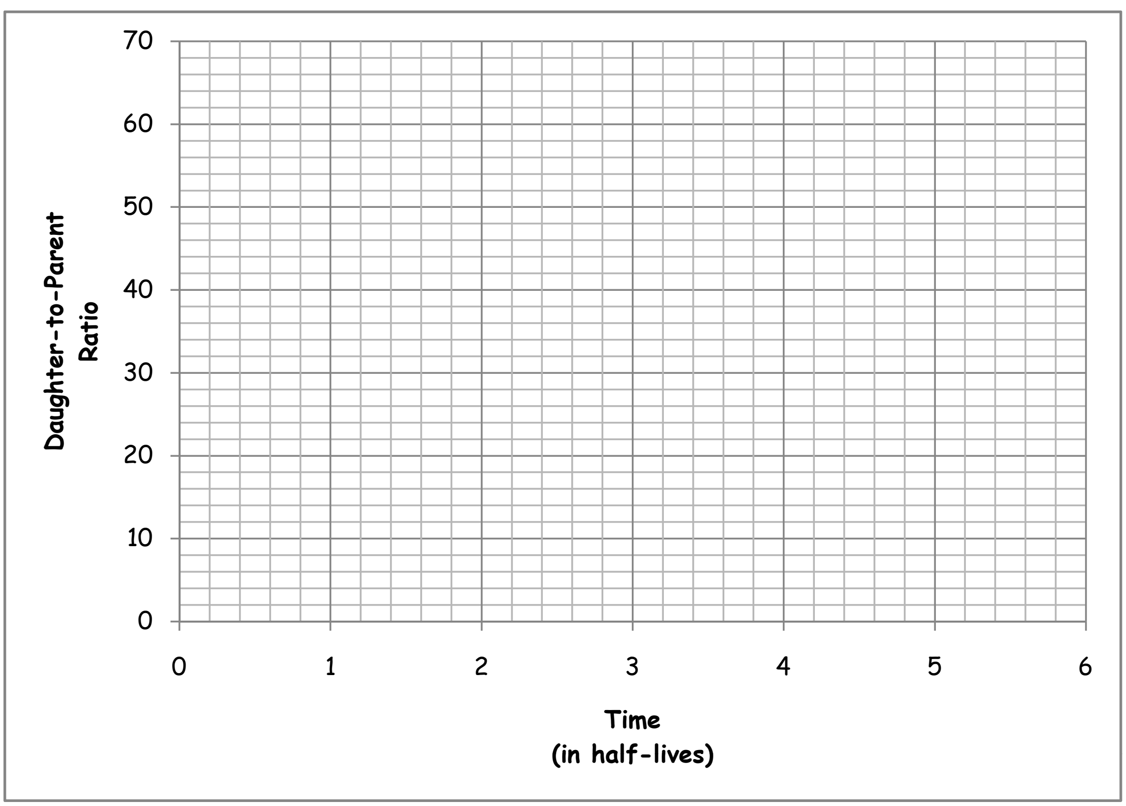
Row 5—calculate the percentage of the parent isotope remaining at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by multiplying the value in Row 4 at time =x by 100 or by converting the fraction to a decimal and multiplying by 100. Show your work.

Row 6—determine the daughter-to-parent ratio at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by dividing *Row 1* by *Row 2* for time=x. Show your work.

2. Plot the information in *Row 1* on the graph below to show the change in the abundance of daughter isotope over time.



3. Plot the information in *Row 6* on the graph below to show the change in the daughter-to-parent ratio over time.



4. Compare the graph of daughter isotope abundance in *Problem 2* with the graph of daughter-to-parent ratio in *Problem 3*. Describe the shape of the curves and their trajectories. If both graphs contain information about the daughter isotope, then why do they behave so differently?

