- 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 radio- active 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.

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 $E=mc^2$ 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.

- 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

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

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.

Explore 4: How Long Is Radioactive Waste Dangerous? (20 minutes)

Presentation Slide 16

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

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 though 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*.)

	Decay products				
Initial element	**- γ particle**	**- γ particle**	**- γ particle**	**- γ particle**	**- γ particle**
Uranium	Th	Ra	Rn	Po	Pb

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 9×10^{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 8.8×10^{10} J.
13. On the other hand when gasoline is converted to energy, 1 gram yields about 5×10^4 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.

U.S. Nuclear Regulatory Commission
http://www.nrc.gov/

Argonne National Laboratory: Nuclear Energy Learning Resources
http://students.ne.anl.gov/schools/us.php

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
http://www.onr.navy.mil/focus/blowballast/sub/work7.htm

Nuclear decay simulator
http://spice.duit.uwa.edu.au/samples/ast0025/

Nuclear chain reaction simulator
http://vlab.infotech.monash.edu.au/simulations/non-linear/nuclear-chain-reaction/demo/

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.

K – What I know	W – What I want to know	L – What I learned

Use a separate piece of paper to sketch a nuclear reactor from the picture presented on the screen. Add the suggested labels.

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

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