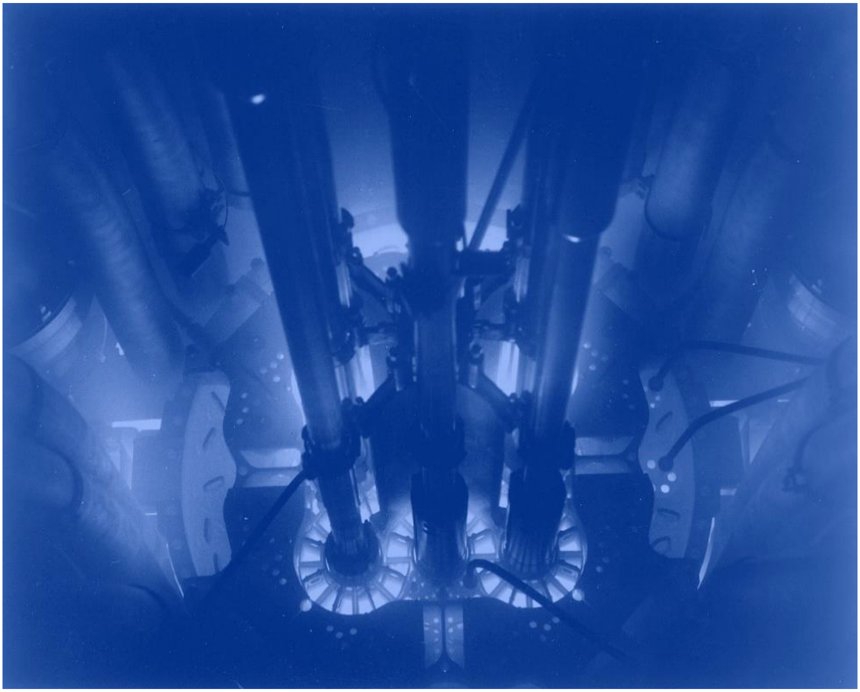

Why Expanding Nuclear Power is Not a Wise Choice

JAMES MICHAEL SNEAD, P.E.

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Preface

Public attention has turned to energy sources that can replace fossil fuels. Proponents of nuclear energy argue that it can be safely scaled up to replace fossil fuels. This white paper examines this argument and explains why it would not be wise to rely upon nuclear fission energy to replace fossil fuels.

I have been examining how to replace fossil fuels with sustainable energy for more than a decade. My eBook *Astroelectricity* explains why only space-based sustainable energy can practically replace fossil fuels. This white paper is an expansion of the topic of nuclear energy addressed in the book.

While I am an engineer, I am not a nuclear engineer. Readers are urged to seek confirmation of my conclusions on why expanding nuclear fission energy to replace fossil fuels is not a wise solution.

James Michael Snead, P.E.

Contents

Amid America's growing public acknowledgement of the need to transition from fossil fuels to sustainable energy, the debate is now turning to what forms of sustainable energy can effectively and safely replace fossil fuels. Nuclear energy is one option being promoted. This white paper explains nuclear energy and why this is not yet a practical solution to scale-up to replace fossil fuels.

1. How many 1-GW nuclear power plants will be necessary to replace fossil fuels?

Since fusion energy is not yet commercialized, this leaves nuclear fission as the only nuclear technology available to replace fossil fuels. How many nuclear power plants would be needed?

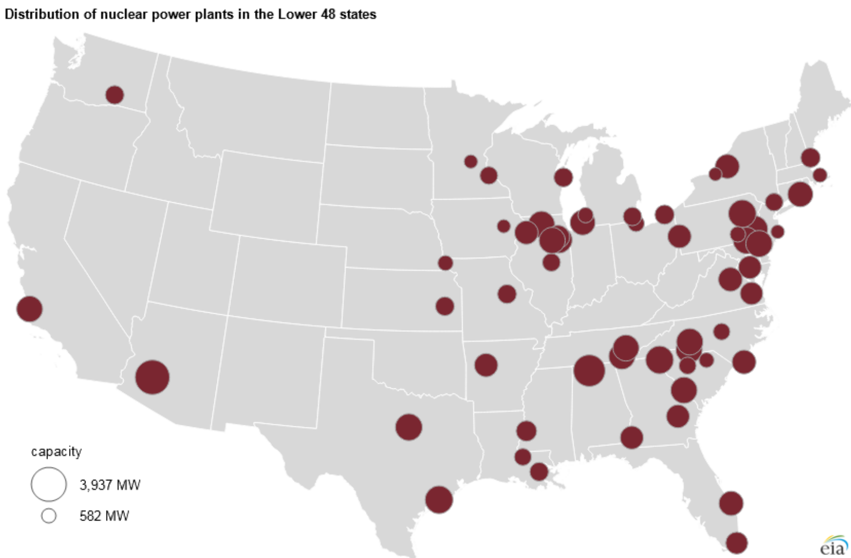


Figure 1: Distribution and capacity of nuclear power facilities in the contiguous United States. (Credit: U.S. Energy Information Administration.)

Figure 1 shows the distribution and total facility capacity of nuclear power plants in the contiguous United States. In total, the

United States has 99 commercial reactors with a combined power output of just over 100 gigawatts (GW). (1 GW = 1000 MW = 1,000,000 kW = 1,000,000,000 watts.) The locations of these power plants are driven by the population distribution, available cooling water, and various safety factors such as the likelihood of earthquakes. Note that few are in the western United States where most population growth is occurring.

In a separate analysis, the author has estimated that a 1-GW nuclear power plant could supply the total energy needs of about 100,000 Americans in the year 2100. This equals ten kilowatts of continuous electrical power per person to meet all energy needs. This estimate includes some key technology advances, such as hydrogen electrolyzer efficiency improvement, and a modest decline in the average energy needed per year per American.

By 2100, the expected U.S. population will be 500 million—about a 50 percent increase from today primarily due to net international migration to the United States. Today, fossil fuels provide about 80 percent of the total energy consumed in America. Thus, a simplistic estimate is that by 2100, the energy needs of 400 million Americans would need to be met by nuclear fission energy. This will require roughly 4,000 GW of continuous nuclear generating capacity.

$$80\% \times 500 \text{ million} = 400 \text{ million}$$

$$\frac{400 \text{ million}}{100{,}000 \ \frac{\text{Americans}}{\text{GW}}} = 4{,}000 \text{ GW}$$

A new nuclear power plant is expected to operate 95 percent of the year. The 5 percent downtime is used for maintenance and refueling. Thus, to provide 4,000 GW of continuous nuclear electrical power, 4,210 1-GW nuclear plants would be needed by 2100.

$$\frac{4{,}000 \text{ GW}}{0.95} = 4{,}210 \text{ 1–GW nuclear plants}$$

This is what is required to replace fossil fuels with nuclear fission just in the United States. The world will require roughly 10 times this number. Is this a wise choice to replace fossil fuels?

2. What is nuclear fission energy?

Nuclear fission energy is a human-created means of extracting useful thermal energy from the fissioning of certain radioisotopes, such as one uranium isotope. A nuclear power plant, such as shown in Figure 2 and Figure 3, is used to produce the thermal energy and convert this heat into electrical power.

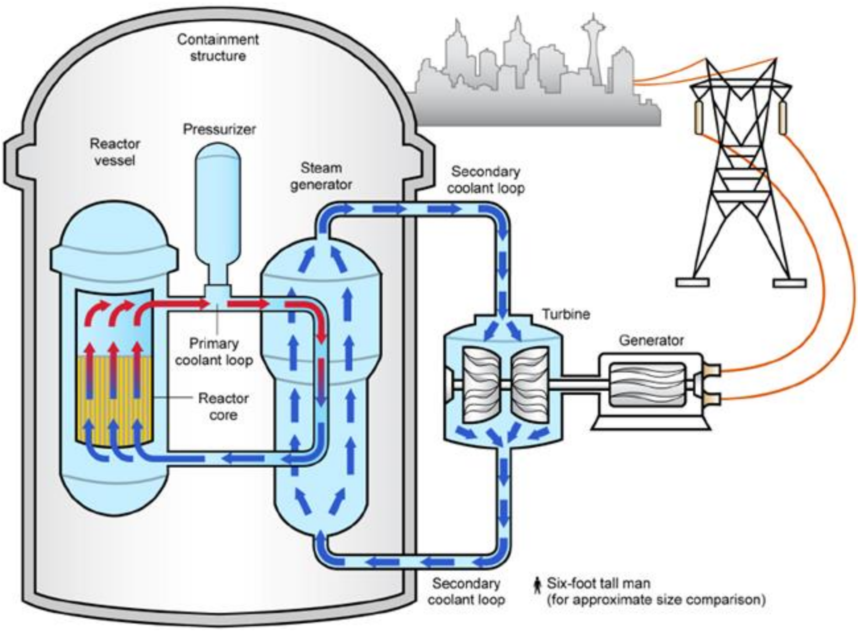


Figure 2: Diagram of one type of a nuclear power plant. Nuclear reactions within the nuclear reactor (left) produce hot water (red arrows). This hot water circulates to the steam generator where a second water loop (blue arrows) boils to produce the steam driving the turbine generator. A third water loop, not shown, disposes waste heat to the local environment. (Credit: U.S. General Accounting Organization, U.S. Government Work.)

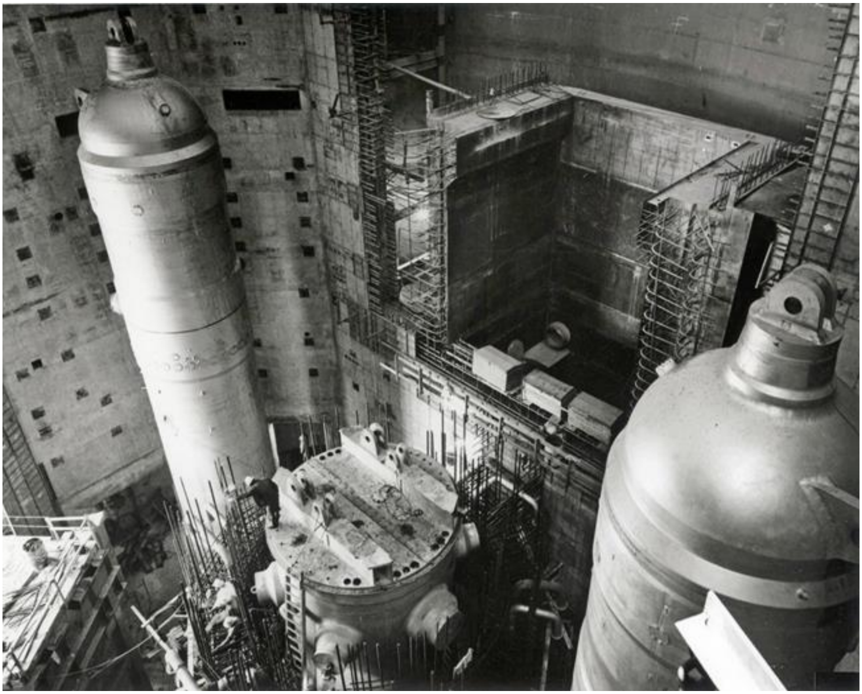


Figure 3: View inside the concrete containment structure of an early nuclear power plant being built in 1973. The nuclear reactor is the flat-top cylindrical object in the center. It will be surrounded by a cement housing. The tall cylinders contain the steam generators that transfer heat from water circulating through the reactor core to a second water loop that boils water to generate steam to drive the turbine generators. The rectangular "room" to the upper right will be the water pool holding new and spent fuel assemblies. (Credit: U.S. Government work.)

3. Why is nuclear fission energy considered a sustainable energy source?

With a sustainable supply of nuclear fuel, nuclear fission energy can produce electrical power indefinitely. Since no combustion of fossil fuels is used, this energy source does not emit carbon dioxide (CO_2) into the atmosphere. While the lack of any CO_2 emissions is an important environmental benefit, nuclear fission energy has drawbacks that need to be understood.

4. How does nuclear fission energy work?

Figure 4: Visible blue light, called Cherenkov radiation, emitted inside a water-cooled nuclear reactor due to high-energy charged particles, created by nuclear reactions, interacting with the cooling water in the reactor. (Original image source: U.S. Government work. Credit: J. M. Snead.)

Our civilization operates on the conversion of one form of energy into another. In the process, electricity is generated or mechanical power is produced. For example, the potential energy of the water stored in the reservoir behind a dam is converted, first, into kinetic energy (speed) of the water entering the turbine; then, into mechanical power of the turbine turning the electrical generator; and, finally, into, electrical power. Another example is the conversion by plants of sunlight into the chemical bonds of the complex carbon molecules forming the plants. This is how plants grow. Releasing this stored chemical energy as thermal energy involves decomposition or combustion to break the bonds. This thermal energy, perhaps from coal, can be used to generate electricity.

