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How a Nuclear Reactor Works

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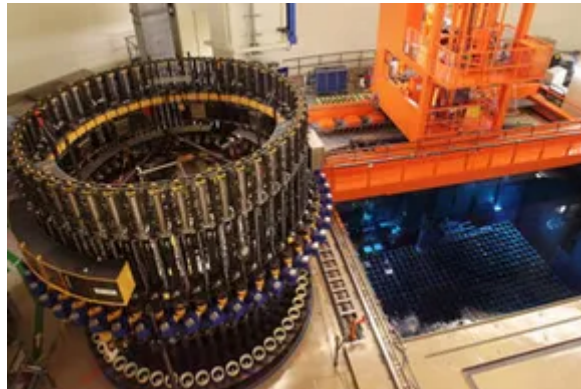


Image Gallery: Inside a Nuclear Power Plant

The fuel assembly storage basin inside the reactor building at the Isar 2 nuclear power plant in Essenbach near Landshut, Germany. See more [pictures inside a nuclear power plant](#).

ALEXANDRA BEIER/GETTY IMAGES

Nuclear reactors have one job: to split [atoms](#) in a controlled reaction and use the released energy to generate [electrical power](#). Over the years, reactors have been viewed as both a miracle and a menace.

When the first U.S. commercial reactor went on line in Shippingport, Pa., in 1956, the technology was hailed as the [energy source of the future](#), one that some believed eventually would make electricity too cheap to meter. Countries around the world built 442 nuclear reactors, and about a quarter of those reactors were built in the United States [source: [Euronuclear.org](#)]. The world has come to depend upon nuclear reactors for 14 percent of its electricity [source: [Nuclear Energy Institute](#)]. In fact, futurists fantasized about having [nuclear-powered automobiles](#) [source: [Ford](#)].

Then, 23 years later, when Unit 2 at the Three Mile Island power plant in

Pennsylvania suffered a cooling malfunction and a partial meltdown of its radioactive fuel, feelings about reactors changed radically. Even though the stricken reactor's containment held and there was no major [radiation](#) release, many people began to see reactors as overly complicated and vulnerable to human and equipment failures, with potentially catastrophic consequences. They also worried about the radioactive waste from reactors. Worse yet, many wondered if government regulators and the nuclear power industry were leveling with the public. As a result, the construction of new nuclear plants stopped in the United States. When a more serious accident occurred at the Soviet Union's Chernobyl nuclear plant in 1986, nuclear power seemed doomed to obsolescence [source: [Union of Concerned Scientists](#)].

But in the early 2000s, nuclear reactors began making a comeback, thanks to rising energy demand, diminishing fossil fuel supplies, and the growing concern about climate change due to carbon dioxide emissions. Late in the decade, the U.S. Nuclear Regulatory Commission began to approve permits for new plants, and President Barack Obama included [nuclear power](#) as a key part of his energy plan.

But then, in March 2011, yet another crisis hit -- this time at the [earthquake](#)-stricken Fukushima Daiichi nuclear power plant in Japan -- raising worries again.

In this article, we'll explain how nuclear reactors work, what happens when they malfunction, and the risks they pose to our health and the [environment](#) compared to other energy sources. We'll also take a look at what technological advances could make the nuclear reactors of the future safer.

But first, let's look at how nuclear fission, the process that actually produces the energy, actually works.

Harnessing a Nuclear Reaction

Put simply, a nuclear reactor splits [atoms](#) and releases the energy that holds their parts together.

If it's been a while since you took high school physics, we'll remind you how **nuclear fission** works: Atoms are like tiny solar systems, with the nucleus where the [sun](#) would be, and electrons orbiting around it. The nucleus is made up of particles called protons and neutrons, which are bound together by something called **strong force**. Perhaps it was named "strong force" because it's almost too powerful for us to imagine -- many, many billions of times stronger than [gravity](#), in fact [source: Bryson]. Despite the strength of strong force, it's possible to split a nucleus -- by shooting neutrons at it. When that's done, a whole lot of energy is released. When atoms split, their particles smash into nearby atoms, splitting those as well in a chain reaction. (Think a multi-car crash on the freeway.)

