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Good Chemistry

Dr. Rebecca Steinmann


Courtesy of Rebecca Steinmann

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While engineers are often involved with designing or improving new technologies, that's not all they do. Many engineers make sure that existing designed systems are safe, reliable, and well maintained. This job is especially important when the designed system in question is as large and complex as a nuclear power plant. Nuclear power plants provide approximately 20 percent of the United States's electrical power. More than 100 nuclear power plants operate in the United States, and each plant must meet stringent federal regulations. These regulations help ensure the plants are safe for the people who work in them, the people who live nearby, and the environment.

I'm Dr. Rebecca Steinman, and I'm a nuclear engineer working at Advent Engineering Services, Inc., a small engineering consulting company based in Ann Arbor, Michigan. As a consultant, I'm often involved in helping nuclear power plants meet federal regulations.

I decided I wanted to become a nuclear engineer when I was a junior in high school. I entered a local science fair that year—and won. The state contest was held at the University of Missouri at Rolla campus, which had a research nuclear reactor. I got to go into the control room! I was fascinated by the fact that the energy released from nuclear reactions is invisible, but we can do so much with it. We use it to generate electrical power, for sterilization, and for medical diagnosis and treatment, along with many other applications.

When I got home from the science fair, I announced to my grandmother and her bridge partners that I planned to become a nuclear engineer. As I expected, they all gasped in disbelief. At the time, very few women worked in engineering and even fewer worked in nuclear engineering. My desire to become a nuclear engineer was really shocking to some people, and I must admit that I sort of enjoyed challenging stereotypes about who should study engineering. I was the only woman out of eighteen nuclear engineering majors in my graduating class at the University of Missouri. Since graduating, I have completed my Ph.D. in nuclear engineering and have worked in the field for several years. Over those years, I have seen the field start to change. Nuclear engineering programs are attracting a more diverse group of students today. I'm glad to see this change happen. I believe nuclear engineering offers many opportunities for anyone who chooses to enter the profession.

The Basics of Nuclear Power Plants

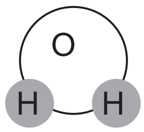
Because I work for a consulting company, I get to work on a variety of different projects, sometimes in teams and sometimes on my own. But nearly all of my assignments involve nuclear power plants.

Much like coal-fired power plants or geothermal power plants, nuclear power plants use hot water or steam to turn a turbine, which spins an electrical generator. The primary difference between these three types of power plants is how the water is heated. In a coal-fired plant, the water is heated by a chemical reaction. A geothermal power plant uses water heated deep in the Earth. A nuclear power plant uses the energy released by nuclear reactions to heat water and drive a turbine.

How Do Nuclear Reactors Work?

To understand how nuclear reactions heat water, it's important to remember that all substances on Earth are made up of molecules. A ***molecule*** is the smallest particle of a material that has all the chemical properties of that material. Molecules are made up of even smaller particles called ***atoms.*** A water molecule, for example, has two hydrogen atoms and one oxygen atom, which is abbreviated H_20.

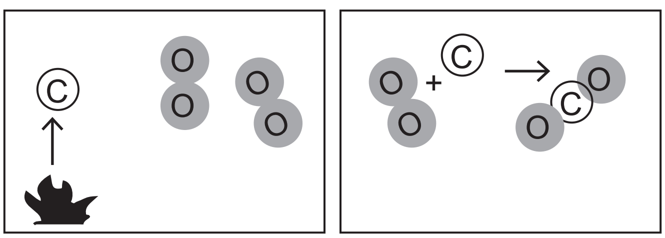
H_2O molecule:
2 Hydrogen atoms
1 Oxygen atoms



Substances that have only one kind of atom are called ***elements.*** Most molecules of oxygen in our air are made up of two atoms of oxygen (O_2). Other substances in the form of a gas at room temperature include hydrogen, helium, neon, and nitrogen. Elements in solid form at room temperature include iron, gold, silver, carbon, and uranium. There are ninety-two natural elements in all.

