Submarines and Aircraft Carriers: 
The Science of Nuclear Power

Science Topic: Physics and Social Science

Grades: 9th – 12th

Essential Questions:

• How does a nuclear reactor work?
• What are the benefits and risks of nuclear power?
• What are basic terms used in the fields of nuclear power and nuclear physics?
• How are quantitative data related to radioactivity analyzed?

Overview
In this lesson, students learn how nuclear physics explains the function of a nuclear reactor, as well as addressing the issues of safety related to nuclear power, and hence the capabilities of a nuclear submarine and other nuclear-powered vessels.

A companion interactive whiteboard presentation that incorporates video and glossary terms used throughout this lesson is provided to use in classroom instruction.

Learning Objectives:
By the end of this lesson, students will be able to:

• Describe the basic operation and principles of a nuclear reactor.
• Compare and contrast the benefits and risks of nuclear power.
• Define basic terms related to nuclear power and nuclear physics.
• Analyze quantitative data related to radioactivity.

Evaluation

• Compare and contrast the benefits versus the risks of nuclear power.
• Prove that nuclear fuel yields more energy per unit weight than fossil fuel.
• Evaluate the safety of nuclear waste based on the principle of nuclear decay.

Synthesis

• Model the process of radioactive decay mathematically.
• Contrast the function of various components of a nuclear reactor.
• Assess the decline in radioactivity of a substance given its half-life.

Analysis

• Analyze data that represents the process of radioactive decay.
• Predict products of a nuclear decay chain.
• Generalize from a nuclear reactor’s operation to describe function of a nuclear powered vessel.
• Recognize that radioactive decay is mathematically represented as exponential decay.

**Application**

• Draw the main features of a simple nuclear reactor.
• Predict products of transmutation following radioactive decay
• Correlate time and radioactive decay.
• Compare the power output of nuclear fuel with a fossil fuel.

**Comprehension**

• Distinguish between nuclear processes, including fission and radioactive decay.
• Illustrate the principle of radioactive decay and half-life graphically.
• Interpret the mathematical relationship between time and radioactivity
• Give examples of elements that undergo radioactive decay.
• Explain the basic principle of a nuclear reactor.
• Determine how an element’s half-life depends on its rate of radioactive decay.

**Knowledge**

• Describe the benefits and disadvantages of nuclear power.
• Know the basic role of nuclear energy in powering nuclear vessels.
• Describe the key features of a chain reaction.
• Describe the basic operation of a nuclear reactor, and label a simple diagram of a nuclear reactor.
• Define key vocabulary terms related to nuclear power.
• Describe how radioactive decay demonstrates an exponential relationship between time and radioactivity.
• Locate radioactive elements on the periodic table.
• List elements used to generate nuclear power.

**National Science Education Standards**

Disciplinary Core Idea PS1.C: Nuclear Processes (Grade 12)

• Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve changes in nuclear binding energies. The total number of neutrons plus protons does not change in any nuclear process.
• Spontaneous radioactive decays follow a characteristic exponential decay law.

Disciplinary Core Idea PS3.D: Energy In Chemical Processes And Everyday Life (Grade 12)

• All forms of electricity generation and transportation fuels have associated economic, social, and environmental costs and benefits, both short and long term.

**Common Core State Standards: Math**

Create equations that describe numbers or relationships: CCSS.Math.Content.HSA-CED.A.2

• Create equations in two or more variables to represent relationships between quantities; graph equations on coordinate axes with labels and scales.

**Time Frame:**

This lesson is designed to be completed in two 90-minute blocks.
Key Vocabulary

- **Alpha Particle**: A helium nucleus emitted during alpha decay. A helium nucleus composed of two protons and two neutrons.
- **Chain Reaction**: A series of similar or identical events initiated by a single event.
- **Critical Mass**: The minimum mass of fissile material required to sustain a chain reaction.
- **Exponential Decay**: A negative power relationship between a changing quantity and time.
- **Gamma Rays**: High-energy electromagnetic radiation comprised of photons with energies typically above 100 keV.
- **Half-Life**: The time taken for a substance or measurement to decline by half.
- **Meltdown**: The overheating of a nuclear reactor core resulting due to loss of cooling ability or control rod operation.
- **Nuclear Decay**: Loss of one or more subatomic particles (alpha or beta) or photons (gamma rays) as a nucleus changes to a more stable configuration.
- **Nuclear Fission**: Splitting of an atomic nucleus resulting in release of energy and formation of radioactive products.
- **Nuclear Reactor**: Device for using controlled fission to heat water in order to turn a turbine
- **Nucleus**: Central component of the atom, comprising protons and neutrons.
- **Radioactivity**: Measured radiation emitted by substances undergoing nuclear decay.
- **Transmutation**: Change in an element to another element as it undergoes nuclear decay.

**Background for the Teacher:**

In this lesson, students learn the science behind nuclear energy. This approach helps students understand why nuclear power is controversial, yet has unique advantages as an energy source. Compared with fossil fuels, nuclear power does not directly pollute the environment with air-borne particulate matter. Compared with renewable energy sources, nuclear energy requires relatively little land area and provides a consistent power source.

Nuclear energy today evolved from studies in the early twentieth century, when the first working reactors were built. The technology evolved out of the work of nuclear physicists such as Ernest
Rutherford and Niels Bohr, who discovered the structure of the atom. These scientists devised the orbital model of the atom, in which electrons surround a dense nucleus of protons and neutrons.