Up until the start of the nuclear age in the 1940s, all energy humans used came originally from natural sources—mostly from the nuclear reactions in the Sun. In these solar nuclear reactions, energy is created from matter. Now, humans can also create energy from matter. This is called nuclear energy. (See Figure 4.)

Human-engineered nuclear energy comes in two forms.

Nuclear fusion energy, once research is successful, will use intense temperature and pressures to mimic the fusion of hydrogen or helium atoms as happens in stars. During this fusion event, useful energy is liberated as a very tiny portion of the mass of the fused atoms converts into energy using Einstein's famous relationship of $E=½mv^2$.

The current commercial form of nuclear energy comes from the fissioning of certain elements. As the nucleus of the atom breaks apart—what is called nuclear fission—heat is created. The heat is used to boil water to produce steam to drive electric generators.

— *Isotopes*

From high school chemistry, recall that each different element has a different number of protons and a matching number of electrons. Carbon, for example, has six protons and six electrons. The number of protons is assigned the letter "*Z*" called the atomic number. Thus, for carbon, Z = 6. The atomic number is used to order the elements in the Periodic Table we saw in high school chemistry class.

With the lone exception of one type of hydrogen which has only a single proton as the nucleus, all other types of nuclei contain protons and neutrons. While the number of protons for an element is fixed, the number of neutrons in the nucleus is not fixed. For example, the element carbon can have fifteen different numbers of neutrons. Each different number of neutrons is called an isotope of the element. Thus, carbon has fifteen known isotopes. The letter "*N*" is assigned to the number of neutrons.

Figure 5 below plots the known isotopes of all elements as a function of the *Z* and *N* values. Each dot in the plot represents a different known isotope—a unique number of protons and neutrons. The atomic (proton) number, *Z*, is plotted on the horizontal axis. The neutron number, *N*, is plotted on the vertical axis.

The dots are color coded. If the isotope is stable—meaning that it will exist for all remaining time—it is represented as a black dot. All other isotopes are unstable and are represented by colors. These are called radioisotopes. They will undergo a spontaneous natural nuclear reaction called radioactive decay. In the plot, the color of the dot corresponds to the half-life of this decay rate. The color code is shown on the scale to the right of the plot. Only a portion of the known isotopes occur in nature. Many are artificially created in high-energy nuclear physics experiments.

A radioisotope's half-life is the amount of time that, for example, 100 atoms of the isotope will decay by one-half to only 50 atoms. Most radioisotopes have very short half-lives. The half-life of each isotope is defined by nature.

Since stable isotopes do not undergo radioactive decay, these are not possible sources of nuclear energy. Conventional fission nuclear energy makes use of only those isotopes where the nucleus can be prompted to fission.

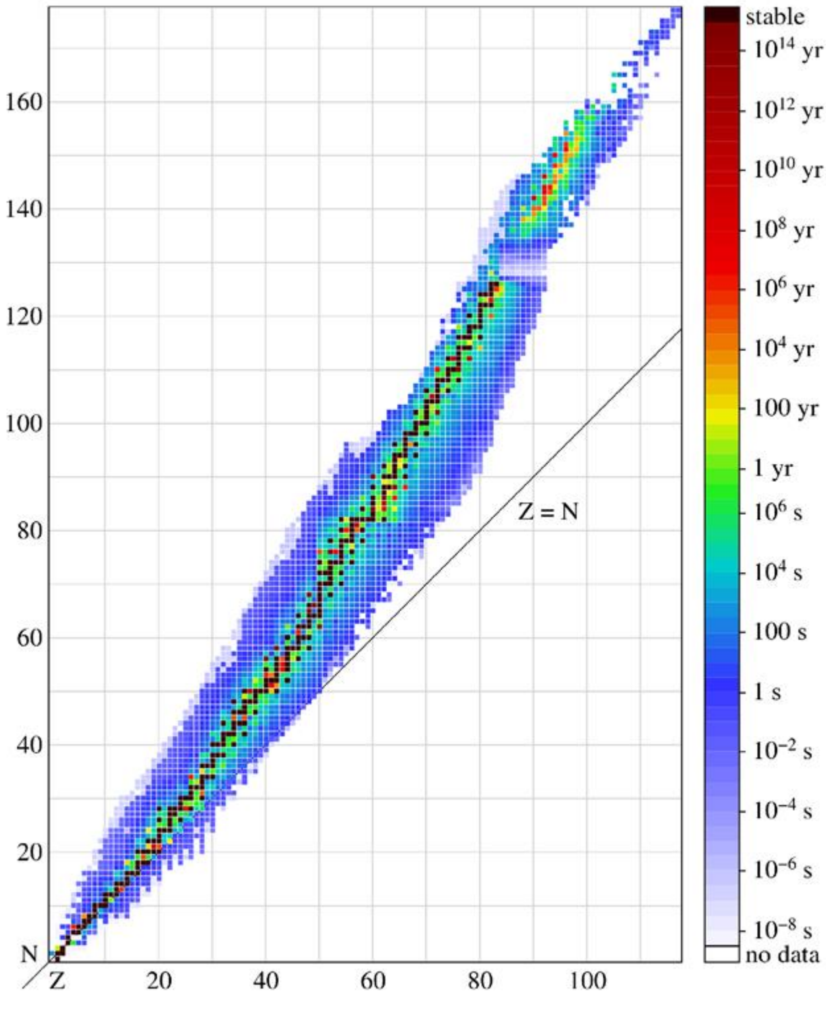


Figure 5: Plot of the number of protons (horizontal axis) vs. the number of neutrons (vertical axis) of all isotopes. (Credit: BenRG, Wikimedia Commons, public domain.)

Of all elements present in nature, only one natural element and one isotope of that element exists on the Earth in quantities sufficient to be used as fuel for commercial nuclear fission energy. This is the element uranium (U) and the U-235 isotope. The number "235" is the total number of protons and neutrons, also called the mass number. Uranium has 92 protons ($Z = 92$). Thus, U-235 has 235–92=143 neutrons.

— *Uranium fission*

Uranium, like many elements, is the product of stellar death. Only when certain types of stars undergo a supernova is uranium created. As the supernova event unfolds, the uranium atoms are cast out literally as stardust to migrate around a galaxy until the formation of a new star pulls it into the star's accretion disk from which new planets are formed. Through this mechanism of cosmic element creation and dispersion, uranium was present as the Earth was formed. It is found throughout the Earth's crust, oceans, and core.

There are two prevalent natural uranium isotopes—U-235 and U-238—both of which are radioisotopes. (See Figure 6.) The thermal energy created in the Earth's core from their decay is a major source of heat keeping the core molten and the Earth habitable. In the Earth's crust, uranium is widely dispersed at very small concentrations. The granite used for kitchen countertops, for example, contains uranium undergoing natural decay but at an extremely slow rate. We live all the time with very low levels of natural radioactivity.

Figure 6: Pieces of uranium metal enriched to 93 percent U-235—sufficiently enriched for use in a nuclear weapon. (Credit: U.S. Government work.)

As mentioned previously, a radioisotope's half-life is the time required for one-half of the atoms to undergo decay. U-235's half-life is 713 million years. If 100 U-235 atoms are placed in a container, on average 50 these would have decayed in about 713 million years—another 25 in another 713 million years and so on until all have disappeared.

When a U-235 atom naturally decays, it is not a single decay event. It starts a sequence of spontaneous nuclear reactions with up to 11 different radioisotopes being sequentially created until, finally, a stable lead atom is created about 33,000 years later.

Not every U-235 decay event is the same. Occasionally, a U-235 nucleus decays in a manner where the nucleus splits—fissions—to form two atoms of two different elements. With a 713 million-year half-life, the rate at which U-235 naturally fissions is very, very slow. However, through nuclear engineering, this can be sped up using a controlled chain reaction created in a nuclear reactor.

— *Engineered nuclear energy*

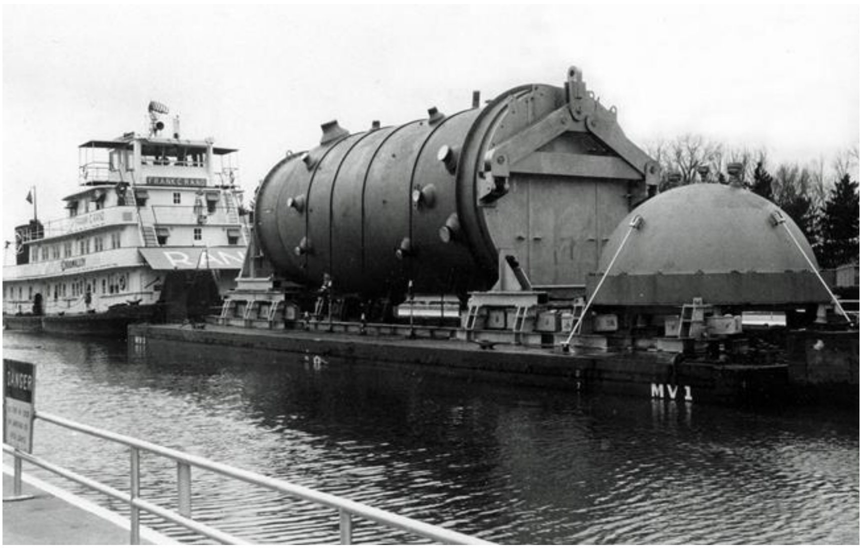


Figure 7: The steel reactor shell of a large commercial reactor being transported to the construction site. (Credit: U.S. Government work.)

Engineered nuclear energy is released by creating a nuclear reaction within a nuclear reactor. (See Figure 7.) The nuclear energy released in the reactor comes primarily from U-235 contained in small fuel pellets housed within fuel rods. Assemblies of these fuel rods are spaced within the reactor to enable the rods to be surrounded by water. (See Figure 8.) Control rods made of elements whose nuclei readily absorb free neutrons but do not fission are located between these fuel assemblies. These rods are used to regulate the number of free neutrons active within the reactor.

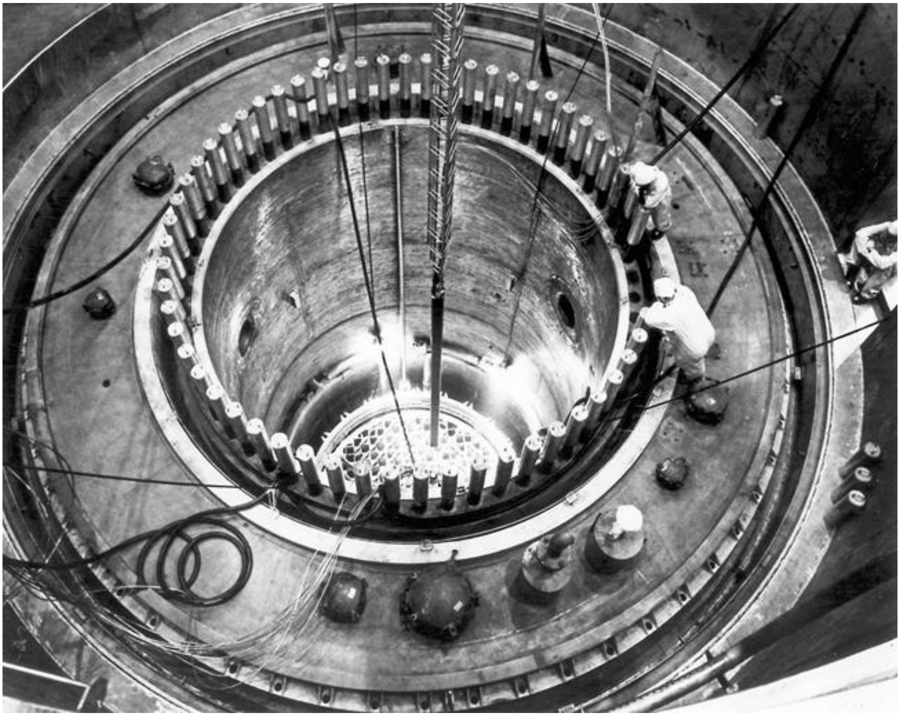


Figure 8: Looking down on top of an open reactor, a fuel rod assembly is being lowered into the reactor. The reactor will be filled with water when it is closed. (Credit: U.S. Government work.)

Nature abhors a free neutron meaning that a free neutron is almost always quickly absorbed—referred to as being captured—within the nucleus of another atom. When a free neutron is captured, one of two events will happen. For most elements and their isotopes, the capture of a free neutron simply increases the element's mass number by one. In a few radioisotopes, the capture of a free neutron can prompt the nucleus to fission.