5. In the *Radiometric Dating Game* the initial abundance of the parent isotope at the formation of our sample was 16 parts per million (ppm). If modern mass spectrometers are capable of accurately measuring isotope abundance down to a level of 10 parts per billion (ppb), after how many half-lives will it no longer be possible to calculate an accurate age for the sample? [Hint: At time t=6, the remaining parent isotope equals ¼ ppm. There are 1000 ppb in 1 ppm. Calculate the amount of the parent isotope remaining in ppb for time t=*x*, where *x*=6, 7, 8, and so on until the quantity remaining is less than 10 ppb.] Show your work.

6. The **K-spar** tuff (volcanic ash) layer near the center of Green River Formation at Fossil Butte National Monument contains a potassium feldspar mineral, **sanidine**. A small fraction of the potassium in sanidine is radioactive potassium-40. Given the amount of argon-40 (daughter) and potassium-40 (parent) present in the sample today, calculate the age of the K-spar tuff using the graph on the following page.

   Several sanidine samples have been analyzed in a mass spectrometer and have an average of 50 parts per billion (ppb) argon-40 (^{40}Ar) and 16,065 ppb potassium-40(^{40}K).

   The graphical solution uses the ratio of argon-40 to potassium-40. This ratio must be adjusted for the difference in their atomic masses. Because it is useful in this problem to work with large numbers, apply a correction factor of 97,838. Use the following formula to calculate the adjusted daughter-to-parent ratio (D^*/P):

$$D^*/P = 97838D/P,$$

   where D^* is the daughter isotope, argon-40 in ppb and P is parent isotope, potassium-40 in ppb. Show your work.

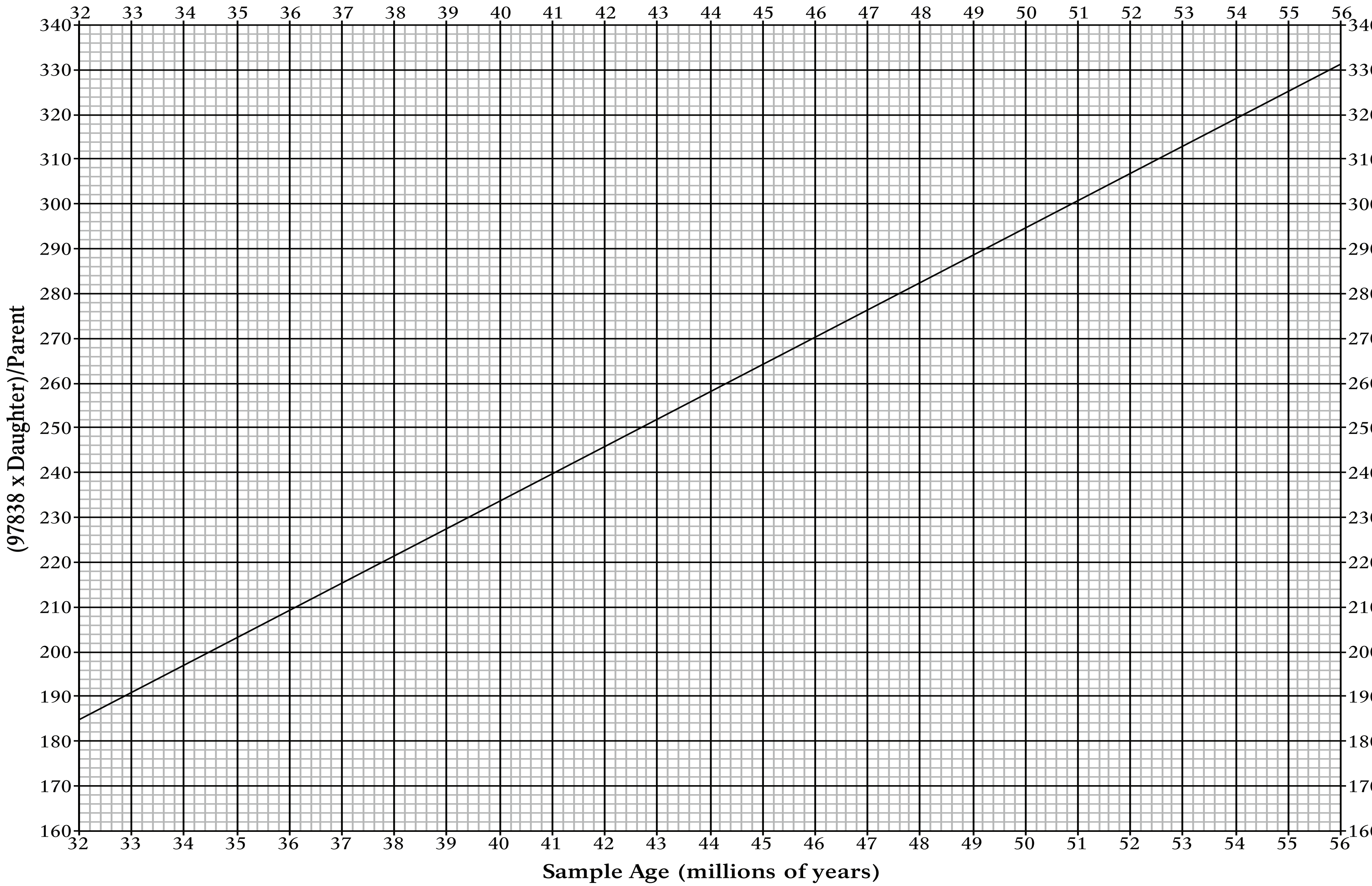
   Step 1—Apply the correction factor to the daughter isotope ^{40}Ar.