Researchers also found that the properties of elements depend on the number of protons and neutrons. For example, the number of protons in an element’s nucleus (the atomic number) determines its chemical identity, and hence its location in the periodic table. Therefore, carbon is different from oxygen because each has a different number of protons in its nucleus. On the other hand, the same element can have different numbers of neutrons yet retain its chemical identity.

Since neutrons weigh the same as protons, they contribute to the atomic weight. An element will always have the same atomic number but can have slightly different atomic weights. These variants, or isotopes, lie at the heart of nuclear chemistry, and its application in science and industry. For example, scientists can date ancient objects from the ratio of one isotope of carbon (carbon-14) to the most common isotope (carbon-12).

The application of nuclear energy to the production of power began with Einstein’s discovery that energy was related to mass, in his famous E=mc² equation. Scientists soon realized that nuclear energy had the potential to provide a clean, reliable power source. However, nuclear chemists also knew that most elements would be unsuitable, because they exist primarily as stable isotopes. From the pioneering work of Marie Curie, Henri Becquerel and others, scientists knew that some elements were radioactive, in which they emitted energetic particles.

The kinds of elements that have persistent radioactivity tend to be very dense and very rare. These elements, such as plutonium, thorium and uranium, have high atomic weights. Their nuclei are relatively large, so the nuclear “glue” keeping the particles together has trouble holding on to the protons and neutrons. Some isotopes such as uranium-235 are especially unstable. The subatomic particles are emitted as radiation, with heat as a byproduct. Despite the rarity of these elements, scientists found that uranium was abundant enough that, if purified, could provide enough energy to be tapped for usable power.

In 1954, the first nuclear power plant began supplying energy to the national electricity grid. Although nuclear power plants have an exceptional record of safety, a handful of major accidents, combined with public fears, have limited the adoption of nuclear energy. For example, the Three Mile Island accident in 1979 resulted in a 33-year moratorium on the construction of new reactors. Accidents at Chernobyl in Russia and more recently in Fukushima in Japan did little to allay public fears.

But what is the source of public anxiety? Most significantly people associate nuclear energy with the atomic bomb. This association is because both the weapon and the reactor rely on the same principle of nuclear physics, nuclear fission. In this process, a loose high-energy neutron collides with the nucleus of a heavy metal atom, typically uranium or plutonium. The collision causes the metal atom to become unstable. The nuclear forces holding together the atom can no longer overcome the repulsive forces of the positive charges among the protons. The nucleus splits in two. The split, or fission, of the nucleus results in two smaller atoms, plus the release of energy and dangerous gamma rays. Additional neutrons are also released. These go on to collide with more metal atoms, which in turn undergo fission themselves. This repeated process results in a chain reaction. In an atomic bomb the uranium is very pure, enabling the chain reaction to propagate throughout the fissile material almost immediately. All the energy is released in an instant, resulting in a powerful explosion. In a nuclear reactor, the uranium isotope that undergoes fission is too low in concentration for the chain reaction to be self-sustaining. The released heat provides energy to heat water that is used to drive electric turbines. Although the nuclear reactor cannot explode, its operation produces radioactive waste that can be accidently released, and which poses problems for long-term storage.
The issue of radioactive waste is addressed in this lesson by helping students understand the process of radioactive decay. Students might not realize that there are different kinds of decay, hence radioactivity, including alpha, beta and gamma. They also might not grasp the concept of half-life, which is a probabilistic process, which is correlated with measurements of radioactivity.

Because both the atomic bomb and nuclear reactors rely on the same nuclear process, much confusion and misunderstanding persists around the way reactors work, and their relative safety. The science behind nuclear energy serves to debunk misconceptions about nuclear power to put its risks into perspective.

In this lesson, hands-on activities introduce students to basic concepts of nuclear physics including fission, radioactivity, nuclear decay and transmutation. Students learn key principles of nuclear physics as it relates to nuclear power.

**Common Misconceptions**

Here are some common misconceptions about nuclear power, followed by the reality:

- All nuclear submarines carry nuclear weapons, which is why they are so named.
  - Nuclear submarines are so named from being powered by nuclear reactors. Some nuclear powered submarines do not carry nuclear weapons.
- Nuclear power is inherently dangerous.
  - The danger of nuclear power comes from poor reactor management or construction leading to uncontrolled release of radiation. Improper waste disposal poses another danger.
- Radiation only comes from nuclear power or nuclear weapons.
  - Many common substances emit forms of radiation. Smoke detectors rely on radioactive decay for their operation. All matter emits electromagnetic radiation.
- Nuclear power directly drives motors or engines.
  - Nuclear decay produces heat, which is used to create steam that can drive turbines.
- When nuclei undergo radioactive decay they disappear, or become non-radioactive.
  - Radioactive decay is the emission of an atomic particle and may result in a change in atomic number. A new element may or may not be radioactive.
- Half-life of a substance is half the time needed for the radioactivity to disappear.
  - Half-life can represent the time taken for half the particles to undergo decay, the time for measures of radioactivity to decline by half, or the probability of a particle undergoing decay within a given time period.
- The greatest danger from a nuclear power plant is a nuclear explosion.
  - The greatest danger from a nuclear power plant is loss of power to control rods, which can cause the core to overheat and release radiation into the atmosphere. A nuclear reactor cannot undergo nuclear explosion.
- Radioactive decay and fission is the same thing.
  - Radioactive decay is emission of subatomic particles. Fission is the splitting of atomic nuclei due to instability.