In ***chemical reactions,*** molecules break apart and the atoms are rearranged into new molecules. When molecules break apart, they release energy, usually as heat and light. When a carbon-based fuel like gasoline burns, for example, the carbon (C) is released from the gasoline molecules and energy is released to the immediate surroundings. The carbon then combines with oxygen from the air (O), forming carbon dioxide gas (CO_2).

$$C + O_2 \longrightarrow = CO_2$$



Burning fuel releases carbon (C) into the air.

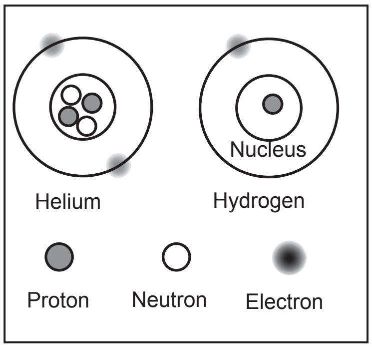
Carbon combines with oxygen in air (O_2), forming carbon dioxide gas (CO_2).

Elements are substances that have only one kind of atom.

Atoms are the smallest particle of a chemical element that retains its chemical properties.

A molecule is the smallest particle of a material that still has all the chemical properties of that material. Usually a molecule has two or more atoms.

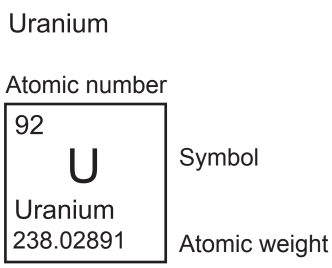
In chemical reactions molecules break apart and atoms are rearranged into new molecules.



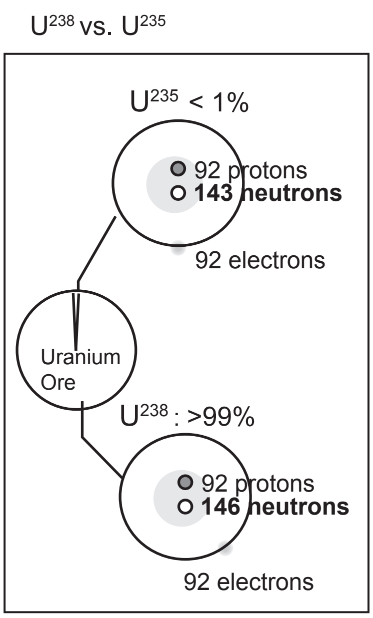
In ***nuclear reactions,*** the atoms themselves—not the molecules—break up. This process releases much more energy. The action happens in the center of each atom, where there is a tiny, dense ball of matter called the ***nucleus.*** The nucleus consists of two types of particles: ***protons*** and ***neutrons.***

The number of protons determines the kind of element. All hydrogen atoms have one proton in the nucleus, while all helium atoms have two protons. Uranium atoms are the heaviest atoms in nature, with ninety-two protons. Atoms of a given element often have the same number of neutrons in their nucleus, or a few more or less.

The element ***uranium*** is especially interesting to nuclear engineers, because it can be used as a remarkably efficient fuel. A pound of the type of uranium used in nuclear power plants, roughly the size of a tennis ball, can release about as much energy as one million gallons of gasoline.

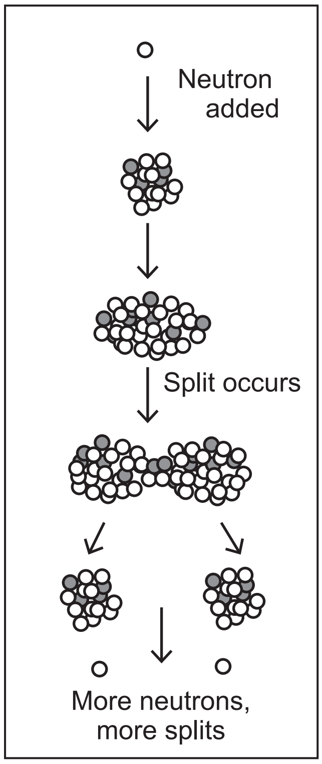


Uranium occurs naturally, often in the form of an ore. This ore is slightly radioactive, which means that some of the atoms in the rock naturally decay, releasing energy in the form of heat and particles as they come apart. More than 99 percent of the uranium in ore is U^{238}, which means it has ninety-two protons for a total of 238 particles in its nucleus. Although U^{238} is not radioactive enough to use in a nuclear reactor, it does contain trace amounts (less than 1 percent) of a different form of uranium, U^{235}, which is much more potent. The uranium atom used in nuclear fuel has 92 protons and 143 neutrons, for a total of 235 particles in its nucleus. This form of uranium is symbolized U^{235}. One of the first steps in producing or supplying a nuclear reactor is to isolate U^{235} from the much more abundant U^{238}.