Recall that U-235 may naturally fission when the nucleus decays. Scientists discovered that the U-235 nucleus can be prompted to fission by bombarding it with free neutrons. When a free neutron is captured, in most cases the U-235 nucleus will fission into two parts with each part becoming the nuclei of a different element. Also, as the nucleus fissions, 2 or 3 of the neutrons in the nucleus become unneeded in the two new nuclei and are released as free neutrons. These free neutrons are then able to create more U-235 fission reactions releasing more neutrons. In this manner, a chain reaction begins and, in a nuclear reactor, continues until the control rods are inserted to absorb the neutrons or the U-235 concentration in the fuel pellets falls below a level that will no longer sustain a chain reaction.

When the U-235 nucleus fissions, a very small amount of mass in the nucleus becomes excess and nature converts this into what is called nuclear energy. Most of this nuclear energy is in the form of the kinetic energy—speed—of the new nuclei and the free neutrons. As the new nuclei form, they are trapped within the fuel pellets containing the U-235, so their kinetic energy becomes heat. This heat increases the temperature of the fuel pellets which, then, heat the surrounding water.

The free neutrons, because of their small size and high kinetic energy, easily pass out of the fuel pellets into the water. These speedy neutrons will usually not be captured by a nucleus until their speed drops almost to zero. Thus, as the free neutrons collide with water molecules, these collisions heat the water as the neutrons are slowed. Through careful design of the reactor, by the time the “moderated” free neutrons reach another fuel pellet containing U-235, their speed has fallen sufficiently to be absorbed, enabling a chain reaction to continue.

Due to the energy released by these nuclear reactions, the temperature of the water in the reactor climbs above the water’s normal atmospheric boiling temperature. However, because the reactor is sealed and the water is pressurized, the heated water does not boil. Instead, the heated water is pumped out of the reactor core to pass through a steam generator where water in a second loop becomes the steam used to drive the turbine generators. The now cooler water from the reactor circulates back into the reactor core to prevent the escape of any possible radioactive contamination. (See Figure 9.)

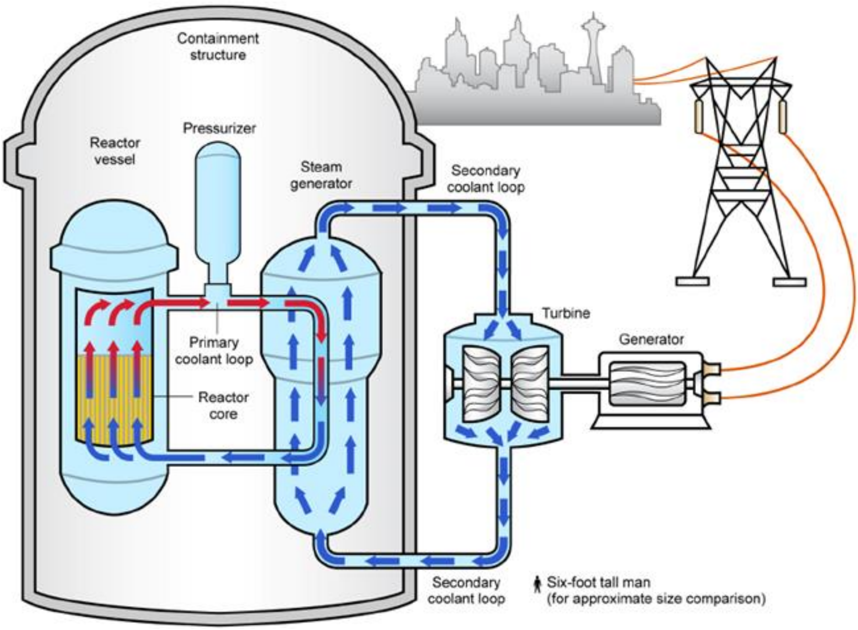


Figure 9: Diagram of one type of a nuclear power plant. Nuclear reactions within the nuclear vessel (left) produce hot water (red arrows). This hot water circulates to the steam generator where a second water loop (blue arrows) boils to produce the steam driving the turbine generator. A third water loop, not shown, disposes waste heat to the local environment. (Credit: U.S. General Accounting Organization, U.S. Government Work.)

Once the nuclear energy is transferred as heat to the water in the reactor core, the nuclear plant operates like any thermal power plant.

This is how a nuclear power plant creates electricity without using a carbon fuel such as coal and emitting carbon dioxide.

5. How is U-235 used in commercial reactors?

While uranium has six isotopes—all unstable—almost all natural uranium is made up mostly of U-238 (99.274 percent) with only a tiny percentage being the useful U-235 (0.72 percent). While U-238 is a radioisotope with a 4.5 billion-year half-life, it cannot be used to sustain a chain reaction.

For a commercial U-235 reactor of the design used in the United States to sustain a chain reaction, the concentration of the U-235 in the fuel pellets must be increased from 0.72 percent to 3–5 percent. Complex uranium enrichment facilities are used to concentrate the percentage of U-235 in the natural ore to that needed for the reactor fuel.

When this enrichment was initially done during the Manhattan Project, this was done by turning the uranium into a chemical compound that became a gas. Under pressure, the gas was forced through special filters. With the nucleus of the U-235 atom being very slightly smaller, the U-235 migrated through the filters slightly faster than the U-238. This enabled the U-235 concentration is slowly increase as it passed through thousands of filters.

Today, the typical concentration method is to use centrifuges. As the gas is spun in the centrifuge, the U-238, being slightly heavier, tends to move to the outside where it can be removed. Using banks of centrifuges, the U-238 concentration can be reduced until the desired U-235 concentration is achieved. The U-238 becomes a waste product known as depleted uranium.

The only difference between reactor-grade and weapon-grade U-235 is the U-235 concentration. Thus, the same enrichment plant used to produce reactor fuel can also be used to produce highly-enriched U-235 for nuclear weapons. (See Figure 6.) Therefore, uranium enrichment which is necessary for creating reactor fuel can enable nuclear weapon proliferation.

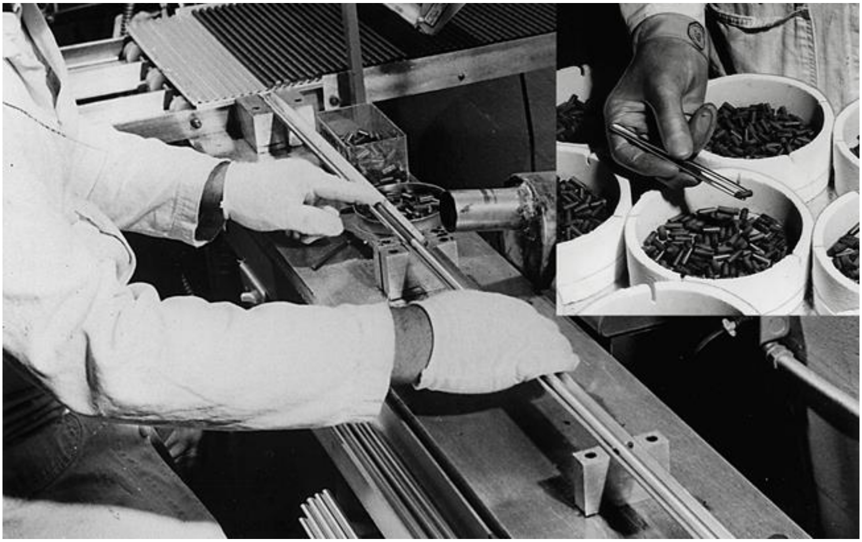


Figure 10: Fuel pellets being loaded into a fuel rod. (Credit: U.S. Government work.)

The concentrated U-235 reactor fuel is formed into small cylindrical pellets that are inserted into hollow tubes called fuel rods. (See Figure 10.) Assemblies of these fuel rods are placed inside the reactor core submerged in the moderating water. Over several years of operation, the U-235 concentration is reduced by the fissioning of the U-235 atoms. Periodically, the reactor is shut down and spent fuel assemblies are removed and replaced with new assemblies. Although called "spent", these fuel rods are still quite radioactive and require special handling, storage, and disposal. In addition to any remaining U-235, the spent fuel rods contain other highly dangerous radioisotopes created by the nuclear reactions taking place as the reactor operates. These spent rods must eventually be placed into permanent geological storage.

6. How much natural uranium fuel is needed?

While nuclear power plants do not use fossil fuels directly, they do require uranium which is a non-renewable fuel source. Thus, the practicality of using natural uranium-fueled nuclear fission to replace fossil fuels depends on the size of the remaining U.S. endowment of natural uranium.

For this discussion, a nuclear power plant is assumed to generate 1 billion watts or 1 gigawatt (GW) of electrical power. A new nuclear power plant will be able to operate continuously until periodically shutdown for refueling and maintenance. On average, this plant may be expected to produce 1 GW of baseload electrical power 95 percent of the year—about 347 days a year or 8,322 hours per year. The total amount of energy produced is simply the product of the output multiplied by the length of time. Thus, a 1 GW plant would produce 8,322 GW-hours of electrical energy each year.

In 2016, the World Nuclear Association reported that each metric tonne of natural uranium (U)—before the U-235 is concentrated—on average produces 44 GW-hours of electrical energy. Using this average value, we can divide 8,322 by 44 to estimate that each 1-GW plant-year of operation requires about 189 metric tonnes of natural uranium to be processed into fuel. (In the following calculations "tU" is used for metric tonnes of natural uranium.)

$$\frac{8{,}322\ \dfrac{\text{GW–hours}}{\text{plant–year}}}{44\ \dfrac{\text{GW–hours}}{\text{t U}}} = 189.136\ \frac{\text{tU}}{\text{year}}$$

Recalling that natural uranium metal contains 0.72 percent of the needed U-235, 189 tU contains 1,362 kg of U-235.

$$189.136\ \text{tU} \times 0.0072\frac{\text{U–235}}{\text{U}} = 1.362\ \text{tU}$$

New nuclear power plants are expected to have a 120-year operational life—a 60-year initial license with extensions up to an additional 60 years. Over this 120-year period, each plant would require 22,696 tU of natural uranium.

$$189.136 \text{ tU} \times 120 \frac{\text{years}}{\text{plant–life}} = 22{,}696 \frac{\text{tU}}{\text{plant–life}}$$

7. How much natural uranium does the United States have?

For the United States to be energy independent in the generation of nuclear electricity, the needed uranium must come from domestic sources. Since industry keeps only a limited fuel supply in inventory, a substantial expansion of domestic nuclear energy must rely upon the remaining resources in the ground—referred to as "in situ" resources.

The Organization for Economic Co-operation and Development, through its Nuclear Energy Agency and in cooperation with the International Atomic Energy Agency, periodically publishes a compendium of the world's uranium resources, production, and demand. This is referred to as the Red Book. From the 2016 edition, as of January 1, 2015, the United States has 138,204 tU in reasonably assured in situ recoverable conventional resources available for mining. (Reference: Red Book Table 1.3a.) These resources would meet the 120-year fuel needs of only six 1-GW nuclear power plants.

$$\frac{138{,}204 \text{ tU}}{22{,}496 \frac{\text{tU}}{\text{plant–life}}} \cong 6 \text{ plants}$$

By some estimates, the United States has up to 2 million additional tU from speculative resources. Uranium prospecting and mining is limited in some areas, such as Arizona and Virginia, where additional recoverable resources may exist. If all of this can be recovered, this would provide for only around 90 1-GW plants for a combined total of about 100 plants. The United States does not have enough natural uranium to expand its use of nuclear energy.

$$\frac{2{,}000{,}000\ \text{tU}}{22{,}496\ \frac{\text{tU}}{\text{plant–life}}} = 88.9\ \text{plants}$$

8. How much natural uranium is available in the world?

The 2016 Red Book reports that the entire world has in the ballpark of 7,600,000 tU from reasonably assured and inferred resources. If all of this is recovered, this would provide a 120-year fuel supply for around 338 1-GW plants.

$$\frac{7{,}600{,}000\ \text{tU}}{22{,}496\ \frac{\text{tU}}{\text{plant–life}}} \cong 338\ \text{plants}$$

For perspective, there are currently 451 operating nuclear reactors with a generating capacity of 394 GW. The world's natural uranium supply will only be able to keep around the current nuclear generating capacity fueled for the next century. This is not a sustainable source of energy. Hence, expectations that the United States will import uranium to enable a substantial expansion of nuclear power are not realistic.

9. Is it practical to recover uranium from seawater?

When the limited supply of natural uranium from land resources is acknowledged, using the ocean as a source of uranium is frequently mentioned. Like most elements, uranium exists in ocean water as a dissolved mineral. The ocean is thought to hold in the ballpark of 4.5 billion tU—enough to make uranium fission nuclear energy a true sustainable energy source. But is this a practical solution?

Figure 11: Mississippi River. (Credit: Preston Keres, U.S. Department of Agriculture, public domain.)