**Prior Knowledge for Students**

- General role of the US Navy
- Basic understanding of atomic structure and subatomic particles
• Ratios, fractions and probability

Classroom Activities:

Materials
For the teacher:
• Power Point capabilities with computer and smart board

For each group of/individual students:
• Student worksheet
• Several packets of branded candy (such as Skittles or M&Ms)*
• Large plastic cup
• Graph paper
• Pencil
• Timer
• Mini-Post-it tape flags (assorted colors)
• Several dozen dominoes (optional)
*The candy needs to be marked with the manufacturers mark on one side only. If candies are unavailable any small flat object with distinguishable sides, such as a dime coin, can be used.

Session 1 (90 minutes)

Session Summary

Engage (5 minutes)

Presentation Slides 1 & 2

1. Show video segment Matter and Energy: Energy From the Atom: Nuclear Power (0:00 to 1:23).
2. Explain that one important use of nuclear power is for the engines of nuclear-powered submarines and warships, such as aircraft carriers.
3. Show students the image of the nuclear submarine.
4. Have students list five facts they already know about a nuclear submarine.
5. Ask students to share their lists.
6. Have students use the information from their lists to answer the question: How does a nuclear submarine stay underwater for months at a time? The first part of the lesson will explore this question.

Explore 1: Life in a Nuclear Submarine (15 minutes)

Presentation Slides 3 to 5

1. Explain to students that they have been promoted to command a nuclear submarine.
2. Show students the image of the nuclear submarine.
3. Tell students their mission is to conduct an exercise during which the submarine has to surface in the Arctic Sea.
4. Show students the slide: Plot your course to the Arctic Sea!
5. Have students use Google Maps (or Google Earth) to plot a course from US Naval Base Kitsap in Washington State to a location in the Arctic Sea. The precise course is not important. They can choose any location in the Arctic Sea north of the Bering Straits. They can use the line
drawing tool to get the distance from the Naval Base to the surfacing site. (If students do not have access to a computer, they can use an atlas to estimate the distance.)

6. Have students calculate the time the submarine will take to reach the surfacing site. Have them use a cruising speed of 20 knots (= 23 mph). Since this is a top-secret mission, the submarine cannot surface due to the possibility of detection by aircraft, ground radar or satellite.

7. Show students the slide: How long underwater?

8. If needed, walk through the example. If the estimated distance is 3,750 miles, the submarine will need to remain underwater for 3,750/23 = 163 hours minimum. That is almost a week underwater.

9. Explain to students that most types of non-nuclear submarines cannot stay that long underwater. With nuclear power, a submarine is limited only by its food supply. (Water is distilled from seawater and air is recycled.) Nuclear power enables the US Navy submarine fleet to operate entirely underwater and deploy worldwide.

Explore 2: What is Nuclear Power? (20 minutes)

Presentation Slides 6 to 10

1. Have students create a K-W-L chart. The chart will depict what they know about nuclear power.

2. Ask students if nuclear power has been in the news recently. (If necessary, prompt them to recall the Fukushima crisis following the tsunami in Japan, or ask if they have heard of Three Mile Island or Chernobyl.)

3. Ask students if they think that a nuclear reactor can explode like an atomic bomb. Show the image of the Fukushima nuclear accident in the slide titles: An image of nuclear energy. Ask students if they think a reactor can explode like a nuclear bomb. They might respond that a nuclear bomb works the same way as a reactor. Ask students whether this is true or not, and explain that they will work to determine how a reactor works.

4. Show the slide titled: Nuclear power is...

5. Have student groups discuss the word “fission.” They can explore a dictionary (online or printed) to investigate the usage of the term. For example, in biology, fission refers to a cell splitting in two. Likewise, in physics, fission refers to the splitting of an atomic nucleus in two.

6. Have students work in small groups and brainstorm how they think a reactor might work. Some may have heard of nuclear fission. Have each group develop a model of how fission might be used to generate nuclear power. If students have access to the Internet, encourage them to explore the concept and its relationship to nuclear power.

7. Encourage students to discuss the concept that nuclear power relies on a subatomic process called nuclear fission, in which an atomic nucleus is split in two.

8. Inform students that they will learn about nuclear fission and the physics of nuclear energy, to learn how the power of the atom can be harnessed for generating electricity.

9. Show the video Matter and Energy: Energy From the Atom: Nuclear Power (from 1:23 to 3:30)

10. Show the slide: Fission. (Do NOT yet click to reveal the labels, since students will be challenged to interpret it for themselves.)

11. Have students investigate the graphic. Ask them if there might be a way to determine the identity of the different items featured in it. Lead them to conclude that they can explore the periodic table to determine the identity of the elements.
12. When they have identified uranium-235 and uranium-236, challenge students to identify the particle colliding with the uranium-235 atom. Lead them to conclude that since the atomic weight changes from 235 to 236, the particle could be a proton OR a neutron. However, the element remains uranium, so it cannot be a proton.

13. Have students investigate why the particle cannot be a proton. (If the particle was a proton it would increase the atomic weight by one, and the element would be neptunium, not uranium.)

14. Have students discuss and research to identify the remaining parts of the graphic, including krypton and barium atoms, the three additional neutrons and the gamma rays and energy.

15. Challenge students to investigate if the three depicted neutrons is the correct number. (They should conclude that it is because the atomic weights of the products krypton and barium, plus the three neutrons add up to the same weight as uranium-236; i.e., 92+141+3=236).

16. Have students explore the fission process, and then create a list of the steps in the process. Their list should include the following steps:
   1) A loose neutron collides with the nucleus of the uranium atom.
   2) The additional neutron destabilizes the uranium nucleus, akin to the proverbial “final straw”.
   3) The nucleus splits, releasing energy and resulting in two different elements. (The illustration shows the products as krypton and barium, but other products, such as xenon and strontium, also occur.) The release of energy includes gamma rays, which are dangerous radiation. Heat is also released.