   Step 2—Calculate D^*/P by dividing the result of *Step 1* by the parent isotope ^{40}K and round to the nearest whole number.

   Step 3—Find the result of *Step 2* on the y-axis of the graph and from that point draw a line parallel to the x-axis until it intersects the diagonal line on the graph.

   Step 4—From the intersection point draw a line parallel to the y-axis until it intersects the *x*-axis. This new intersection point gives you the age of the sample.

Potassium-Argon Radiometric Dating Graph
Eocene Epoch (55.8-33.9 million years ago)



Radiometric Dating Game Student Worksheet

Name:______________________________ **Date:**______________

1. Copy the data from the *Radiometric Dating Game* data table into Rows 1-3 of the blank table below. Fill in the empty spaces in Rows 1-3 (Time (in half-lives)=5 and 6) based on your knowledge of the behavior of parent and daughter isotopes, and the definition of a half-life. To complete the remainder of the table follow the instructions below.

		Time (in half-lives) 0	1	2	3	4	5	6
Row 1	Daughter Isotope (in parts per million)	0	8	12	14	15	15 1/2	15 3/4
Row 2	Parent Isotope (in parts per million)	16	8	4	2	1	1/2	1/4
Row 3	Sum of Isotopes (Row 1 + Row2)	16	16	16	16	16	16	16
Row 4	Parent Isotope (fraction remaining)	1	1/2	1/4	1/8	1/16	1/32	1/64
Row 5	Parent Isotope (percentage remaining)	100%	50%	25%	12.5%	6.25%	3.125%	1.5625%
Row 6	Daughter-to-Parent Ratio	0	1	3	7	15	31	63

Row 4—determine the fraction of parent isotope remaining at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by placing the amount of the parent isotope (*Row 2*) at time=x in the numerator, and the initial abundance of the parent isotope (*Row 2*) at time =0 in the denominator. Simplify your fractions. Show your work.

t=0, 16/16=1 t=1, 8/16=1/2 t=2, 4/16=1/4

t=3, 2/16=1/8 t=4, 1/16

t=5, (1/2)/16=1/32 t=6, (1/4)/16=1/64

Row 5—calculate the percentage of the parent isotope remaining at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by multiplying the value in Row 4 at time =x by 100. Show your work.