- U^{238} is not radioactive enough to use in a nuclear reactor.
- U^{235} is much more potent than, but not as abundant as, U^{238}.
- U^{235} needs to be isolated from U^{238}.
- Nuclear reactors need U^{235}.

Inside a nuclear reactor are thousands of nuclear fuel pellets made of U_{235}. When a neutron wanders by, it will be "captured" and form a slightly larger nucleus. This larger nucleus cannot hold together very long, so it splits into two smaller nuclei, releasing energy. This splitting of the nucleus is called nuclear ***fission.***



When it splits, the uranium nucleus also emits two or three more neutrons, each of which can be captured by two or three other uranium nuclei. These nuclei also emit energy and each releases more neutrons, which are captured by more nuclei and so on. This is called a chain reaction. If enough uranium exists in one place and the reaction continues unchecked, the result would be a nuclear explosion. However, in a power reactor, control rods are used to absorb some of the neutrons. The splitting of the nuclei of uranium atoms generates heat, which heats water in a boiler creating steam.

Nuclear reactors come in many different designs. Each reactor is designed to be as efficient and safe as possible. Most reactors in the United States are "Pressurized Water Reactors." In this kind of reactor, the uranium fuel is made into ceramic pellets about the size of a fingertip. Hundreds of these pellets are sealed in strong metal tubes and inserted into a pool of water. Control rods are also dispersed in the water, between the tubes of uranium pellets. This assembly is called the reactor core. Fission begins when enough uranium is inserted into the core to maintain a chain reaction. By controlling the position of the control rods, operators can keep the chain reaction going at a constant rate.

As the fission reaction continues, the water in the reactor becomes very hot. However, it is kept under pressure so it does not turn to steam. The hot water is then used to heat a second tank of water called a boiler. When water in the second tank is heated, it turns into steam. The steam drives a turbine, which spins an electrical generator. The hot water in the second tank is then cooled in a cooling tower and is recycled or discarded.

Nuclear Power: Perceptions and Facts

Nuclear power plants have some important advantages over fossil fuel power plants. Because they do not require combustion, nuclear power plants do not release air pollution. And they do not use oil, which is a diminishing natural resource. Because of these advantages, the federal government has recently invested in national and international efforts to boost nuclear power production to help meet the world's rapidly growing electrical power needs in a more environmentally friendly way.

While nuclear power generation is a cleaner alternative to fossil fuel power generation in terms of air pollution, nuclear power has some risks associated with it. Nuclear power plants use radioactive materials, such as uranium, which emit radiation. High levels of radiation can damage or destroy cells of living organisms, potentially leading to cell mutation or cancer. This risk explains why there are so many laws regulating the nuclear power industry.


Courtesy of Morguefile

In nuclear power plants that meet federal regulation, however, the risks are very, very minimal. Well-constructed and well-managed plants release very little radiation into the environment. In fact, coal-fired power plants often emit more radiation than nuclear power plants do because radioactive materials naturally occurring in coal are released during the combustion process.

Even though the safety record of nuclear power plants in the United States is very good, nuclear power remains a controversial means of producing power in our country. Many people perceive nuclear power plants as dangerous. The perception may stem, in part, from an accident that occurred in 1979 at the Three Mile Island nuclear power station near Harrisburg, Pennsylvania. It was the worst accident in U.S. commercial reactor history. During the accident, coolant escaped from the reactor due to a mechanical malfunction and human error.

No one was injured, and no overexposure to radiation resulted. But major media outlets across the nation greatly publicized the story. Public demand for stricter plant regulation soon followed. Later that year, the United States Nuclear Regulatory Commission (NRC) imposed stricter reactor safety regulations and more rigid inspection procedures to improve the safety of reactor operations. The NRC continues to create regulations and industry standards, enforce laws, and license and certify all U.S. nuclear power plants. As a part of this mandate, the NRC has developed the environmental qualification process.