Uranium, an element with really big atoms, is perfect for atom splitting because its strong force, though powerful, is relatively weak compared to other elements. Nuclear reactors use a particular isotope called **uranium-235** [source: [Union of Concerned Scientists](#)]. Uranium-235 is rare in nature; the ore from uranium mines only contains about 0.7 percent uranium-235. That's why reactors use **enriched uranium**, which is created by separating out and concentrating the uranium-235 through a gas diffusion process [source: [NRC](#)].

This process is what gives an [atomic bomb](#), like the ones that were dropped on Hiroshima and Nagasaki, Japan, during World War II, such terrible power. But in a nuclear reactor, the chain reaction is controlled by inserting control rods made of a material like cadmium, hafnium or boron, which absorb some of the neutrons [source: [World Nuclear Association](#)]. That still allows the fission process to give off enough energy to heat [water](#) to a temperature of about 520 degrees Fahrenheit (271 degrees Celsius) and turn it into steam, which is used to turn turbines and generate [electricity](#) [source: [Union of Concerned Scientists](#)]. Basically, a nuke plant works like a coal-powered electrical plant, except that the energy to boil water comes from splitting atoms instead of burning carbon [source: [Nuclear Regulatory Commission](#)].

In the next section, we'll talk about the different types of reactors and how their key parts work.

Which countries depend upon nuclear power the most?

The United States gets about 20 percent of its electricity from nuclear reactors, but other countries rely more heavily upon them. Here's a list of countries and nuclear power percentages:

Lithuania -- 76.2 percent

France -- 75.2 percent

Slovakia -- 53.5 percent

Belgium -- 51.7 percent

Ukraine -- 48.6 percent

Armenia -- 45.0 percent

Hungary -- 43.0 percent

Switzerland -- 39.5 percent

Slovenia -- 37.8 percent

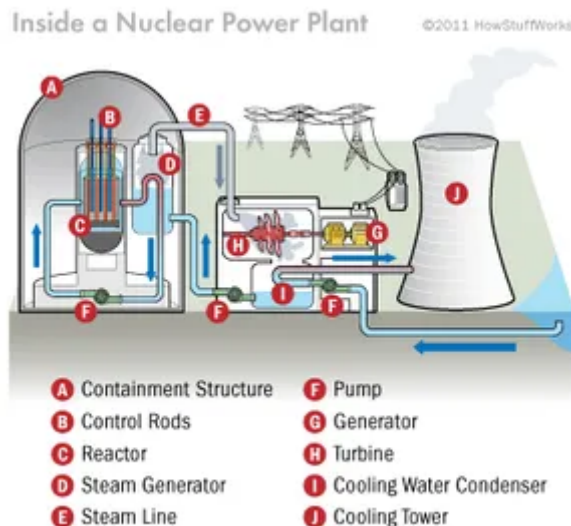
Sweden -- 37.4 percent

Bulgaria -- 35.9 percent

S. Korea -- 34.8 percent

[source: [Nuclear Energy Institute](#)]

Nuclear Reactor Components



This diagram shows all the parts of a nuclear reactor.

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There are several different types of [nuclear reactors](#), but they all have some common characteristics. All of them have a supply of radioactive fuel pellets -- usually uranium oxide, which are arranged in tubes to form fuel rods in the **reactor core** [source: [World Nuclear Association](#)].

The reactor also has the previously mentioned **control rods** -- made of neutron-absorbing material such as cadmium, hafnium or boron -- which are inserted into the core to control or halt the reaction [source: [World Nuclear Association](#)].

A reactor also has a **moderator**, a substance that slows the neutrons and helps control the fission process. Most reactors in the United States use ordinary water, but reactors in other countries sometimes use graphite, or **heavy water**, in which the hydrogen has been replaced with deuterium, an isotope of hydrogen with one proton and one neutron [source: [World Nuclear Association](#), [Federation of American Scientists](#)]. Another important part of the system is a **coolant** -- again, usually ordinary water-- which absorbs and transmits heat from the reactor to create steam for turning the turbines and cools the reactor core so that it doesn't reach the temperature at which uranium melts (about 6,900 degrees Fahrenheit, or

3,815 degrees Celsius) [source: [World Nuclear Association](#)]. (We'll explain why a meltdown is a very bad thing later in this article.)