t=0, 1x100=100% t=1, 1/2x100=50% t=2, 1/4x100=25%

t=3, 1/8x100=12.5% t=4, 1/16x100=6.25%

t=5, 1/32x100=3.125% t=6, 1/64x100=1.5625%

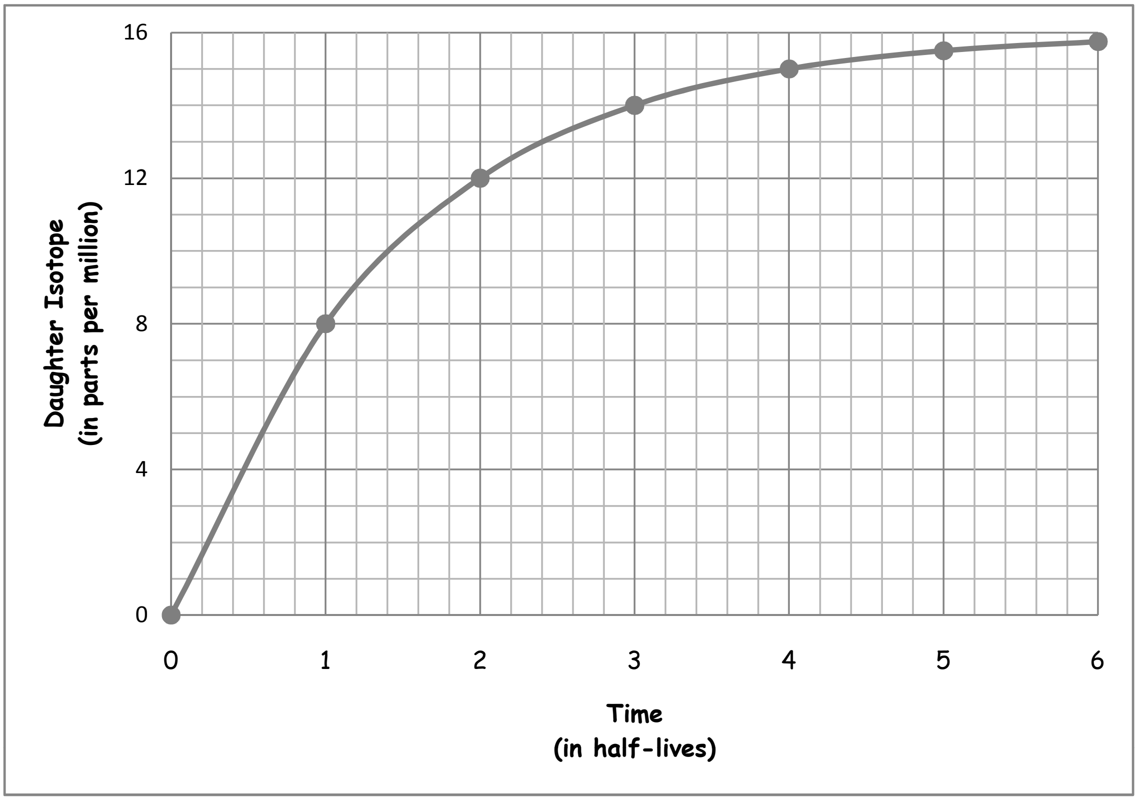
Row 6—determine the daughter-to-parent ratio at time (in half-lives)=x, where x=0, 1, 2, 3, 4, 5, or 6 by dividing *Row 1* by *Row 2* for time=x. Show your work.