The Mississippi River has an average flow of 646,000 cubic feet per second or 18,300 cubic meters per second. (See Figure 11.) Seawater has a uranium concentration of 3 milligrams or 0.000003 kg per cubic meter. If the Mississippi River water was seawater, each second of flow would contain only 0.055 kilograms of uranium.

$$18{,}300\ \frac{\text{m}^3}{\text{sec}} \times 0.000003\ \frac{\text{kg U}}{\text{m}^3} = 0.0549\ \frac{\text{kg U}}{\text{sec}}$$

Annually, this totals 1,731 tU. This would fuel about nine 1-GW nuclear power plants.

$$0.0549\ \frac{\text{kg U}}{\text{sec}} \times 31{,}536{,}000\ \frac{\text{sec}}{\text{year}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} = 1{,}731\ \frac{\text{tU}}{\text{year}}$$

$$\frac{1{,}731\ \frac{\text{tU}}{\text{year}}}{189.136\ \frac{\text{tU}}{\text{plant–year}}} \cong 9\ \frac{\text{plants}}{\text{year}}$$

Methods to recover uranium from seawater were first considered in the late 1940s as a means of obtaining uranium. Today, the most common approach being tried is to adsorb—meaning to adhere on the surface—minerals in the seawater using a special filter material, remove the filter from the ocean, and, then, chemically separate the uranium from the trapped sludge.

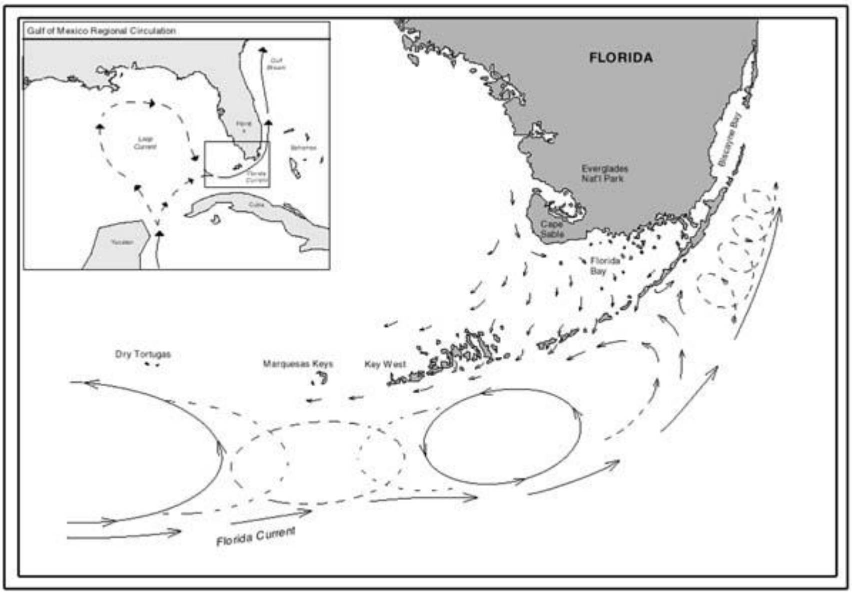


Figure 12: Chart of the Florida Current. (Credit: NOAA.)

The primary challenge is that seawater must flow through whatever filter is used to adsorb the minerals. The only possible way for this to happen is to make use of major ocean currents such as the Florida Current which turns into the Gulf Stream. (See Figure 12.) The average flow rate where the Florida Current passes the Florida Straight is about 30 million cubic meters per second. At this location, the current is about 43 miles (70 km) wide and 650 ft (200 m) deep. (The sea floor may be up to 6,000 ft deep.)

If all uranium in the Florida Current could be recovered, this would provide 90 kg per second.

$$30{,}000{,}000\ \frac{\text{m}^3}{\text{sec}} \times 0.000003\ \frac{\text{kg U}}{\text{m}^3} = 90\ \frac{\text{kg U}}{\text{sec}}$$

Annually, this totals nearly 3 million tU. This would fuel about 15,000 1-GW nuclear power plants. Such gross estimates encourage the hope that extracting uranium from the ocean would provide a sustainable natural uranium supply.

$$90\ \frac{\text{kg U}}{\text{sec}} \times 31{,}536{,}000\ \frac{\text{sec}}{\text{year}} \times \frac{1\ \text{tonne}}{1000\ \text{kg}} = 2{,}838{,}240\ \frac{\text{tU}}{\text{year}}$$

$$\frac{2{,}838{,}240\ \frac{\text{tU}}{\text{year}}}{189.136\ \frac{\text{tU}}{\text{plant–year}}} \cong 15{,}000\ \frac{\text{plants}}{\text{year}}$$

Research is underway in several countries to develop uranium filter technology. One effort, at the U.S. Department of Energy's Oak Ridge National Laboratory, has recently demonstrated the capability to extract 6 grams of uranium per kilogram of filter—or 6 kg per metric tonne of filter—when submerged for 56 days.

$$\frac{6\ \text{gram U}}{1\ \text{kg–filter}} \times \frac{1\ \text{kg}}{1000\ \text{gram}} \times \frac{1000\ \text{kg}}{1\ \text{tonne}} = \frac{6\ \text{kgU}}{\text{tonne-filter}}$$

Each tonne-year of submerged filter material would recover 39 kg of uranium per year. This recovery rate is 0.039:1 per year.

$$6\ \frac{\text{kg U}}{\text{tonne–filter}} \times \frac{365\ \frac{\text{days}}{\text{year}}}{56\ \text{days}} = 39.1\ \frac{\frac{\text{kg U}}{\text{year}}}{\text{tonne–filter}}$$

To extract one tU of natural uranium per year would require about 26 tonnes of filter.

$$\frac{1}{39.1\,\dfrac{\frac{\text{kg U}}{\text{year}}}{\text{tonne–filter}}} \times \frac{1000\text{ kg U}}{\text{tU}} = 25.58\,\frac{\text{tonne–filter}}{\text{tU}}$$

To extract the 189 tonnes of uranium needed for one plant-year of operation, nearly 5,000 tonnes of plastic filter material would need to be continuously submerged. (This ideally assumes that all trapped uranium is converted into fuel.)

$$189.136\,\frac{tU}{plant\text{–}year} \times 25.58\,\frac{tonnes\text{–}filter}{tU} = 4{,}838\,\frac{tonnes\text{–}filter}{plant\text{–}year}$$

Assuming that 56 days is the optimum submersion time, every 56 days these filters would be removed and replaced by fresh filter, transported to a land processing plant, acid cleaned to remove the collected minerals and trapped organic matter, and returned to the ocean. Each day, about 13 tonnes would need to be processed per nuclear power plant. After 12–18 months of usage, the plastic filters would be recycled to produce new filter material to refresh the adsorbing capability.

$$\frac{4{,}838\text{ tonnes–filter}}{365\,\frac{\text{days}}{\text{year}}} \cong 13\,\frac{\text{tonnes–filter}}{\text{day}}$$

Figure 13: Kelp forest. (Credit: National Oceanic and Atmospheric Administration.)

The filter material would most likely be deployed as artificial kelp, attached to buoys anchored to the seafloor, and floating in the current. (See Figure 13.) Assuming a mass of 0.5 kg per meter of this artificial kelp, roughly 9,700 km or about 6,000 miles of artificial filter kelp would need to be continuously submerged to yield the uranium needed to fuel one 1-GW plant.

$$\frac{\left(4{,}843\,\frac{\text{tonnes of filter}}{\text{plant–year}} \times \frac{1000\text{ kg}}{\text{tonne}}\right)}{\left(0.5\,\frac{\text{kg–filter kelp}}{\text{m}} \times \frac{1000\text{ m}}{\text{km}}\right)} = 9{,}686\ \frac{\text{km of filter kelp}}{\text{plant–year}}$$

Each day 27 km of the artificial filter kelp would need to be removed/replaced for each 1-GW plant.

$$\frac{9{,}686\text{ km}}{365\ \frac{\text{days}}{\text{year}}} = 26.5\text{ km of filter kelp}$$

Of course, these are very crude estimates, but they provide an idea of the difficulty of recovering large amounts of uranium from seawater. Imagine how many kilometers of artificial kelp would need to be in the Florida Current and how many ships would be needed to recover and transport the filter for processing to supply 4,000 1-GW reactors. Using the ocean to supply uranium to fuel an expansion of nuclear power is not practical.

10. Can the needed nuclear fuel be safely bred?

With land uranium resources being insufficient and large-scale uranium recovery from seawater being impractical, breeding fuel is the final option for making nuclear fission a sustainable energy source.

— *What is nuclear breeding?*

Within a nuclear reactor, free neutrons are released when some radioisotopes spontaneously fission or are prompted to fission. Every free neutron released in this manner will be captured by a nucleus somewhere. This happens within milliseconds of the fission event. If the neutron is captured in the nucleus of an isotope that does not fission, the capture event will increase the neutron count by one, increasing the isotope number by one. Sometimes the new isotope will be stable. Most of the time the new isotope will be unstable making it a radioisotope.

Nature likes the nucleus to be stable. When the nucleus is unstable, nature triggers a decay event or a series of decay events intending to make the nucleus stable. Of course, this may take billions of years for the decay event to occur. Usually, it happens much quicker.

One possible natural method of decay is to convert a neutron in the nucleus into a proton and an electron or convert a proton in the nucleus into a neutron and an anti-electron. (This anti-electron is called a positron and is antimatter. Yes, antimatter is being created all the time, including within your body.) Because the number of protons—the Z number—defines the element, as the number of protons change, the original element transmutes into a different element.

Some of the transmuted elements are stable but most are not. Nuclear engineering uses this transmutation to selectively breed radioisotopes that, like U-235, are capable of being prompted to fission within a nuclear reactor or nuclear weapon core. This is referred to as breeding.

There are two paths to use this natural transmutation behavior to breed useful nuclear fuel. One path involves creating U-233 from thorium and the other involves creating plutonium from U-238.

— *How is breeding U-233 achieved?*

Uranium has 92 protons (Z = 92) while thorium (Z = 90) has two fewer protons. Of the six thorium radioisotopes, Th-232 comprises 99.98 percent of the natural thorium on the Earth. It has a half-life of 14 billion years. When bombarded with free neutrons, the Th-232 nucleus can capture one additional neutron to become Th-233. This thorium radioisotope has a half-life of only about 22 minutes. Recall that this means that for every 100 Th-233 atoms, half will decay within 22 minutes compared to half decaying within 14 billion years for the initial Th-232 isotope. The capture of the additional single neutron makes a big difference changing a very long-lived radioisotope into a short-lived radioisotope.

When a Th-233 nucleus decays, one possible action is to convert one neutron into a proton and an electron. (The electron escapes the nucleus.) Since the new proton remains in the nucleus, suddenly what was the element thorium (Z = 90) is transmuted into the element protactinium (Pa-233) with Z = 91. Even though transmutation occurs, the total number of protons and neutrons remains the same.

The Pa-233 nucleus is also unstable with a half-life of 27 days. When Pa-233 (Z = 91) decays, it can transmute into the U-233 radioisotope of uranium (Z = 92) when another neutron spontaneously changes into a proton and an electron. Like U-235, U-233 is a fissionable radioisotope capable of fueling a nuclear reactor or building a nuclear weapon. The ability to transmute thorium into U-233 was discovered in 1942 and the concept for a Thorium–U breeder reactor was originated in 1946.

Figure 14: Fort St. Vrain nuclear power plant in Colorado. (Credit: U.S. Government work.)

A prototype commercial reactor that used thorium-bred U-233 as a fuel extender was built in Colorado and operated for ten years from 1979–1989. (See Figure 14.) The design of the reactor was substantially different from conventional commercial reactors in that helium was used as the coolant instead of water. The fertile Th-232 was mixed with fissionable U-235 fuel to enable U-233 to be bred within the reactor to extend the life of each U-235 fuel load. (The fissioning of the U-235 supplied the needed neutrons.) This demonstration and other similar tests have shown the technical feasibility of breeding U-233 from thorium. Other nations, such as India, have also done work on using thorium to breed U-233.

The Fort St. Vrain reactor was operated in an open mode. This means that the bred U-233 remained in the reactor and was consumed as the reactor produced power. It is also possible to tailor the design and operation of the reactor and the handling of the fuel to enable the bred U-233 to be separated in order to stockpile U-233 fuel. This is achieved by, after a period of breeding, removing the fuel from the reactor and chemically separating the U-233 from the remaining thorium. Operating the reactor to stockpile fuel is called a closed mode of operation. The actual design of the reactor would be tailored for use in an open or closed fuel cycle.

— *How is breeding plutonium achieved?*

While we now know that trace amounts of plutonium exist in nature, all that we use has been created artificially from uranium. A plutonium radioisotope was first created in late 1940.

During the Manhattan Project in the early 1940s, special nuclear reactors were built to intentionally breed plutonium for a nuclear weapon. (See Figure 15.) These reactors used graphite as the neutron moderator instead of water. This enabled the 0.72 percent natural concentration of U-235 in uranium to be used to sustain a chain reaction without needing to enrich the U-235 concentration. (The technology to enrich U-235 was not yet developed.) At the same time, the 99 percent concentration of U-238 in the uranium fuel enabled plutonium to be bred.