Finally, a reactor is encased in a **containment**, a big, heavy structure, typically several feet thick and made of steel and **concrete**, that keeps radioactive gases and liquids inside, where they can't hurt anyone [source: [World Nuclear Association](#)].

There are a number of different reactor designs in use, but in the United States, about two-thirds of the reactors are **pressurized water reactors** (PWRs). In a pressurized water reactor, the water is pumped into contact with the core and then kept under pressure, so that it can't turn into steam. That pressurized water then is brought into contact with a second supply of unpressurized water, which is what turns to steam to turn the turbines. The remaining third of reactors in the United States are **boiling water reactors** (BWRs). With BWRs, the water that comes directly into contact with the reactor core is allowed to become steam for generating **electricity** [source: [World Nuclear Association](#)].

In the next section, we'll look at the potential risks nuclear reactors pose, and how to evaluate them.

How Safe Is a Nuclear Reactor?

The answer to that question is pretty complicated, and it depends who you ask and how you define "safe." Are you concerned about **radiation** routinely leaking from plants or about the radioactive waste generated by **reactors**? Or, are you more worried about the possibility of a catastrophic accident? What degree of risk do you consider an acceptable trade-off for nuclear power's benefits? And to what extent do you trust the government and the nuclear power industry to keep things safe and provide accurate information to the public?

"Radiation" is a loaded word, mostly because we all know that big doses of radiation -- from a **nuclear bomb** blast, for example -- can kill scores of people or make them horribly ill.

Advocates of nuclear power, however, point out that we all routinely are exposed to radiation from a variety of sources, including cosmic rays and radiation naturally emitted by the [Earth](#) itself. The average annual exposure to radiation is about 6.2 millisieverts (mSv), half of it from natural sources and half from man-made sources, ranging from chest X-rays to smoke detectors and luminous watch dials [source: [Nuclear Regulatory Commission](#)]. How much do we get from nuclear reactors? A tiny fraction of a percent of our typical annual exposure -- 0.0001 mSv [source: [Nuclear Regulatory Commission](#)].

While all nuclear plants inevitably leak small amounts of radiation, in the United States, regulators hold operators to a stringent standard. They can't expose people living around the plant to more than 1 mSv of radiation per year, and workers in the plant have a threshold of 50 mSv per year. That may sound like a lot, but according to the Nuclear Regulatory Commission, there's no medical evidence to show that annual radiation doses below 100 mSv pose any health risks [source: [Nuclear Regulatory Commission](#)].

But it's important to mention that not everybody agrees with that assessment of radiation risks. For example, Physicians for Social Responsibility, a longtime critic of the nuclear industry, cites a 2009 study of children living around German [nuclear power](#) plants. The study found that those living within 3.1 miles (5 kilometers) of the plants had twice the risk of contracting leukemia as those living farther away [source: Physicians for Social Responsibility].

There's also the problem of radioactive waste generated by reactors. We'll cover that challenge on the next page.

How is radiation measured?

The unit for quantifying radiation dose is a **Sievert** (Sv). It's the ratio of radiation energy (joules) to total body mass exposed (kilograms). A Sievert is a lot of radiation -- an instantaneous dose of 1 to 3 Sv could cause you

severe nausea and cripple your immune system, and 10 Sv all at once could kill you. Normally, people are exposed to much smaller doses, which are measured in **millisieverts** (mSv) that amount to 0.001 of a Sievert. The average person is exposed to about 6.2 mSv annually from natural and manmade sources [source: [National Institutes of Health](#)].

Nuclear Reactor Waste



This man is testing radioactive waste at a nuclear power plant.

STEVE ALLEN/BRAND X
PICTURES/GETTY IMAGES

Nuclear power is touted by supporters as "clean" energy because it doesn't put large amounts of **greenhouse gases** into the atmosphere, the way coal-burning power plants do. But critics point to another environmental problem: disposing of nuclear waste. Some of the waste is spent fuel from reactors, which continues to give off radioactivity. Another waste material that must be stored is high-level radioactive waste (HLW), a liquid residue that's left over when spent fuel is reprocessed to remove and recycle whatever usable uranium remains in it. Right now, most of this waste is stored onsite at nuclear power plants, in pools of water that absorb some of the leftover heat generated by the spent fuel and help to shield workers from **radiation** exposure [source: [Environmental Protection Agency](#)].