t=0, 0/16=0 t=1, 8/8=1 t=2, 12/4=3

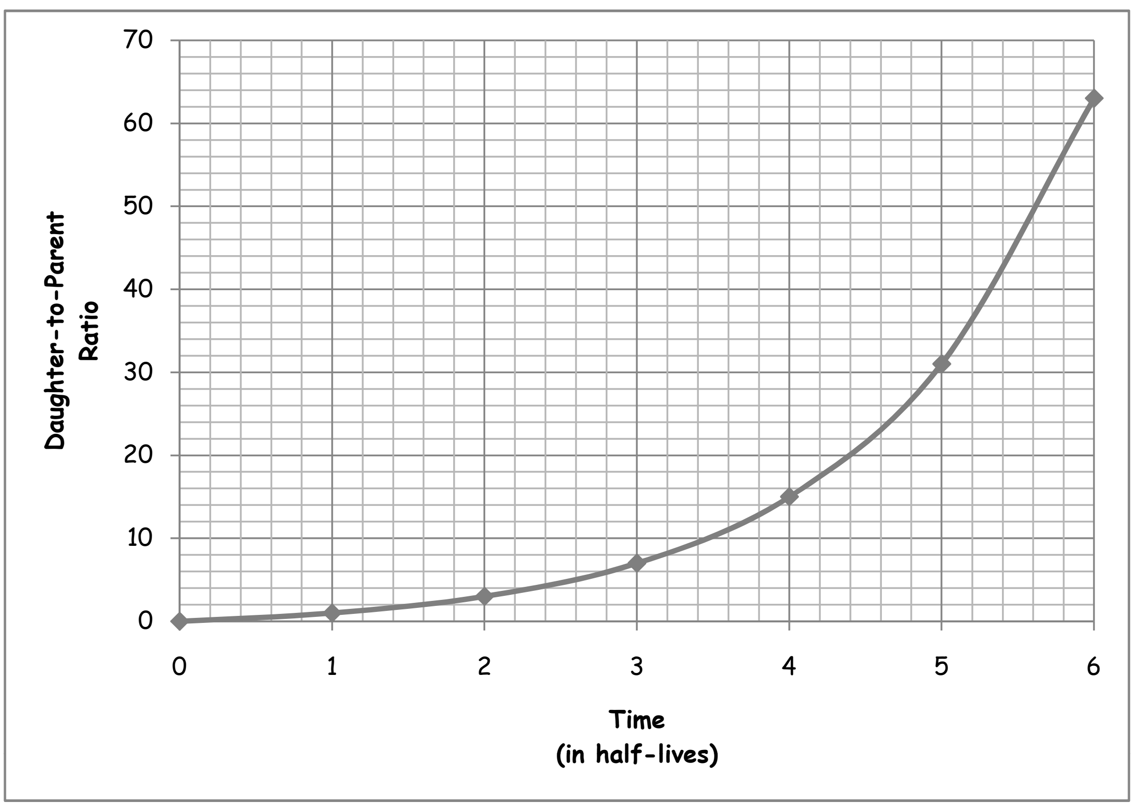
t=3, 14/2=7 t=4, 15/1=15

t=5, (15 1/2)/(1/2)=31 t=6, (15 3/4)/(1/4)=63

2. Plot the information in *Row 1* on the graph below to show the change in the abundance of daughter isotope over time.



3. Plot the information in *Row 6* on the graph below to show the change in the daughter-to-parent ratio over time.



4. Compare the graph of daughter isotope abundance in *Problem 2* with the graph of daughter-to-parent ratio in *Problem 3*. Describe the shape of the curves and their trajectories. If both graphs contain information about the daughter isotope, then why do they behave so differently?

   The curve in the problem 2 graph is convex and rises rapidly early before leveling out. The curve in the problem 3 graph is concave and rises slowly at first before ascending rapidly. In the first graph the definition of a half-life explains the rapid change early followed by a leveling out as the abundance of the daughter isotope approaches its maximum more slowly. The second graph tracks the ratio of daughter-to-parent, which means small changes early as values for the daughter and parent diverge slowly, and rapid changes later as the daughter approaches its maximum and the parent its minimum pushing the value of the ratio towards infinity.