17. Click to reveal the labels on the slide and have students compare their lists with the sequence of events depicted on the slide.

18. Have students recall that in a nuclear reactor, this heat is used to heat water, which is used to drive steam turbines.

19. Have students, in their individual groups, brainstorm what could happen to the additional released neutrons. Lead them to conclude that those neutrons can, in turn, collide with more uranium nuclei, causing fission, leading to release of more neutrons, resulting in more fission, and so on.

20. Show the slide: Chain reaction. This chain reaction is the key to both the explosion of a nuclear weapon, and of harnessing energy from fission.

21. Explain that, in a nuclear weapon, the chain reaction is uncontrolled, occurring so quickly that all the uranium present undergoes fission.

22. In an uncontrolled fission reaction, the huge amount of energy released in such a short time creates the powerful explosion, which in turn results in the familiar mushroom cloud.

23. Challenge students in their groups to investigate how a chain reaction might be limited or controlled. Lead them to conclude that if each neutron does not collide with a new atom, the chain reaction will be slowed or stopped. Explain that in the next session they will explore how a nuclear reactor accomplishes control of the chain reaction.

24. For the activity, tell students they will use dominoes to model the chain reaction. (If necessary, go back to the slide: Chain reaction.) Explain to students that the activity will demonstrate the principle of nuclear fission. This reaction creates the heat that is harvested by nuclear reactors.

25. Have students consider how accurately a set of falling dominoes can model a chain reaction. For example, they can explore the similarities and differences compared with a nuclear chain reaction. (If they have trouble grasping the concept you can show the online simulation: Nuclear chain reaction simulator.) If time allows, have students experiment with the actual dominoes to model the chain reaction.

How a Reactor Works (20 Minutes)

Presentation Slides 11 to 13
1. Have students watch the video segment *Nuclear Fission and Power Plant*, to reinforce learning, have students watch the video segment *Generating Electricity* (0:00 to 2:00).
2. Ensure students make notes of the operation and function of a nuclear power plant.
3. Present the students the diagram of the unlabeled nuclear reactor. (You will click to reveal labels after the next few steps.)
4. Allow students a few minutes to explore the diagram, and to discuss in small groups how this depiction relates to the content of the video segments and to their operation and function of a nuclear power plant.
5. Have students make a sketch of the diagram. The sketch need not be identical to the diagram, but it should include the main elements. (If time is short you can prepare handouts with a picture of the unlabeled reactor. You can just print the slide from the presentation.)
6. Point out to students the list of labels for the nuclear reactor, as shown on the slide.
7. Have students write each of the terms on to a mini-Post-it so they have one label for each term.
8. Have them apply their Post-its to label the diagram.
9. Once they have completed this task, have students further discuss the basic steps of reactor operation to determine the correct labels for their diagram.
10. Once students are think they have all the parts correctly labeled, click through to reveal the sequence of labels that illustrates the reactor’s operation:
    1) Water is heated in the reactor vessel.
    2) Inside the reactor vessel, *control rods* are raised or lowered to decrease or increase reactor heat output.
    3) Water reaches high pressure in the pressurizer.
    4) It heats water in a separate system in the steam generator.
    5) These functions are carried out in the containment structure.
    6) Steam drives a turbine.
    7) The turbine drives an electric generator that provides electricity.
    8) Steam is returned to the generator via a condenser through which cold water circulates.
11. As you click to reveal each of the labels in the diagram, have students indicate if they applied the Post-it label to the correct part of the diagram. If they applied it to the wrong part of the diagram, have them move the label to the correct location.
12. When all the labels are applied correctly students can write in the labels on their drawing.
13. Have students recall the previous session’s discussion of a chain reaction, and challenge them to determine how the reactor controls the rate of the chain reaction. For example, they can identify where the reactions are taking place. (Reactions occur in the reactor vessel). Students should conclude that the control rods control the loose neutrons by slowing or stopping them.
14. Encourage students to discuss and research what kinds of material might be suitable absorbing material. They will discover that the control rods are made of graphite. (If necessary review the nature of graphite, as a form of carbon.)
15. Have students brainstorm how the control rods work. For example, they should conclude that the rods are lowered into the reactor core, where they absorb neutrons. Because the graphite absorbs neutrons, they cannot collide with the uranium nuclei. If the operator needs to increase the rate of reactions, the rods can be raised, increasing the power output of the reactor.
16. If students have access to the Internet, they can explore the online animation (NRC: The Pressurized Water Reactor, see *Additional resources* below). This shows the functioning of the reactor more clearly.
17. Due to the water system, it is called a *pressurized water reactor*. This is the most common type of commercial reactor in the United States. Have students discuss this type of reactor. They can investigate other types of reactor, and what other configurations are possible.

18. Also point out that in a naval vessel, the steam turbine is connected to the propeller shaft to provide propulsion directly.