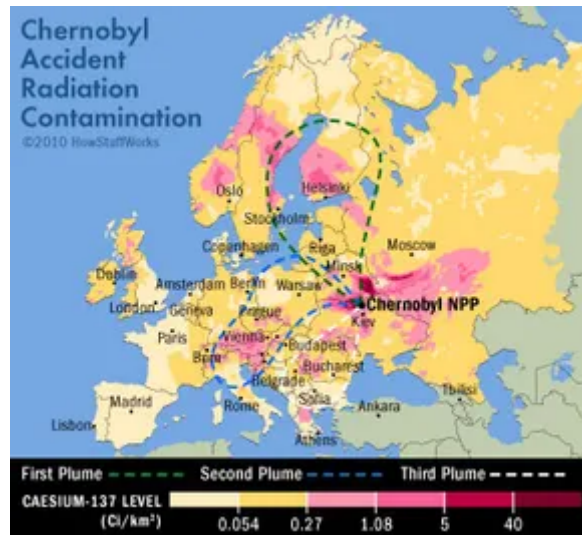
One problem with spent nuclear fuel is that it's been changed by the fission process. When big uranium atoms are split, they create byproducts -- radioactive isotopes of several lighter elements, such as cesium-137 and strontium-90, called **fission products**. They're hot and very radioactive, but eventually, over a 30-year period, they decay into less dangerous forms. That period is called the **half-life**. Additionally, some uranium atoms also capture neutrons and form heavier elements, such as plutonium. These transuranic elements don't generate as much heat or penetrating radiation as fission products, but they take a lot longer to decay. Plutonium-239, for example, has a half-life of 24,000 years [source: [Nuclear Regulatory Commission](#)].

This **high-level radioactive waste** from reactors is dangerous to humans and other life because it can give off a huge, fatal dose of radiation from even a short exposure. A decade after a fuel assembly is removed from a reactor, for example, it gives off 200 times as much radioactivity in an hour as it takes to kill a person. And if the waste gets into groundwater or rivers, it could enter the food chain and endanger large numbers of people [source: [Nuclear Regulatory Commission](#)].

Because the waste is so dangerous, many people are uneasy about having 60,000 tons of it sitting at nuclear plants close to major cities. But finding a safe place to store it hasn't been easy. For decades, the U.S. federal government, for example, has been studying the possibility of storing it inside Yucca Mountain in Nevada, 90 miles (144.8 kilometers) outside of Las Vegas. Despite strong local objections, Congress approved the project in 2004. But in 2009, Obama Administration Energy Secretary Steven Chu announced that the plan was being shelved, and that waste will be stored at local plants until the government finds another solution [source: [Hebert](#)].

Radioactive waste is what concerns people most about nuclear reactors -- that is, beyond the obvious and more frightening possible scenario: a reactor breakdown that triggers potentially catastrophic consequences. We'll discuss that type of scenario on the next page.

What Can Go Wrong With a Nuclear Reactor?



A diagram of radiation contamination after the Chernobyl disaster.

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With government regulators looking over their shoulders, engineers have spent a lot of time over the years designing reactors for optimal safety -- not just so they work properly, but so there are backup safety measures in place when something breaks down. As a result, year in and year out, nuclear plants seem pretty safe compared to, say, air travel, which routinely kills anywhere from 500 to 1,100 people annually worldwide [source: [Daily Mail](#)].

Nevertheless, nuclear reactors have suffered major breakdowns. On the International Nuclear Event Scale (INES), which rates accidents on an escalating scale of 1 to 7, there have been five accidents since 1957 that rated between 5 and 7 [source: [International Atomic Energy Agency](#)].

The worst nightmare is a breakdown of the cooling system, which would allow the fuel to overheat and experience a meltdown. With a **meltdown**, the fuel turns to liquid and then burns through the containment vessel, spewing **radiation** far and wide. In 1979, Three Mile Island's Unit 2 came perilously close to this scenario, with the core partially melting down and flowing to the floor of the containment vessel. Fortunately, as scientists later discovered by lowering a camera into the unit, the

well-designed containment was strong enough to stop the radiation from getting out [source: [Smithsonian](#)].