To produce the desired plutonium-239 radioisotope, U-238 in the reactor captures a free neutron creating U-239. Up to three-quarters of the time, the U-239 nucleus transmutes relatively quickly into Neptonium-239. Within a couple of days, Np-239 transmutes into the desired Pu-239. This Pu-239 can be used in both power reactors and nuclear weapons.

After the war, a short-term shortage of uranium and the wartime high cost of enriching the U-235 concentration created interest in breeding plutonium to fuel nuclear reactors. Such reactors could be operated in an open mode to just produce electrical power or a closed mode to also produce excess plutonium to stockpile for reactors or nuclear weapons. Discovery of additional uranium deposits and substantial reductions in the cost of U-235 enrichment ended American interest in using plutonium to fuel commercial nuclear power plants. Direct U.S. plutonium production, primarily for nuclear weapons, ended in 1994 with 111.4 metric tonnes produced.

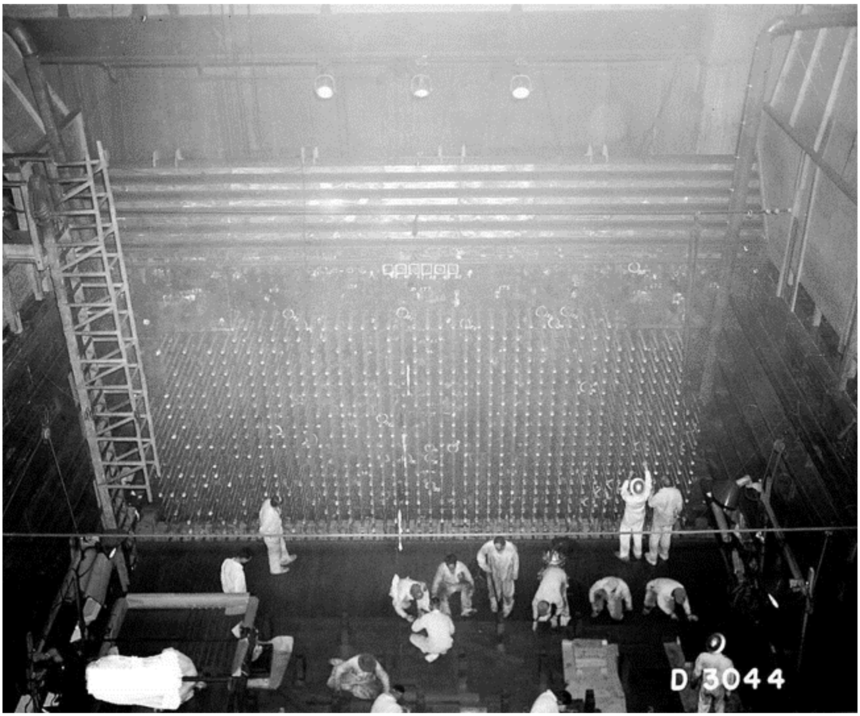


Figure 15: View inside one of the first U.S. plutonium breeder reactors during construction in 1943. (Credit: U.S. Government, Wikimedia Commons, public domain.)

Plutonium is created in any nuclear reactor that contains U-238. Some of the U-238 in the fuel pellets used in commercial nuclear power plants is transmuted into Pu-239 as the plant operates. Some

Pu-239 fissions to add to the energy released as the primary U-235 fuel fissions. However, when spent fuel pellets are removed from the reactor during refueling, several hundred kilograms of plutonium, as well as U-235, remain in the removed pellets. In some countries, these spent fuel pellets are then processed to chemically separate the plutonium. This plutonium can be used as reactor fuel or used in a nuclear weapon.

11. What type of reactor would use the Th–U fuel cycle?

The Th–U fuel cycle has the advantage that the Th-232 isotope comprises nearly 100 percent of the thorium resources estimated to be in the millions of metric tonnes. To breed U-233, the Th-232 has to be bombarded with free neutrons within a nuclear reactor where the fission of U-235, plutonium, or U-233 creates these free neutrons. The current preferred reactor design is referred to as a molten salt reactor. (See Figure 16.)

A molten salt reactor is a class of reactor designs that, instead of circulating a gas or water through the reactor to remove heat, a molten salt is used. This idea originated in the 1950s as a means of putting a compact nuclear reactor in an airplane to use the reactor heat to propel the aircraft. Various molten salt reactor designs intended for producing electrical power have been researched and new designs are being proposed.

In chemistry, a “salt” is a chemical molecule formed from the reaction of an acid and a base. Table salt, for example, is formed by the reaction of chlorine and sodium to form sodium chloride. In a molten salt reactor using the Th–U fuel cycle, the fissile Th-232 is used in the form of a salt that when heated becomes molten. Thus, fuel rods and assemblies used in conventional reactors are not needed. The graphite form of carbon, replacing water used in a conventional reactor, may be used to moderate the released neutrons to promote neutron capture within the circulating salt enabling a chain reaction to be maintained.

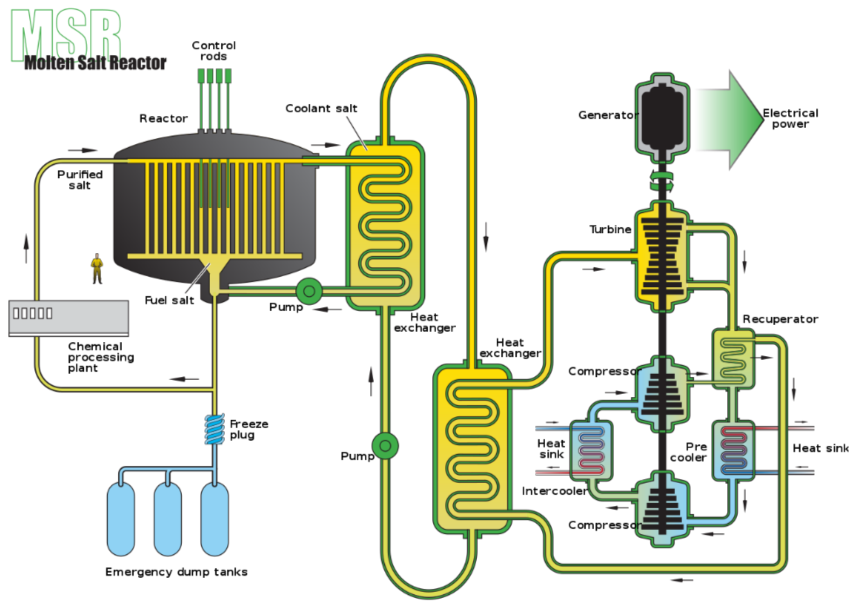


Figure 16: Diagram of a molten salt reactor using the Th—U fuel cycle. (Credit: U.S. Department of Energy, Wikimedia, public domain.)

When the reactor starts operation, the thorium salt is seeded with a fissionable fuel such as a plutonium radioisotope. As the seed fuel fissions, it releases neutrons that begin the transmutation of the Th-232 and generates heat that warms the salt to a molten state. Pumps then begin to circulate the primary reactor salt through the first heat exchanger where a second circuit of coolant salt transfers heat to the final set of heat exchangers that boil water to produce steam to drive turbines to generate electricity.

These molten salt reactors are still in the early stage of research and development. Significant engineering design challenges must be solved, and development and prototype commercial reactors built and satisfactorily tested before regulatory approval to proceed to commercialization can be made.

12. Does breeding fuel increase the risk of nuclear weapon proliferation?

As United States foreign policy engagement with North Korea and Iran shows, the threat of nuclear weapon proliferation is considerable. Advocacy for expanding the use of nuclear fission energy as a sustainable energy source to replace fossil fuels is also advocacy for breeding fuel. While the United States already has nuclear weapons, most other nations that would seek nuclear fission reactors to replace fossil fuels do not have these weapons making the risk of proliferation very real.

— What is the threat from U-233 breeding?

Recognizing the potential to make proliferation easier, Th-U reactor designs have been proposed that are said to be proliferation resistant. However, being proliferation resistant is not the same as being proliferation proof. The issue is that a Th-U fuel reactor could he used to produce and stockpile U-233. The 2016 Red Book published by the International Atomic Energy Agency confirms the ability to stockpile U-233.

> *Similar to uranium, thorium can be used as a nuclear fuel. Although not fissile itself, 232Th, when loaded into a nuclear reactor, absorbs neutrons to produce 233U, which is fissile (and long-lived). Much of the 233U will then fission in the reactor. The used fuel can then be unloaded from the reactor and the remaining 233U can be chemically separated from the thorium and used as fuel in a nuclear reactor.*

In Figure 16, the diagram of a generic molten salt reactor shows that the salt containing the U-233 would be diverted through a chemical processing plant. This processing would be done to remove chemical and radioactive impurities that form while the plant is operating. This is also where U-233 could be removed for stockpiling.

Therefore, a reasonable concern is that a closed Th–U fuel cycle or a covertly modified open Th–U fuel cycle could enable nuclear weapon proliferation. Advocates may argue that the Th–U fuel cycle naturally prevents this possibility since the same breeding process that produces U-233 also produces the U-232 radioisotope, but in smaller concentrations. When U-232 decays, it emits gamma radiation with an intensity that can be dangerous.

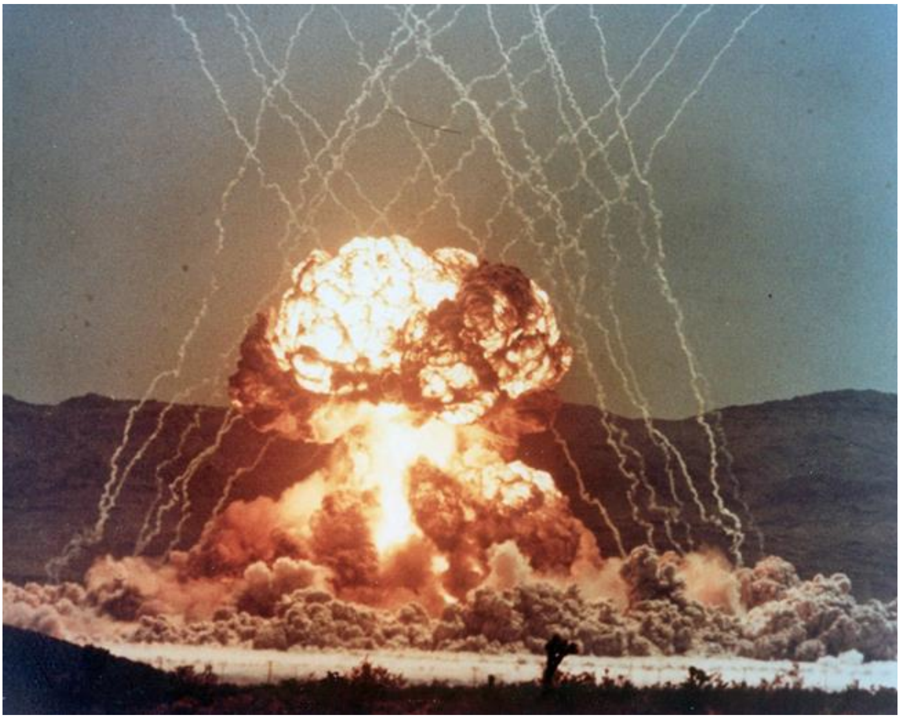


Figure 17: United States nuclear weapon test using an experimental core containing U-233 and plutonium, April 15, 1955. (Credit: National Nuclear Security Administration, Nevada Site Office, Wikimedia Commons, public domain.)

Some argue that the presence of the U-232 gamma emitter makes any uranium separated too dangerous to handle. However, despite such difficulties, it is reported that the United States has produced 1.5 tons of U-233 as part of its nuclear technology development efforts. Also, public documents indicate that methods to remove the U-232 were, at least, identified by government investigators. Further, the United States tested an experimental nuclear weapon core in 1955 that used U-233 and plutonium in the core. (See Figure 17.) It is reported that the Soviets tested a hydrogen bomb that included U-235 and U-233 in the core and India tested a small experimental U-233 device.

These actual weapon development tests demonstrate a very real proliferation risk that a determined rogue nation, willing to accept the increased danger of handling U-232/233, could exploit a Th–U fuel cycle reactor to obtain U-233. If the United States could prepare a core containing U-233 seventy years ago, today this should not present a significant technical challenge to a rogue nation.

— *What is the threat from plutonium breeding?*

Rogue nations, like North Korea, will build identifiable nuclear reactors specifically to breed plutonium. This form of nuclear weapon proliferation is addressed through direct national policy. The concern with the potential proliferation of plutonium weapons is the ability to covertly produce plutonium or divert plutonium for use in nuclear weapons.