5. In the *Radiometric Dating Game* the initial abundance of the parent isotope at the formation of our sample was 16 parts per million (ppm). If modern mass specrometers are capable of accurately measuring isotopic abundance down to a level of 10 parts per billion (ppb), after how many half-lives will it no longer be possible to calculate an accurate age for the sample? [Hint: At time t=6, the remaining parent isotope equals ¼ ppm. There are 1000 ppb in 1 ppm. Calculate the amount of the parent isotope remaining in ppb for time t=x, where x=6, 7, 8, and so on until the quantity remaining is less than 10 ppb.] Show your work.

   At t=6, the remaining parent isotope is 1/4 or 0.25 ppm, which is equivalent to 250 ppb (0.25x1000). Given that with each half-life, one half of the remaining parent decays it follows that at

   t=7 parent=125 ppb t=8 parent=62.5 ppb t=9 parent=31.25 ppb
   t=10 parent=15.625 ppb t=11 parent=7.8125

   So between 10 and 11 half-lives the amount of the parent isotope will fall below 10 ppb, the minimum detection level of modern mass spectrometers.

6. The K-spar tuff (volcanic ash) layer near the center of the Green River Formation at Fossil Butte National Monument contains a potassium feldspar mineral, sanidine. A small fraction of the potassium in sanidine is radioactive potassium-40. Given the amount of argon-40 (daughter) and potassium-40 (parent) present in the sample today, calculate the age of the K-spar tuff using the graph below.

   Several sanidine samples have been analyzed in a mass spectrometer and have an average of 50 parts per billion (ppb) argon-40 (^{40}Ar) and 16,065 ppb potassium-40 (^{40}K).

   The graphical solution uses the ratio of argon-40 to potassium-40. This ratio must be adjusted for the difference in their atomic masses. Because it is useful in this problem to work with large numbers, apply a correction factor of 97,838. Use the following formula to calculate the adjusted daughter-to-parent ratio (D^*/P):

   $$D^*/P = 97838D/P,$$

   where D^* is the daughter isotope, argon-40 in ppb and P is parent isotope, potassium-40 in ppb. Show your work.

   Step 1—Apply the correction factor to the daughter isotope ^{40}Ar.

   Step 2—Calculate D*/P by dividing the result of *Step 1* by the parent isotope ^{40}K and round to the nearest whole number.