The Soviets had worse luck. The worst nuclear accident in history was the April 1986 catastrophe at Unit 4 of the Chernobyl nuclear plant in the then-USSR, which was caused by a combination of system breakdowns, design flaws and badly trained personnel. During a routine test, the reactor suddenly surged, and the control rods jammed, preventing an emergency shutdown. The sudden buildup of steam caused two explosions, exposing the reactor's graphite moderator to air and setting it on fire. With nothing to cool them, the reactor's fuel rods then overheated and suffered a full meltdown, in which the fuel turned to liquid form [source: [World Nuclear Association](#)]. Thirty plant workers were killed. Unlike the plant at Three Mile Island, Chernobyl's stricken reactor apparently lacked a sturdy containment vessel, and large amounts of radiation spewed out over an area of 125,000 square miles (323,749 square kilometers). The number of deaths caused by radiation-related illnesses is still unclear, but a 2006 World Health Organization study estimated that it may have caused 9,000 [cancer](#) deaths [source: [World Health Organization](#)].

In the next section, we'll look at how the crisis at the Fukushima Daiichi nuclear plant in Japan compares to past accidents, and how nuclear catastrophes are averted.

Fukushima Daiichi Nuclear Plant Crisis



Concerns about radiation exposure swept through Japan and around the world after a March 2011 earthquake and tsunami crippled the Fukushima Daiichi

nuclear plant.

JEREMY SUTTON-HIBBERT/GETTY

IMAGES

Nuclear reactor designers build safeguards based on a **probabilistic assessment**, in which they try to balance the potential harm from an event with the likelihood of it actually occurring [source: [Nuclear Regulatory Commission](#)]. But some critics say they should be preparing, instead, for the rarest, most unlikely but highest-impact events -- what philosopher Nassim Nicholas Taleb calls "black swan" events [source: [Gold](#)].

Case in point: The [March 2011 crisis](#) at the Fukushima Daiichi nuclear plant in Japan. The plant reportedly was designed to withstand a major earthquake, but not a disaster as big as the 9.0 quake that sent 46-foot-high (14-meter) tsunami waves crashing over seawalls designed to withstand 18-foot (5.4-meter) waves [source: [Swinford, Fisher](#)]. The [tsunami](#) onslaught destroyed the diesel backup generators that were in place to power the cooling systems for the plant's six reactors, in the event [electricity](#) was cut off. Thus, even after the Fukushima reactors' control rods shut down the fission reactions, the still-hot fuel caused the temperature to rise dangerously inside the stricken reactors [source: [Nosowitz](#)].

Japanese officials resorted to an extreme measure: flooding the reactors with massive amounts of seawater laced with boric acid, which might stave off meltdowns, but would destroy the reactor equipment in the process [source: [Nosowitz](#)]. Eventually, with the help of fire trucks and U.S. Navy barges, the Japanese were able to pump freshwater into the reactors [source: [Nuclearstreet.com](#)]. But by then, the reactor buildings and containments had suffered extensive damage, and monitoring already showed alarming levels of radiation in the surrounding land and water. In one village 25 miles (40.2 kilometers) from the plant, cesium-137, a radioactive element, was measured at levels much higher than the standard the Soviets used as a gauge in recommending abandoning land around Chernobyl, presenting the prospect that the area might become permanently uninhabitable [source: [Wald](#)].

While the Japanese disaster has triggered public qualms about U.S. nuclear power, William Levis, CEO of nuclear operator PSEG Power, told Congress in March 2011 that U.S. plants could withstand a similar event here. Levis said that U.S. utility companies spent \$6.5 billion in 2009 alone to replace old equipment and improve precautions, and that plants are prepared for extreme events ranging from fires and explosions to loss of cooling pumps and multiple safety system failures. He also said nuclear plant operators were reassessing plants' vulnerability to massive earthquakes and might add more protective measures [source: [PR Newswire](#)].

Lots More Information

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- [Union of Concerned Scientists: Nuclear Power](#)

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