When Pu-239 is bred, invariably the sister radioisotope Pu-240 also forms. If the Pu-240 concentration is too high—greater than seven percent—this makes creating a properly functioning nuclear weapon more difficult. To produce Pu-239 suitable for nuclear weapons requires that the breeding process be undertaken in ways that limit the Pu-240 percentage. This can readily be done as percentages as low as four percent have been routinely produced.

When the Pu-240 concentration is greater than seven percent, this is referred to as reactor-grade plutonium. The United States conducted one underground test of a weapon using reactor grade plutonium showing that a weapons potential does exist.

While a plutonium-fueled nuclear power plant may need around 1,500 kg per year, a single nuclear weapon only needs less than 10 kg. Any nuclear reactor containing U-238 produces plutonium through transmutation. Covertly, such a reactor—especially if it is just one of tens or hundreds of reactors—could be operated in a manner that yields weapons-grade plutonium. However, even when using reactor-grade plutonium, a nuclear weapon could be created, While this nuclear weapon core will likely “fizzle” meaning that a reduced nuclear explosion will occur, the explosion will disperse the remaining plutonium to contaminate the surrounding area with this dangerous radioisotope. (A similar threat would result from a U-233 fizzle weapon that contains the especially dangerous U-232 radioisotope.)

— *Can these proliferation risks be avoided?*

A primary concern with nuclear weapon proliferation is the threat by a rogue nation or organization to use a nuclear weapon or their possession of nuclear weapons to shield other belligerent or illegal activities. For a proliferation threat to be credible, access to nuclear materials is required.

The use of nuclear fission energy worldwide to replace fossil fuels will require the substantial breeding of U-233 and/or Pu-239—on the order of thousands of metric tonnes per year to fuel thousands of nuclear reactors. It will be impossible to guarantee that the small quantities of nuclear material required to make a nuclear weapon have not been covertly diverted or acquired. Thus, any threat of the use of a nuclear weapon by a rogue nation or organization would need to be treated as a credible threat. Only the avoidance of breeding U-233 and Pu-239 will prevent this situation from occurring.

13. Does spent reactor fuel reprocessing increase the risk of nuclear weapon proliferation?

In current commercial U-235 reactors, fuel assemblies are periodically removed and replaced with new assemblies when most but not all of the U-235 in the fuel pellets is consumed. These "spent" fuel pellets still contain U-235 and will also contain other radioisotopes created through transmutation including plutonium.

These spent fuel pellets can be chemically reprocessed to remove non-uranium elements. The remaining uranium can be enriched to produce new reactor fuel pellets or, potentially, weapons-grade U-235. Also, plutonium can be separated to provide new reactor fuel or, potentially, nuclear weapon cores.

Under Section 123 of the Atomic Energy Act, the United States establishes agreements with other nations that receive American nuclear energy products, services, and technology with the aim to prevent proliferation. Spent fuel reprocessing has generally not been permitted through these agreements. The 2018 Congressional Research Service report, *Nuclear Energy: Overview of Congressional Issues*, notes examples of proliferation concerns:

> *During negotiations on the U.S.-South Korea nuclear cooperation extension, which entered into force November 25, 2015, South Korea had sought advance U.S. consent for spent fuel reprocessing and uranium enrichment. The United States did not provide such consent, on general nonproliferation grounds and because such consent could affect other ongoing issues on the Korean peninsula.*
>
> *Japan's longstanding nuclear cooperation agreement with the United States automatically renewed on July 17, 2018, and will remain in force indefinitely unless terminated by either side. The agreement allows Japan to reprocess spent nuclear fuel from its U.S.-designed reactors, separating*

plutonium and uranium for use in new fuel. A commercial reprocessing plant at Rokkasho is scheduled to be completed in 2021. Some nuclear nonproliferation groups had urged the United States to use the renewal of the U.S.-Japan nuclear cooperation agreement as an opportunity to urge Japan not to begin its reprocessing program. They noted that Japan already has substantial stockpiles of previously separated plutonium that could potentially be used for weapons as well as reactor fuel.

Recent discussions between the United States and Saudi Arabia toward drafting a peaceful nuclear cooperation agreement have prompted substantial controversy. The U.S. nuclear industry strongly supports an agreement so that it could supply reactors and other nuclear technology to Saudi Arabia. However, nuclear nonproliferation groups want any nuclear cooperation agreement to include a binding commitment from Saudi Arabia to forswear uranium enrichment and spent fuel reprocessing on its territory. Secretary of State Mike Pompeo testified to the Senate Foreign Relations Committee May 24, 2018, that the United States was insisting that Saudi Arabia accept such a commitment as part of any 123 agreement, despite Saudi arguments that the country has a right to enrich and reprocess under international inspections.

To replace fossil fuels worldwide with nuclear fission will likely require spent fuel reprocessing to recover useful U-239 and plutonium and to minimize nuclear waste storage needs. Stockpiling plutonium and enabling U-235 enrichment will likely become common and, most likely, an asserted sovereign right.

14. To locate and use a commercial nuclear plant, what are the key safety considerations?

All forms of intense energy operations require appropriate safety protocols. For nuclear fission, these involve plant siting, radioactive waste disposal, consideration of potential accident consequences, and preventing reoccurrence of past failures/accidents.

Selecting a location for a nuclear power plant requires assessing many factors. A recent site survey for a new American nuclear power plant included over 30 factors. Key considerations include an adequate cooling water supply for plant cooling and earthquake and flooding risks.

— *Plant waste heat disposal*

Nuclear power plants are thermal power plants in that the heat released by nuclear reactions is used to boil water to produce steam to drive the turbine generators. As an unavoidable thermodynamic consequence of converting heat into the mechanical power spinning the generators, roughly two-thirds of the heat produced in the reactor becomes waste heat that must be rejected to the plant's surrounding environment. (The same is true for conventional power plants as well as for many industrial thermal processes.)

A nuclear power plant generating 1 GW of electrical power will discharge about 2 GW of primary waste heat. In addition to this primary waste heat, waste heat from secondary equipment must be rejected. Also, emergency cooling capabilities must be provided should the primary cooling system fail. The 2011 Japanese nuclear power plant incident, discussed in detail below, highlights the need for having significant emergency cooling and external power supply capabilities.

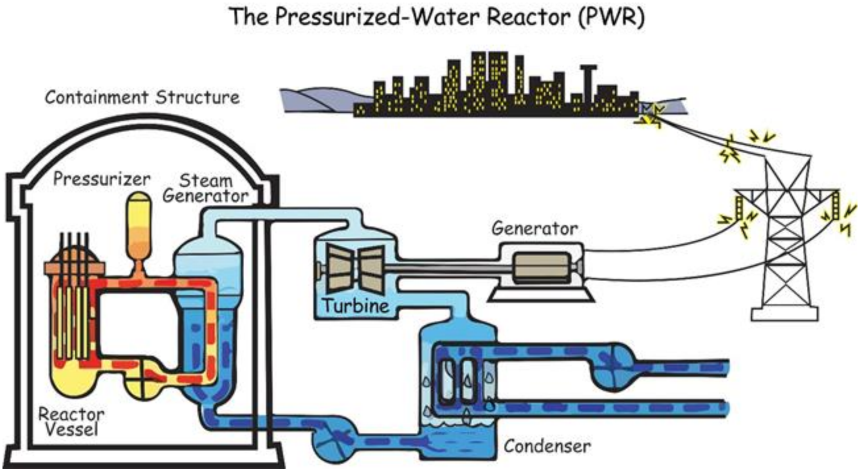


Figure 18: Diagram of a pressurized-water nuclear power plant showing the three loops of cooling water. (Credit: U.S. Nuclear Regulatory Commission.)

A typical pressurized nuclear power plant operates with three circulating water loops to transfer heat. (See Figure 18.) The first loop—colored red and yellow in the figure—transfers heat from inside the reactor to the steam generators which are boilers. This loop is closed to prevent any water that has been exposed to nuclear materials from escaping. Also, the water is pressurized to prevent it from boiling.

The second loop (blue) is the closed steam loop. Pressurized water in the second loop entering the steam generator boils to produce steam as it extracts heat from the reactor's primary water loop (red). By creating steam, thermal energy from inside the reactor is transferred to produce hot, pressurized water vapor (steam) that is useful for converting thermal energy into mechanical energy.

On exiting the steam generator (boiler), the steam passes through the turbines driving the electrical generators. As steam passes through a turbine, the thermal potential energy of the hot, pressurized steam changes into the mechanical power rotating the turbines. Using a drive shaft, the turbine's rotational mechanical power turns the electrical generator to convert this rotational mechanical power into electrical power. On exiting the turbine, most of the water remains a vapor, but at a lower pressure and temperature.

Even though the steam exiting the turbines is at a lower pressure and temperature, about two-thirds of the heat generated in the reactor remains as thermal energy in this low-pressure steam. This is called waste heat because this is thermal energy that our technology is unable to practically convert into electrical energy. (The hot exhaust from a car is another example of waste heat.)

While this steam could easily be dumped into the atmosphere, a steam condenser is used to turn it back into a liquid before a pump pressurizes the liquid to return it to the steam generator to start the cycle again. This is done because it is more energy efficient to pump and pressurize water as a liquid than to use a turbine to pressurize water vapor. Also, this enables the same water to be reused to prevent additional contaminants from collecting within this cooling loop.

The third or waste heat loop transfers waste heat from the steam condenser to the plant's local environment. For everything that we do that uses energy, the Earth's environment is where this energy ends up as waste heat. The Earth then rejects this energy into space using thermal radiation from the surface and the atmosphere.

When transferring thermal energy, the efficiency of the transfer depends on the temperature difference. When the temperature difference is large, the transfer efficiency is high and the equipment size needed is smaller. Conversely, when the temperature difference is lower, the efficiency is lower and the equipment size is larger. The third or waste heat loop is handling 66 percent of the original heat produced in the reactor but at much smaller temperature differences.

This means that the equipment needed to reject this waste heat to the local environment will be large.

For small systems where it is necessary to dump waste heat, a closed loop radiator is often used. A car engine, for example, circulates a cooling liquid through the engine core to extract waste heat and, then, uses air flowing through a radiator to dump this waste heat to the atmosphere. A house air conditioner also uses a cooling liquid to transfer heat from inside the house to the outside radiator where this heat is dumped to the atmosphere. The problem with using this approach for nuclear power plants is the sheer magnitude of the heat—two billion watts—that must be rejected. Large fans would be needed to force air through the radiators to dump the waste heat into the atmosphere. Besides the mechanical complexity, too much electrical power would be required to drive the fans.

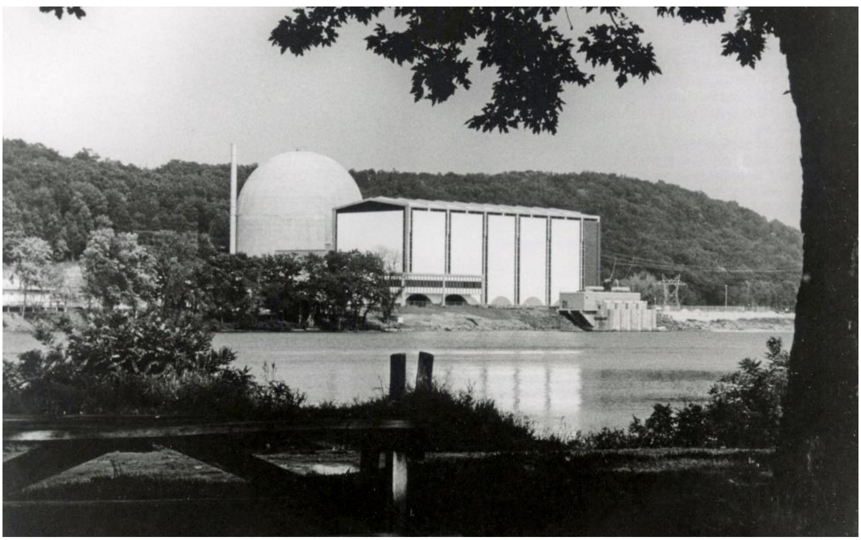


Figure 19: A nuclear power plant that directly uses water from the ocean to dump waste heat. (Credit: U.S. Government work.)

For thermal power plants there are two thermodynamically efficient methods to dispose of the low-temperature waste heat. The first is to pump cool water from a large lake, river, or the ocean through the third cooling loop and back to where it originated. (See Figure 19.) Technically, this is an open loop. The cooling water's temperature will typically increase by about 30°F (17°C) before returning to the lake, river, or ocean. For a 1-GW plant, up to one million gallons per minute passes through this final cooling loop. The increase in the temperature of the water has a local environmental footprint. Thermal power plants typically need to be tens of miles apart to enable the concentrated heat input to dissipate to prevent environmental harm. Therefore, the need for a large lake, major river or the ocean as the water source is obvious.