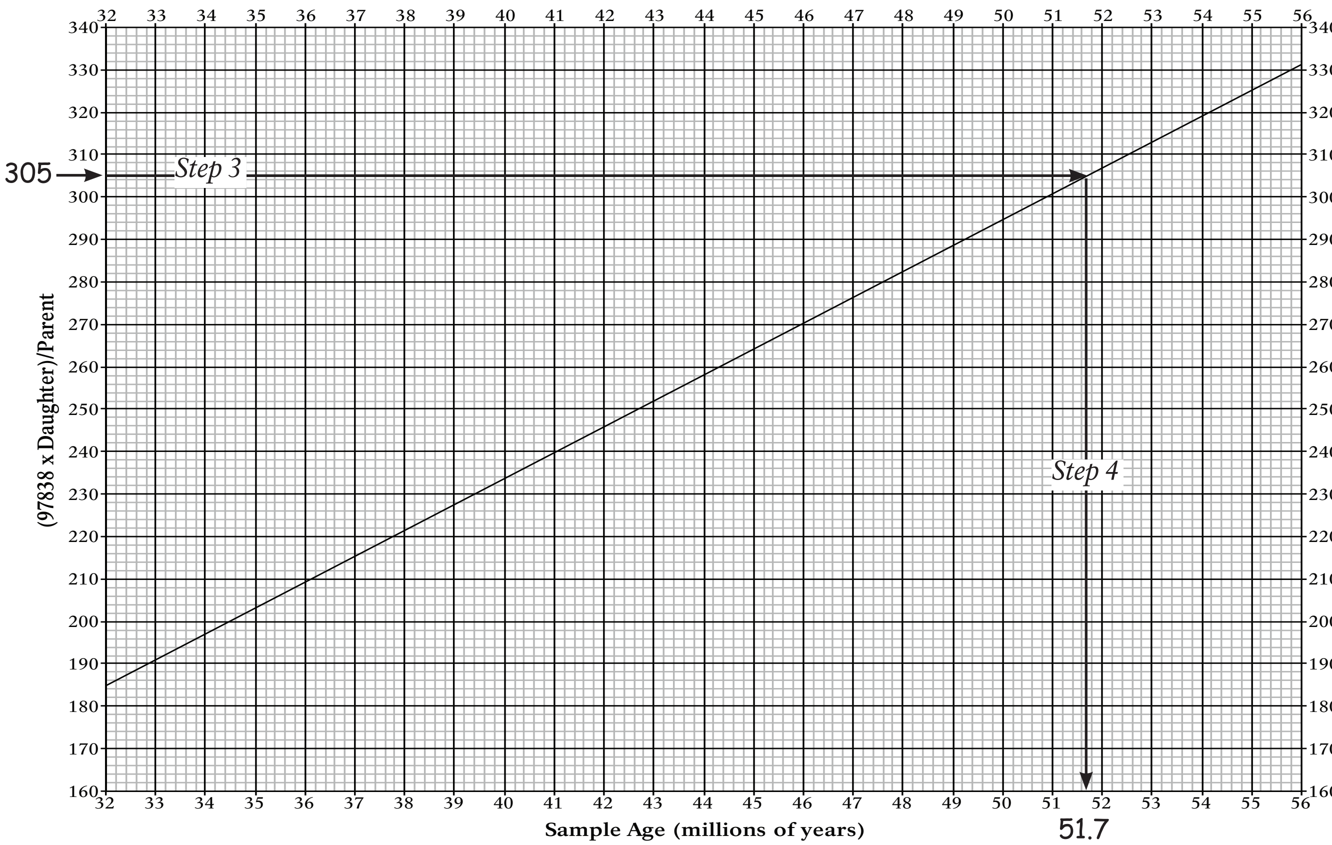
   Step 3—Find the result of *Step 2* on the y-axis of the graph and from that point draw a line parallel to the x-axis until it intersects the diagonal line on the graph.

   Step 4—From the intersection point draw a line parallel to the y-axis until it intersects the *x*-axis. This new intersection point gives you the age of the sample.

Step 1 D*= 50 ppb x correction factor
= 50 ppb x 97838
= 4,891,900 ppb

Step 2 D*/P = D x 97838/P
= 4,891,900 ppb / 16,065 ppb
= 304.5 or 305

Potassium-Argon Radiometric Dating Graph
Eocene Epoch (55.8-33.9 million years ago)



The K-spar tuff layer near the center of the Green River Formation at Fossil Butte National Monument was formed approximately 51.7 million years ago.

Teacher's Note on *Problem 5* —The following provides a more rigorous mathematical solution:

$P_t = P_i/2^t$, where P_t is the amount of parent isotope remaining at time (in half-lives) t and P_i is the initial amount of the parent isotope at sample formation. To solve for t the equation becomes $t=log_2 (P_i /P_t)$. In the problem, P_i=16 ppm or 16,000 ppb and P_t=10 ppb the minimum detection level of modern mass spectrometers, therefore

$$t=log_2(16,000/10)$$
$$=log_2 1,600$$
$$=10.644 \text{ half-lives}$$

If it is assumed that the sample is being dated using the potassium-40/argon-40 dating method where a half-life equals 1.25 billion years, then it would be over 13.3 billion years before the potassium-40 cannot be accurately measured; this is nearly three times the age of the Earth, or about equal to the age of the universe.