**Explore 3: Are reactors safe? (10 Minutes)**

*Presentation Slide 14*

1. For students to consider the safety of the nuclear reactor, have small groups explore the question, could a nuclear explosion occur within the reactor?
2. Show the slide titled: *Nuclear reactor safety - explosion?*
3. Have students in small groups explore question of whether a nuclear explosion can in a reactor. For example, they can research the events at Three Mile Island, Chernobyl and Fukushima to investigate why those incidents did not result in a nuclear explosion. Their research will show that a nuclear explosion only occurs if there is enough material to sustain an uncontrolled chain reaction. If the amount or mass of the material is too low, a chain reaction will not occur quickly enough to cause an explosion.
4. Have students investigate the actual amount of material needed for an uncontrolled explosion. They should discover that this amount is called the **critical mass**.
5. Click through on the slide to show the definition of critical mass. (The minimum amount of material needed to sustain an uncontrolled chain reaction, and therefore cause a nuclear explosion.)
6. Have students explore the possibility that the fuel of a nuclear reactor reaches a critical mass. They can research online to discover that a very pure isotope of uranium is required for a nuclear chain reaction to be self-sustaining. (Weapons-grade uranium is 90 percent pure U-235. In the case of a fission reactor, the uranium needs only to comprise 3 percent U-235.)
7. With this information have students consider the reason that a nuclear reactor cannot cause a nuclear explosion. (The fuel in a reactor is not pure enough to achieve critical mass, and it will not undergo a nuclear explosion.)
8. Click through on the slide to reveal the summary information.
9. Have students consider other aspects of reactor safety. Show the slide *Nuclear reactor safety – waste*.
10. Have the students recall that the fission of fuel results in gamma rays.
11. Have the students research how a reactor can malfunction. They should discover that if cooling systems fail or control rods become inoperable, a reactor could undergo **meltdown**, resulting in release of radioactive materials. In the normal course of operations, a reactor produces radioactive materials. Radioactivity damages biological tissues. Exposure to high levels of radioactivity can be fatal, cause cancer and other diseases. Have students consider the consequences of their findings.
12. Click through the slide to summarize these findings. Lead students to the key conclusions: (A) Workers need to be protected from radioactivity; (B) radioactive waste needs to be safely disposed of.
13. Explain that they will next investigate how long radioactive waste remains dangerous.


*Presentation Slide 16*
1. Have students in small groups addressed the question: what happens to radioactivity over time? Have them brainstorm the possibilities. They should conclude there are three possibilities. Radioactivity could (1) increase, (2) stay the same or (3) decrease. Have groups explore these options. They should consider that if a substance is radioactive, it is most likely emitting something. Over time, that something must decrease, (due to conservation of mass). Therefore students should conclude that radioactivity of a substance declines over time.

2. Explain to students that this decline is called “decay” and it follows a well-defined mathematical relationship.

3. Show students the slide: Exponential decay.

4. Have students consider the graphic of exponential decay and discuss the nature of the correlation it depicts. They should conclude that is a negative power relationship. Mathematically inclined students may wish to learn more about the exponential equation, but for now, just point out the power exponents to emphasize that this is a power relationship.

5. Since the graphic shows “Number of items” in the y-axis label, have students investigate what those items might be. You can provide the hint that it could refer to different kinds of things. For example, in terms of radioactivity, the number of items could be the number of radioactive atoms in a sample, a measure of radioactivity or a probability that an atom will emit a radioactive particle.

6. To better understand how the decline in radioactivity can be measured in more than one way, students will conduct an activity at the beginning of the next session.

Session 2 (90 minutes)

Demonstrate Radioactive Decay (25 minutes)

Presentation Slides 16 to 19

1. Explain to students that the activity will demonstrate the principle of nuclear or radioactive decay. This is a process that happens in nature spontaneously (i.e., it does not require a neutron, as in fission).

2. Have students discuss what will happen to the danger from radioactive waste over time if radioactivity declines. They should conclude that the danger would also decline. For that reason, it is important to have a measure of the decline in radioactivity.

3. Have the students research how the decline in radioactivity is measured. They will discover that instruments such as the Geiger counter can measure radioactivity.

4. Have students address the question, how can different elements be compared in terms of their rate of decline radioactivity? Return to the slide Exponential Decay and click through the two additional curves. Have students consider what the curves represent. They should conclude that the lower curve represents a substance that decays more quickly (loses its radioactivity faster) and that the upper curve represents a substance that decays more slowly (loses its radioactivity slower). Explain to students that they will model the process of decay to investigate the rate of decline in radioactivity over time.
5. Divide the class into small groups. Half the groups are designated *Uranium*. The other half are designated *Plutonium*. To model radioactive decay, have groups follow the procedure below:

1) Have each group label a cup accordingly. Uranium groups label their cup U-232. This number represents the isotope of uranium with an atomic weight (neutrons plus protons) of 232. Plutonium groups label their cup P-238.

2) Have each group count out 100 candies. (This activity will work with fewer candies, but better results are obtained with using as many candies as possible.) These are placed into the paper cups. The 100 candies represent each of the radioactive atoms before they have decayed.

3) For each round, have a student shake their cup and empty the candies onto a clean sheet of paper.

4) The candies that fall with the label up are removed. These represent atoms that have undergone radioactive decay.

5) Have students write the number of remaining candies (atoms) in the first column of the table on their worksheets. They only need to complete the top row at this point.

6) Have students repeat Steps 2 to 5, recording the number of remaining candies in each successive column in the table.

7) Groups with the U-232 cups should repeat the steps every 70 seconds.

8) Groups with the P-238 cups should repeat the steps every 90 seconds.

9) Have students repeat the steps until no more of the candies remain. Have students make a note of the total time taken to use up all the candies.

10) Have students plot their data points on the graph paper, and draw a line to connect the points.

11) Collect data from each group and average for each repeated step and then graph each of the points. Join the points so that student charts have a second value.

6. Have students calculate the predicted values for the number of candies for each half-life. Plot these on the same graph and label each of the lines.

7. Have students write a brief description to compare and contrast each of the lines. Ask each group to comment on their observations.

8. Ensure students grasp that each time candies are removed, that represents a half-life time period for decay of the atoms.