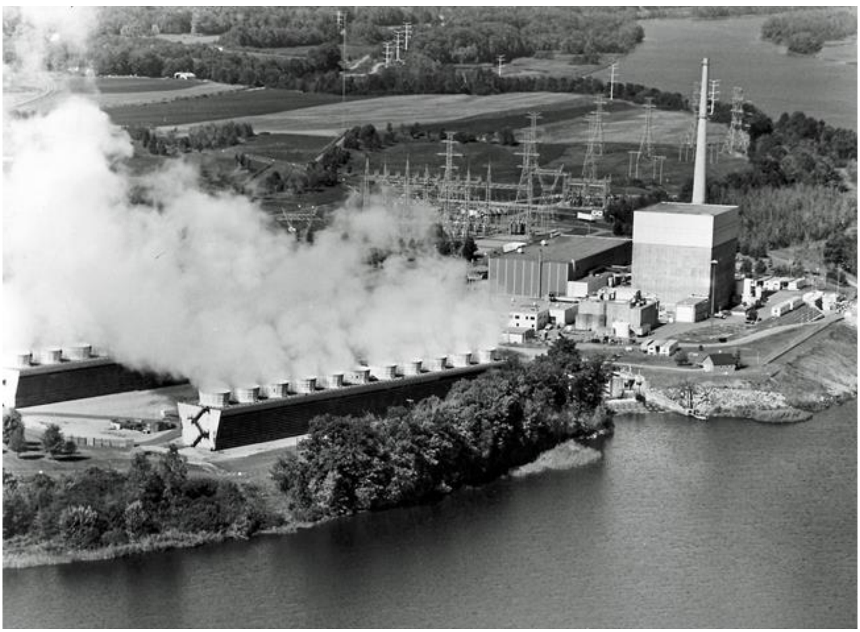


Figure 20: Hot water vapor, carrying waste heat, rises from two banks of cooling towers used to cool the nuclear power plant. (Credit: U.S. Government work.)

Where dumping waste heat into the local water source is not acceptable or where the available water supply is inadequate, the atmosphere is used as the heat dump. This is accomplished using an evaporation system inside the cooling towers. (See Figure 20.) The warm water in the third loop is pumped into the cooling towers, flowing down the inside of the cooling towers exposing the water to the air. Some of the water evaporates, transferring heat to the air in the process. As this happens, the rest of the water cools, is collected and is pumped back to condense more steam. About five percent of the water is lost on each pass through evaporation and must be made up from local water supplies—perhaps on the order of 40,000 gallons per minute.

Locating a nuclear power plant requires sufficient clean water supplies year-round with consideration for reduced supplies in times of drought that periodically hit all parts of the country. As a baseload power plant, the nuclear plant should be capable of operating under such conditions as the need for energy does not diminish during droughts. Further, this demand for water should not compete with other local needs for drinking water or other existing industrial needs, especially during times of drought. Thus, surface water availability and suitability are key plant siting considerations.

— *Earthquake damage*

Nuclear power plants are designed with the intention that they safely withstand natural hazards such as earthquakes and floods. The level of risk to which the plant will be exposed is dependent on its location. As with all natural hazards, the probability of an event happening grows with time. A permanent and substantial reliance on nuclear energy to replace fossil fuels will increase the cumulative probability of exposure to such natural hazards.

An earthquake causes tremors in the ground that induce movement of structures in or on the ground. Essentially, ground movement drags the structure to a slightly different location, exerting an inertial load on everything in the structure. As the ground shakes, this load oscillates in magnitude and direction.

For an assumed set of earthquake conditions, engineers aim to design a nuclear power plant to safely resist the imposed loads. However, there are limits on what is practical to build both physically and financially. Thus, there are locations where it is not reasonable to build nuclear plants. Further, while the nuclear plant may survive the earthquake, damage to less protected external services vital to keeping the plant safe—water supplies, external emergency power, personnel access, as examples—will further eliminate areas from consideration.

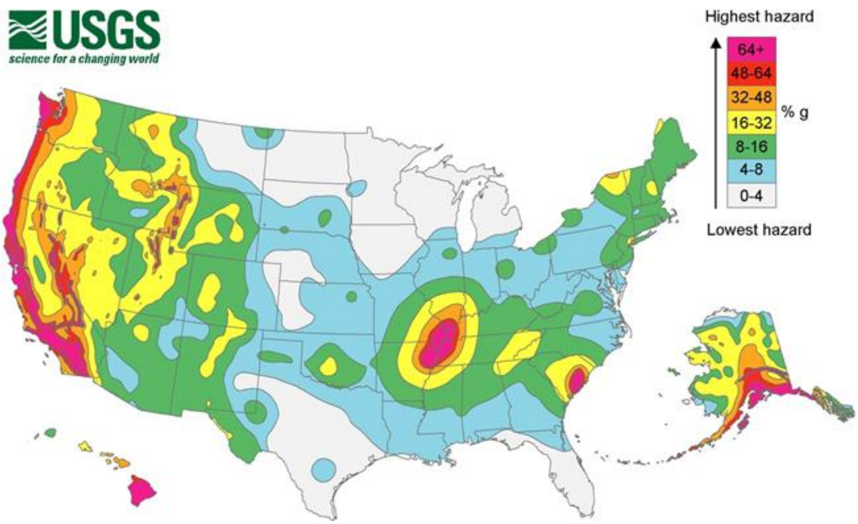


Figure 21: Map showing possible earthquake intensity in the United States. (Credit: U.S. Geological Survey.)

The Figure 21 map illustrates the parts of the United States that may be subject to damaging earthquakes. From this map, it is apparent that many parts of the country are unlikely to be suitable for locating nuclear power plants. Note that the high-risk area in the central United States is on the Mississippi River placing this area and downstream areas at risk. Also note that the entire western coast, along with parts of Alaska and Hawaii, where plants could be located to use seawater cooling, are at high risk of severe earthquakes.

— *Inland flooding*

Figure 22: Severe 1927 flood of the Mississippi River. (Credit: Library of Congress, LC-DIG-npcc-16869, no known restrictions on publication.)

With the need to locate inland nuclear plants on rivers or lakes for cooling, the possibility of flooding is a significant siting consideration. The flooding of America's major rivers is an unavoidable natural occurrence. (See Figure 22.) River levees and dams are used to control moderate flooding, but there is no practical way to control major events. Some argue that levees make flooding more frequent and more severe. While plants can be protected with permanent seawalls, serious flooding also impacts other considerations such as the ability to respond forthrightly to critical plant equipment failures; preventing and repairing damage to water intakes; enabling operating and emergency personnel continuing access to the plant; assuring continuity of power transmission from the plant; assuring off-site emergency backup power availability; enabling the reactor to be safely shutdown; and, enabling the entire plant complex to be maintained in a safe shutdown condition. (See the discussion below of the 2011 Japanese nuclear accident.)

15. What is nuclear radiation?

During the decay of all radioisotopes, nuclear radiation is released from a decaying atom as it changes into a different isotope's atom with a specific number of neutrons, protons, and electrons. The term "nuclear radiation" is a general term used to describe these emissions. When the nucleus of a radioisotope decays, its composition of neutrons and/or protons changes. Through nuclear radiation, nature expels unneeded nuclear particles and/or electromagnetic energy to achieve the needed different isotope's composition.

There are four primary types of nuclear radiation:

- Alpha particle radiation (α) is two protons and two neutrons bound together. (See Figure 23.) The alpha particle is the same as the element helium's nucleus. The name alpha was selected because this was the first type of radiation to be discovered. In most cases, alpha radiation is not a significant threat to living tissue as the alpha particle is not capable of penetrating the outer layer of skin or clothing.
- Beta radiation (β– or e–) is an elementary particle with a negative charge. (See Figure 23.) A beta particle is an electron that is not bound to a nucleus.

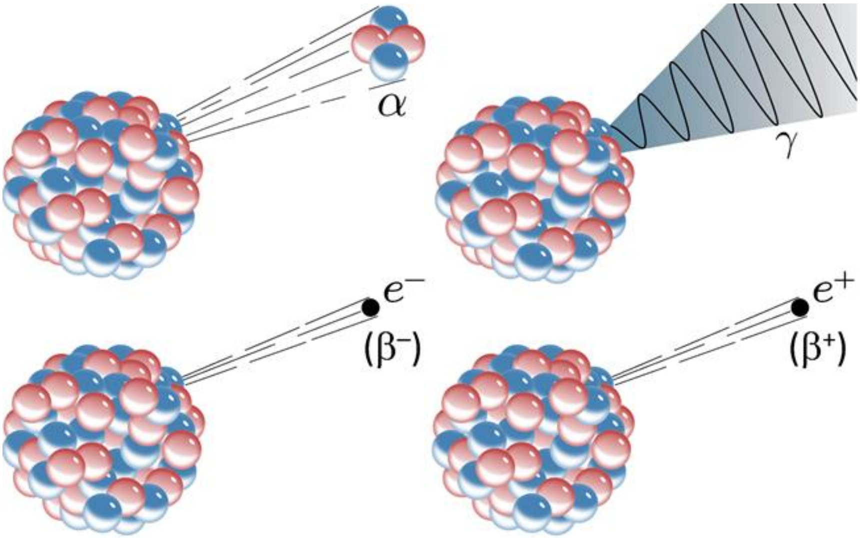


Figure 23: Four types of radiation occurring during a decay event. (Original images credit: Inductiveload, Wikimedia Commons, public domain. Composite image credit: J. M. Snead.)

- Gamma radiation (γ) is not a particle with mass, as is an electron, but is an elementary unit, called a "photon", of pure electromagnetic radiation. (See Figure 23.) Being pure energy, it has no mass. In a vacuum, a photon moves at the universal constant speed of all electromagnetic radiation—what is colloquially called the "speed of light". A photon's behavior is very complex. However, one easily understood characteristic is the frequency or wavelength at which the photon oscillates while it moves. When a photon of nuclear radiation is emitted during the decay event, it will have a very rapid frequency or very short wavelength. When a photon's frequency is very rapid, it is generally referred to as a gamma ray or gamma radiation. These gamma radiation characteristics enable the photon emitted during a decay event to easily penetrate solid matter such as human tissue, possibly causing harm.

- Positron radiation (β+ or e+) is an unbound elementary particle with a positive charge. (See Figure 23.) This is one form of antimatter—the mirror matter version of an electron. Positron radiation is not a dominant form of nuclear radiation in nature because positron emission is not a dominant form of radioactive decay.

Nature abounds with nuclear radiation. Sunlight is electromagnetic radiation consisting of photons with a broad range of frequencies. (Some people enjoy "bathing" in solar nuclear radiation.) Nature uses these many forms of radiation to maintain balance in the physical universe. Using our scientific knowledge, we understand how some forms of radiation are biologically dangerous and take appropriate steps to eliminate or minimize the danger just as is done for other threatening circumstances.

Some forms of natural radiation present no danger. Bananas are often eaten because they are high in potassium. One natural isotope of potassium is a radioisotope that decays by positron (β+) emission. The positron, being antimatter, will annihilate with an electron releasing a burst of very low-intensity gamma radiation. Our bodies need potassium to be healthy meaning that the production of positrons and the internal exposure to gamma radiation occurs naturally in our bodies throughout our lifetime. Many other radioisotopes, releasing radiation as they decay, exist in our body in very small quantities because they exist in nature. The danger from radiation comes from failing to provide circumstance-driven safety protections from dangerous levels of harmful radiation. This includes protection from excessive sunlight exposure which can cause skin and eye damage and, even, death.

16. How does a nuclear plant create nuclear waste?

The operation of a nuclear fission reactor intentionally releases free neutrons by prompting U-235 nuclei to fission. Free neutrons do not, however, remain free for very long. When a free neutron is released during a U-235 fission in a reactor, it will be captured into another nucleus typically within 0.0001 seconds. If this capture is by a U-235 nucleus, another fission event will likely happen, releasing more neutrons. However, the neutrons are not targeted only at U-235 nuclei. They can be captured by almost every nucleus in the reactor. Each of these neutron capture events creates a different isotope. The new isotopes may be a radioisotope that will decay, releasing radiation, or they may transmute into another element just as U-238 transmutes into Pu-239.

When the nuclear fuel is initially inserted into the reactor, the only active radioisotopes are U-235 and, perhaps, Pu-239 if old nuclear weapon cores are being disposed of. When the spent fuel is removed from the reactor, not only do some U-235 and Pu-239 remain, but there are additional radioisotopes created through decay and transmutation. All of these are releasing radiation as they decay which makes the spent fuel radioactive and still producing heat. The radiation released by some of the radioisotopes is very intense making it a hazard to humans and the natural environment. The duration of this hazard is dependent on the half-life of the dangerous radioisotopes. The length of time that these remain dangerous can be thousands of years.