Teacher's Note on *Problem 6* —^{40}K (potassium-40) decays to both ^{40}Ca (calcium-40, 89.52%) and ^{40}Ar (argon-40, 10.48%). To calculate the age of rocks in the ^{40}K-^{40}Ar system scientists use the following formula:

$t=(1/\lambda)ln[(^{40}Ar/^{40}K)(\lambda/ \lambda_e)+1]$, where λ is the decay constant of ^{40}K-^{40}Ca-^{40}Ar system (5.543×10^{-10}/yr and λ_e is the decay constant for the ^{40}K-^{40}Ar system (0.581×10^{-10}/yr). And *ln* is the natural log. The ratio of $^{40}Ar/^{40}K$ must be adjusted for the difference in atomic weight. The correction factor is 0.97838 (39.0983/39.9623).

The mathematical solution for problem #3 follows:

$$t=(1/5.543 \times 10^{-10})\, ln[(50/16065 \times 0.97838)(5.543/0.581)+1]$$
$$=(1.804 \times 10^{9})\, ln[(3.045 \times 10^{-3})(9.540)+1]$$
$$=(1.804 \times 10^{9})\, ln(1.02905)$$
$$=(1.804 \times 10^{9})(2.864 \times 10^{-2})$$
$$=5.167 \times 10^{7} \text{yrs or 51,670,000 years ago}$$

Radiometric Dating Game

Name:________________________________ **Date:**______________

Instructions—Write a story, compose a song, prepare a graphic organizer, or draw a comic strip that describes the *Radiometric Dating Game*. Your story, song, graphic organizer, or comic strip must demonstrate an understanding of the scientific concepts and illustrate the changes that occurred over time, but gives you the opportunity to be creative.

Assessment Rubrics

The presentation exhibited…	Points	Excellent x5	Good x4	Needs Improvement x3	Unacceptable x2	Not Attempted x0
A clear understanding of the following terms: radioactivity, isotope, parent, and daughter.	6					
The incremental changes that occurred in the system with time (half-life).	6					
Logical organization.	3					
Creativity.	3					
Neatness.	1					
Attention to detail, i.e. labels, and few spelling, punctuation, or grammatical errors.	1					

Glossary

Alteration—any physical or chemical change in the mineral composition of a rock.

Biotite—a dark-colored tabular mineral of the mica group composed mainly of potassium, iron, magnesium, aluminum and silica; useful in potassium-argon age dating.

Carbonate—(a) a mineral that is composed of a metal and the carbonate (CO_3^{-2}) ion. (b) a rock composed of more than 50% carbonate minerals.

Closed system—a system in which no matter is allowed to enter or leave.

Daughter—a nuclide produced by the disintegration of a radioactive precursor (parent).

Decay constant (λ)—a rate proportion relating the change in the amount of a radionuclide to the period of time over which it occurred (dN/dt).

Dolomite—a sedimentary rock composed of more than 50% calcium magnesium carbonate.

Element—a substance that cannot be broken down into any other substance by chemical or physical means.

Half-life—the time required for one half of a given amount of a radionuclide to decay.

Isotope—one of two or more species of the same chemical element having a different atomic masses because they have different numbers of neutrons.

K-spar—short for potassium feldspar, a common rock-forming mineral; K is the symbol for potassium in the periodic table.

Limestone—a sedimentary rock composed of more than 50% calcium carbonate.

Metamorphism—the mineral, chemical and physical changes that solid rock undergoes at depth below the Earth's surface primarily due to heat, pressure and mineralized fluids.

Nuclide—a species of atom characterized by the number of protons and neutrons in its nucleus.

Open system—a system in which matter can enter or escape to the surroundings.

Parent—a radioactive nuclide related by its decay to another nuclide (daughter).

Pristine—unchanged chemically or physically.

Radioactivity—the emission of energetic particles and/or radiation from the nucleus of an atom during radioactive decay.

Radiometric dating—determining the absolute age of geologic materials by measuring the parent and daughter isotopic abundance given the known decay rate of the radioactive parent.

Sanidine—a high temperature potassium feldspar mineral characteristics of silica-rich volcanic rocks; useful in potassium-argon age dating.

Tuff—consolidated or cemented volcanic ash.

Weathering—the physical breakdown, or chemical decomposition of solid rock into fragmentary particles and dissolved ions.