9. You can prompt them with the following questions (show the slide *Results of half-life activity*):

   1) What shape are the curves that they observe? (Emphasize that this type of curve is an exponential decay with a negative power relationship.)

   2) Which of the lines, the class average or the group line, is closest to the theoretical line? (The class average is closer to the theoretical line. This is because decay is probabilistic. Therefore larger sample sizes will more closely approximate the theoretical predictions.)

   3) What is the difference in the average time for U-232 and P-238 groups to use up all their candies? (The *Uranium* groups use up all their candies sooner.)

   4) What does this difference represent? (The difference represents the different half-lives of U-232 and P-238. The half-life of uranium 232 is shorter than the half-life of plutonium 238 (68.9 years versus 87.7 years).)

10. Show the slide *Radioactive decay*. Have students investigate how it relates to the curves they obtained from the activity data. Students should discover that it resembles the exponential decay curve.

11. Have students research the definition of the word “half-life.”

12. Students should discover that during each time period, the amount of radioactivity is halved. This is the **half-life**. Basically, this means that over a given period of time a substance’s radioactive atoms will halve. They should also conclude that this time period differs greatly depending on the type of element. Have students investigate what factors cause the half-life to vary. They should realize that the half-life is independent of any chemical process. That is, heating or cooling a substance does not change its half-life. The cause of variation in nuclear
decay is between radioactive elements or, more strictly, their isotopes. That is the half-life of
different elements differs because of nuclear processes that are independent of external factors.
13. Click through the slide to emphasize these learning points.
14. Finally, have students explore The Berkeley Laboratory Isotopes Project periodic table to
investigate examples of how different elements have different half-lives.
15. To help students relate the concept of half-life to radioactive waste, show the slide: *Half-life of
top 10 fission products*.
16. Have students consider the relevance of the data in the “Yield %” column. They should
understand that percent yield is the relative amount of each element resulting from fission of
U-235, which is the primary fuel of nuclear reactors (although plutonium is also used).
17. Direct students to consider the implications of the data in the “Half-life” column. They should
conclude that some fission products have half-lives of less than a century or even just hours.
Other fission products have half-lives of hundreds of thousands or even millions of years.
18. Click through the slide to reinforce these learning points.
19. Have students now integrate their learning points on half-lives and radioactive decay with the
problem of nuclear waste. Have them brainstorm or discuss as needed so they conclude that it
is the longest-lived waste products that pose the most difficulties for long-term storage of
nuclear waste.
20. If time allows, have students research options for dealing with waste. They should realize that
considerable debate surrounds long-term disposal. On the other hand, some technologies, such
as reprocessing fuel, aim to use up all the long-lived fission products so that waste is rendered
relatively safe within a few decades. Another option is to use a different nuclear fuel (e.g.,
thorium) that produces fewer waste products. However, these methods have yet to be widely
adopted.

**Predict Decay Products (20 minutes)**

*Presentation Slides 20 to 26*

1. Inform students that on the duty roster they are assigned to monitor the reactor of a nuclear-
powered submarine or aircraft carrier. Their job is to determine the decay products of elements
involved in nuclear reactions.
2. Allow students a few minutes to discover what the different kinds of decay are. They should
quickly realize there are alpha, beta and gamma types of decay.
3. Divide students into groups of three. In each group have each student investigate one of the
different kinds of decay. They can research such properties as the cause, the type of particle
penetrating power and examples.
4. So students can check their research, show students the slide *Types of radioactive decay*. Have
students compare the description of the different kinds of radioactive decay with the
descriptions they determined during the group exercise.
5. Ensure students understand that an **alpha particle** is a helium nucleus.
6. Have students explore the periodic table to answer the question: “What subatomic particles
comprise a helium nucleus?” (It is comprised of two protons and two neutrons.)
7. Show the slide *Penetrating power of decay products* and have students interpret the graphic.
   In groups of three, students can consider how their different type of radioactivity require
different kinds of shielding. Have students explore what other materials might stop each type
of radiation. For example, paper will stop alpha radiation. Water will stop gamma radiation.
You can add that a thin layer of lead stops X-rays because they are less powerful than gamma rays, but thick lead is needed to stop gamma rays.

8. Show students the slide Predicting decay products, and have students investigate what happens to an element if it loses an alpha particle.

9. Have students explore the periodic table to discover the atomic weight and atomic number of helium. They should conclude that by emitting an alpha particle, a nucleus loses two protons and two neutrons (a helium nucleus).

10. Have students consider the implications by furthering exploring the periodic table. They should conclude that since the atomic number decreases by two, the original element will change, resulting in transmutation to another element.

11. Click through the slide to emphasize these conclusions.

12. Show students the slide Example of alpha decay. Challenge students to complete the sample problem. They can work in small groups to solve the problem. If they need help, you can suggest the following approach.

13. Have students complete the first section of the “Decay Products” table on the activity sheet as follows:
   1) Have students access a periodic table (such as Ptable).
   2) Have students use the periodic table to determine the atomic number of uranium (92).
   3) Have students predict the decay product of uranium. You can prompt them to answer the question, which element has an atomic number two less than uranium? (It is thorium, i.e., 92 – 2 = 90)?

14. Have students answer the following questions on their worksheet:
   1) What is an alpha particle? (It is a particle comprising two protons and two neutrons emitted from the nucleus of a radioactive element.)
   2) What subatomic particles comprise a helium nucleus? (A helium nucleus comprises two protons and two neutrons.)
   3) How does emission of an alpha particle change an element’s atomic number? (Since an alpha particle has two protons, the element’s atomic number is reduced by two protons.)
   4) How does the element itself change upon emission of an alpha particle? (The element undergoes transmutation to become the element with an atomic number of two less than the original element.)
   5) What is the first decay product of uranium upon alpha decay? (Since uranium has an atomic number of 92, when it loses two protons it has an atomic number of 90, which is thorium.)