Environmental Qualification

Numerous processes and programs have been established to ensure that all nuclear plant equipment will function as expected under normal and possible accidental conditions. Environmental qualification is a process for ensuring that all of the plant's electrical equipment will function properly, even during the extreme temperatures and pressures that could exist in the event of an accident at the plant. All nuclear power plants in this country must undergo this process to receive a license to operate. As a consultant, I am often involved in conducting tests to certify a plant's environmental qualification.

During the initial environmental qualification of the plant's electrical equipment, my team double-checks that every safety-related piece of electrical equipment (including sensors, wiring, connectors, and so on) has passed rigorous tests. Then, over the life of the plant, we ensure the equipment is maintained and operated in a manner that ensures that it will function as expected in an accident.

The diversity and quantity of equipment requires that a team consist of many different skill sets. Electrical engineers confirm that the plant's electrical wiring is updated and functioning well. Mechanical engineers ensure that the plant's environments are suitable for equipment and personnel. Structural engineers make sure the plant is structurally sound and that the equipment is properly protected from accidental damage.

In addition to environmental qualification, a plant must meet hundreds of pages of federal safety regulations. These regulations extend to the employees as well. Every employee of a plant must be extensively trained in operations and safety procedures. Employees must take measures to reduce exposure to radiation, such as wearing protective clothing or gear.

As a nuclear engineer, I also help power plants develop emergency procedures. According to law, every nuclear plant must have evacuation plans. Plants are required to develop an evacuation plan for an area within a ten-mile radius of the plant, and another plan for an area within a fifty-mile radius of the plant. Designing an evacuation plan can be very complex. If a plant is located near a city, or an area where the population does not have access to transportation, we must prove that systems are in place for moving all of those people out of the evacuation zone quickly and safely.

Processing Spent Fuel

I've also designed systems for the safe transportation of any spent nuclear fuel left over from the fission process. Even though a lot of energy is extracted in a reactor, the spent nuclear fuel is still radioactive and will remain so for hundreds of years. Therefore, it must be handled carefully. Power plants store much of their spent fuel in large pools of water on the power plant grounds. But many plants are running out of room for spent fuel and must start considering other storage options.

Currently, the federal government is planning to build a large repository for spent fuel in the Yucca Mountain in Nevada. To get the spent fuel to Yucca Mountain for storage, power plant operators will need to ship it by truck or train. Obviously, if a train or truck carrying radioactive materials were to have an accident, there would be a risk of releasing radioactive materials into the environment. To prevent such an accident, strong casks must be used to ship spent fuel. These casks can withstand high forces without breaking, and I mean very high forces! To test the casks thoroughly, researchers drive trains into them and even drop them from helicopters. Of course, even a very strong cask could break if it experiences high enough forces during a collision. Breakage is unlikely, but just in case, it's necessary to plan routes that will allow vehicles carrying radioactive materials to avoid areas with large populations, agricultural areas, or water supplies as much as possible. This strategy means damage would be minimized in the event of an accident and a cracked cask.

Nuclear power has great potential to help our nation meet its energy needs. But, as with any designed system that involves the use of hazardous materials, nuclear power plants must be maintained and updated continuously to keep them as safe as possible.

What's the Story?

1. What are the benefits of nuclear power plants?

2. List three ways that engineers ensure the safety of nuclear power plants.

Designing with Math and Science

3. What is the difference between a chemical reaction and a nuclear reaction? When coal is burned, is it a chemical reaction or a nuclear reaction?

4. How do the control rods in a nuclear power plant control the rate of the nuclear reaction?

Connecting the Dots

5. How is nuclear power generation similar to power generation at a geothermal power plant? How is it different?

What Do You Think?

6. Conduct library and Internet research and write a paragraph about how and where spent nuclear fuel is stored. Write at least one paragraph describing the controversy surrounding the storage of spent fuel.

7. Dr. Steinman mentions some other applications, aside from generating electrical power, that use nuclear reactions. What are they? Conduct library and Internet research, and write a list of at least five specific technologies.