15. Click through the slide to help students if necessary or just so they can self-check their solutions to the problem, and the answers to their questions.

16. Have students investigate what happens if alpha decay continues. For example, what happens to thorium? Don’t reveal the answer, since they will determine it in the next activity. However, be sure students realize that the element will continue to undergo transmutation into new elements.

17. Have students that explore the periodic table to predict how alpha decay affects the isotopes over successive alpha decays. Have students complete the table for the remaining decay products to lead.

18. Ensure students complete the table with the remaining products of alpha decay. (Use the chemical symbols with their atomic number)

19. Once students have completed their table, show the completed decay chain on the white board. (The slide titled Radioactive decay chain.)

<table>
<thead>
<tr>
<th>Initial element</th>
<th>Decay products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>- γ particle</td>
</tr>
<tr>
<td></td>
<td>Th</td>
</tr>
<tr>
<td></td>
<td>- γ particle</td>
</tr>
<tr>
<td></td>
<td>Ra</td>
</tr>
<tr>
<td></td>
<td>- γ particle</td>
</tr>
<tr>
<td></td>
<td>Rn</td>
</tr>
<tr>
<td></td>
<td>- γ particle</td>
</tr>
<tr>
<td></td>
<td>Po</td>
</tr>
<tr>
<td></td>
<td>- γ particle</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
</tr>
</tbody>
</table>
20. Ensure students derive lead (Pb) as the final element in the decay chain of uranium. Point out that lead considered the final element in the decay chain, because it is stable and not radioactive.

21. Show students the slide: *How long is radioactive waste dangerous?*

22. Have students explore the answer in their small groups. Have groups write down one short answer to the question. Compare the groups’ various answers.

23. Click through the slide so that students can compare their answers. They should conclude that the answer is complicated because different products of fission and decay have different half-lives and are produced in different proportions. Also, some storage techniques are safer than others.

24. Show the video segment: *Matter and Energy: Energy From the Atom: Nuclear Power* (5:33 to 8:00). Have students discuss the benefits and risks of nuclear power and make notes as needed.

**Session 3**

**Explain (15 minutes)**

*Presentation Slide 27*

1. Have students complete their K-W-L chart from the first and second sessions.
2. Divide the class into small groups to compare their K-W-L charts. Encourage them to ask questions about gaps or misunderstandings in the L column.
3. Have each group create a concept map with the central topic “the science of nuclear power”. Have students explore the topic online and in small group discussions.
4. Allow the small groups to brainstorm for a few minutes for relevant terms. They may wish to include terms or concepts that were not covered earlier in the lesson, such as fusion. Once students have completed their concept maps, show the slide: *The science of nuclear power* to prompt students to include these example concepts in their map.
5. Challenge groups to create a simple demonstration or presentation that illustrates one or more principles or concepts related to nuclear power. This may include a PowerPoint, a skit, or specifications for a smart phone app.
6. Have each group devise a sample problem related to radioactive decay or fission, and then challenge another group to answer the problem.

**Elaborate (20 minutes)**

*Presentation Slides 28 to 30*

1. Tell students they will answer the question: How does a nuclear powered submarine or aircraft carrier work?
2. Show the slide depicting a nuclear powered engine. (You can supplement this by showing an animation of this graphic on the Office of Naval Research website.)
3. Explain that a nuclear powered vessel engine works the same way as a nuclear power station. Instead of using steam to drive an electric generator, the steam is used to drive a turbine connected to a propeller shaft.
4. Have students recall the information from the first session regarding the capacity of a nuclear submarine to remain submerged indefinitely.

5. Challenge students to determine why a nuclear submarine can remain submerged indefinitely.

6. Ask students to consider how long the nuclear fuel can last.

7. Show the photo of Operation Sea Orbit. This image features the nuclear-powered carrier USS Enterprise. Note the statistic that the fleet sailed around the world in 65 days without refueling. In fact, a nuclear-powered vessel can operate for 20 years without refueling. How could this be?

8. Ask students what $E = mc^2$ implies. Since $c^2$ is very large, converting a small amount of matter ($m$) will result in a large amount of energy.

9. Have students hold in their hands a dollar bill, or a paper clip. Explain that these items weight about a gram.

10. Then provide the example that, in theory, 1 gram of matter converted to energy will yield about $9 \times 10^{13}$ J (joules). That's enough energy (in the dollar bill or paper clip) to meet an average US household's energy needs for more than 2,000 years, or enough energy to power 2,000 households for a year.

11. Show the slide Energy yield of nuclear fuel.

12. Explain that nuclear power is not 100 percent efficient. This means that not all the energy is converted to usable heat. In a reactor, a gram of uranium yields about $8.8 \times 10^{10}$ J.

13. On the other hand when gasoline is converted to energy, 1 gram yields about $5 \times 10^4$ J. That is, a gram of nuclear fuel provides around 1.76 million times the amount of energy of a gram of gasoline. If your car was nuclear powered, it could travel about 5 billion miles to the gallon (weight equivalent)!

14. Have students consider the advantages of nuclear power for a submarine or other naval vessel. Given the amount of energy provided by nuclear fuel, a vessel can remain at sea for a long time, needing to return only for food supplies. Navy surface vessels operate for 20 or so years without refueling.

15. Explain to students that when nuclear-powered vessels need refueling, they must undergo complex procedures to avoid contaminating the surroundings, since the nuclear core is highly radioactive. Such refurbishment can take up to three years. During this time additional refitting and reconditioning of the vessel will take place. Nevertheless, the advantages of long service life outweigh the cost and expense of refueling.

16. For students with additional interest in the Navy and careers, show the video At Sea: Submarine Warfare (requires additional class time).

**Evaluate (10 minutes)**

1. Have students consider their K-W-L charts and concept maps. Students should be able to answer each of the Essential (Guiding) Questions:
   1) How does a nuclear reactor work?
   2) What are the benefits and risks of nuclear power?
   3) What are basic terms used in the fields of nuclear power and nuclear physics?
   4) How are quantitative data related to radioactivity analyzed?

2. Students should also be able to define each of the key words.

3. For struggling students, emphasize the key principle that nuclear power is derived from the controlled fission of uranium, and that nuclear waste is a problem because of the long half-life of some radioactive elements.

4. Advanced students can be provided problems related to fission, radioactive decay and transmutation.
Additional activities
To further stimulate interest in this topic have students use Web 2.0 tools as an extension to this lesson. Possible approaches include:

1) Have students access the online applets that simulate a nuclear chain reaction and nuclear decay.
2) For the nuclear decay simulator, students can compare the rates of decay for different elements. They can also compare the increase in number of nuclei of the decay product following transmutation compared with the original element.
3) Students can adjust the timescale to emphasize how different elements or their isotopes decay at different rates. For example, have students plot the decay of Iodine-131 to Xenon-131 with the time scale set at 0 to 100 years. The decay lines are straight because the very short half-life of Iodine-131 means that no decay events register on that time scale. On the other hand, if the time scale is set at 0 to 100 days, the decay of all the Iodine-131 nuclei to Xenon-131 is complete after about 50 days.
4) For the nuclear chain reaction simulator, students can vary the speed and the packing density. The speed just runs the simulation faster or slower, but the chain reaction is easiest to observe with at intermediate speeds.
5) Students can vary the packing density to simulate the proportion of U-235. For example, if the packing density is 90% (equivalent to weapons grade uranium), the energy yield rises and falls almost immediately. However, if the packing density is 5% (equivalent to U235 in nuclear fuel), the energy yield is spread out over time.
6) Have students use an online visual tool such as Glogster to develop their concept maps with photos and videos and to share ideas and thoughts. They can also use the mobile app Mindmeister to create concept maps on mobile devices.
7) Students can create slide presentations to summarize their learning and share their presentations online through Slideshare.
8) Students can review and edit or create wiki articles (e.g., simple.wikipedia.org) related to the nuclear power.
9) Students who are challenged by vocabulary can use Wordle to create word clouds based on specific topics. For example, they could copy and paste text from the nuclear power article on HowStuffWorks.com to determine the words most closely associated with the phrase, “nuclear power”.

Additional resources and further reading

Wolfram Research Periodic Table
http://periodictable.com/

Ptable
http://www.ptable.com/
Nature: In a hole – It is in Britain’s best interests to keep looking for a site for a deep nuclear-waste repository.
http://www.nature.com/news/in-a-hole-1.12361

NRC: The Pressurized Water Reactor (PWR)
http://www.nrc.gov/images/reading-rm/basic-ref/students/student-pwr.gif

Nuclear powered Engine
https://www.energy.gov/science-innovation/energy-sources/nuclear
Lean Mean Submarine: The Science of Nuclear Power

Science Topic: Physics and Social Science

STUDENT WORKSHEET

What is nuclear power?
Complete the following table with your existing knowledge about nuclear power (K) and what you’d like to know (W). At the end of the lesson, complete the final column (L) with what you have learned about nuclear power.

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<tr>
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<tbody>
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</tr>
</tbody>
</table>

Use a separate piece of paper to sketch a nuclear reactor from the picture presented on the screen. Add the suggested labels.
Use this table for the radioactive decay activity

<table>
<thead>
<tr>
<th>Candies remaining (your value)</th>
<th>Initial Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time taken</td>
<td>NA</td>
<td></td>
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<tr>
<td>Candies remaining (class value)</td>
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<td>Predicted value</td>
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</tbody>
</table>

Complete this table with the remaining products of alpha decay from uranium 235 as the starting element. Use the chemical symbols with their atomic number. (Hint: subtract an alpha particle from the atomic number of each preceding element to find the atomic number of the new element.)

<table>
<thead>
<tr>
<th>Initial element</th>
<th>Decay products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- γ particle</td>
</tr>
<tr>
<td>Uranium</td>
<td>- γ particle</td>
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<td>- γ particle</td>
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<td></td>
<td>- γ particle</td>
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<td></td>
<td>- γ particle</td>
</tr>
</tbody>
</table>
What is an alpha particle?

What subatomic particles comprise a helium nucleus?

How does emission of an alpha particle change an element’s atomic number?

How does the element itself change upon emission of an alpha particle?

What is the first decay product of uranium upon alpha decay?

What is the final element in the decay chain of uranium? Why is this considered the final element in the decay chain?

Write a list of concepts to include in your concept map titled “The Science of Nuclear Power.”

**Answer the Essential Questions:**

How does a nuclear reactor work?
What are the benefits and risks of nuclear power?

What are basic terms used in the fields of nuclear power and nuclear physics?

How are quantitative data related to radioactivity analyzed?

Define each of the key words:

- Alpha particle
- Chain reaction
- Critical mass
- Exponential decay

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- Gamma rays
- Half-life
- Nuclear decay
- Nuclear fission
- Nuclear reactor
- Nucleus
- Radioactivity
- Transmutation