Initially, as seen in Figure 24, the fuel rod assembly—housed within the white canister while being moved—is placed in a water pool adjacent to the nuclear reactor. The water moderates and shields the facility from radiation being released by the fuel. Also—and very important—the water cools the fuel to remove the heat being released as the remaining radioisotopes decay. The fuel rods will stay in the pool for 3–5 years during which time the water must be circulated to reject the heat through external heat exchangers.

Otherwise, the water would boil away exposing the fuel rods to the atmosphere and, possibly, enabling the release of radioactive materials.

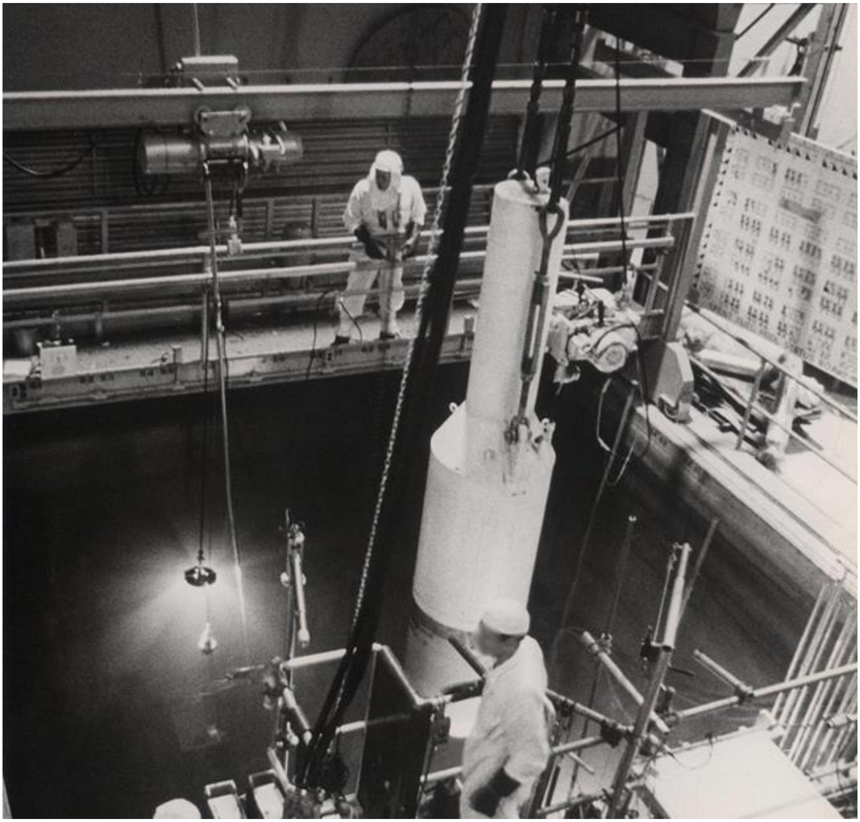


Figure 24: Spent fuel rods, once removed from the reactor, are stored in an adjacent water pool. (Credit: U.S. Government work.)

After several years for each batch of spent fuel assemblies, the more active radioisotopes, due to their short half-lives, will have decayed away. Harmful radioisotopes will remain, but the radiation level is reduced because these decay at a slower rate or have less intense emissions, e.g., beta radiation. For this reason, the spent fuel rods must be placed into safe, long-term storage for tens or hundreds of thousands of years. This controlled storage is needed to prevent potentially harmful concentrations of the radioisotopes from escaping into the environment, such as into surface or underground water sources. How to undertake this long-term storage has created significant political controversy.

Figure 25: Nuclear waste being transported in casks. (Credit: U.S. Government work.)

After spent fuel assemblies have adequately aged in the water pool, they are removed and placed into dry storage. One dry storage approach is to put spent fuel assemblies, along with other low-level radioactive materials from inside the reactor, into sealed containers called casks. (See Figure 25.) These are usually fabricated from steel and concrete. Substantial effort has been made to produce robust casks that will not only provide sufficient radiation shielding, but also will prevent the internal chamber from being breached through some external force, such as an explosion or an accident during transport.

A cask will hold 10–15 tons of nuclear materials. The U.S. Nuclear Regulatory Commission says that 2000–2400 tons of nuclear waste requiring such storage is created each year. Currently, the United States has about 100 GW of nuclear generating capacity. Thus, very approximately, two new casks per GW of generating capacity would be needed each year. To replace fossil fuels, about 4,000 GW of nuclear capacity will be needed by 2100. Thus, by 2100, in the ballpark of 8,000 casks—holding 80,000 tons—would be needed each year forever.

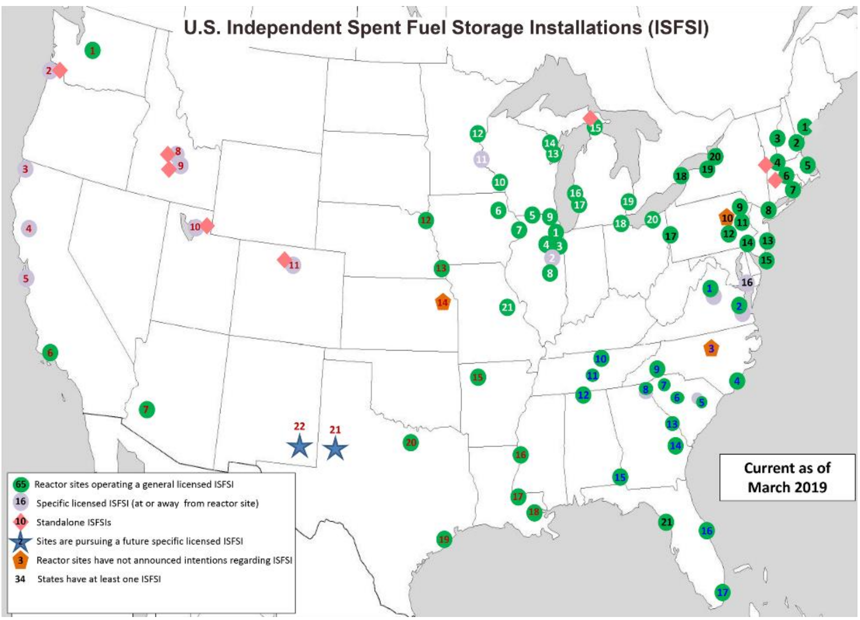


Figure 26: Locations in the contiguous United States where dry cask storage is used. (Credit: U. S. Nuclear Regulatory Commission.)

Once loaded and sealed, the cask is transported to a storage location. The storage location may be at the plant site or it may be elsewhere in the contiguous United States. (See Figure 26.) Of course, the long-term durability of the casks is not known indicating that periodic replacement will be needed until geologically-permanent storage is implemented.

17. What options exist for the permanent storage of dangerous nuclear waste?

Obviously, surface storage of high-end radioactive waste is a temporary measure. Compared with the life of dangerous concentrations of harmful radioisotopes in the waste, there is no certainty that any human-made contrivance located anywhere on the surface will provide long-term protection.

In 2012, one member of Congress illustrated the safety challenge associated with cask storage.

> *So, today, we return to Pennsylvania, to a power plant called Limerick. Limerick has 1,143 metric tons of uranium spent fuel on site. At Limerick, the waste is stored above the ground in pools and in casks. It is 20 feet above the groundwater, and it is on the Schuylkill River, which is 40 miles from Philadelphia, Pennsylvania. That is where we currently store high-level nuclear waste.*

From the map in Figure 25, the situation at the Limerick facility may be typical of other locations around the United States. With the need for a more permanent solution, disposal at sea, burial underground, or disposal in outer space are the three permanent disposal options.

— *Disposal of nuclear waste at sea*

From 1946–1993, the ocean was used by some countries—including the United States from 1946–1970—for dumping radioactive waste. Roughly, 85,000 tons may have been dumped. Due to the corrosive nature of seawater and the immense pressure at deep locations, there is no way to assuredly prevent waste from escaping a storage container. Ocean dumping was banned by international treaty in 1994 although some illegal dumping is likely still occurring. Disposal at sea is not an option.

— *Underground storage of nuclear waste*

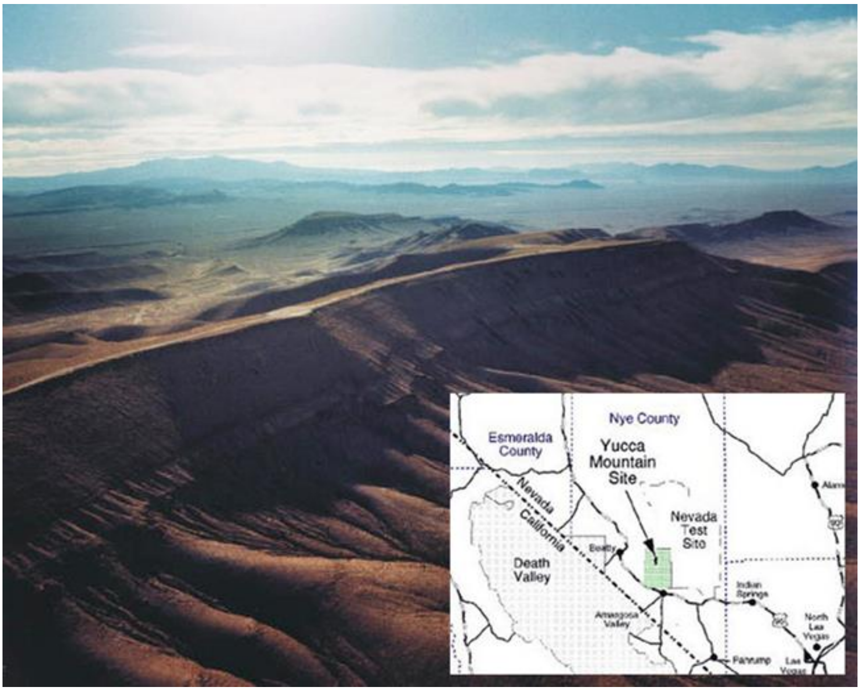


Figure 27: Yucca Mountain site of the intended underground nuclear waste repository. (Yucca Mountain photograph and map credit: U.S. Nuclear Regulatory Commission.)

The remaining option available today for high-end nuclear waste is underground storage. In the United States, steps have been taken to provide enduring underground storage for the most dangerous nuclear waste. This is the Yucca Mountain nuclear waste repository in southern Nevada about 100 miles northwest of Las Vegas. (See Figure 27.) It is intended to be an underground complex of 40 miles of tunnels to hold 85,000 tons of dangerous nuclear waste. (See Figure 28.) This project began in 1978. It is interesting to note that the planning horizon for ensuring containment is one million years—roughly 250 times the age of the pyramids!

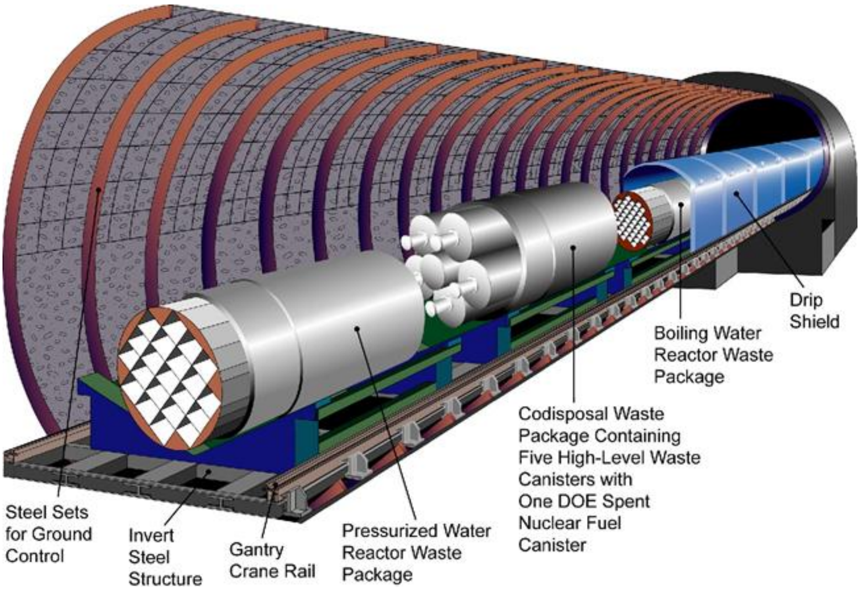


Figure 28: Illustration of how nuclear waste would be stored inside the Yucca Mountain nuclear waste repository. (Credit: U.S. Department of Energy.)

The Yucca Mountain facility has yet to be opened for use due to political opposition and legal challenges. Should it open, its total storage capacity may already be taken by existing high-end military and civilian waste accumulated over the past 80 years. This includes the commercial waste from the roughly 100 nuclear power plants.

As noted previously, each 1-GW nuclear power plant may be expected to produce roughly 20 tons of high-end nuclear waste per year that will require permanent disposal. (The plants also produce low-end waste with less intensive and dangerous forms of radiation. These are disposed of in other ways.) A Yucca Mountain scale facility is, thus, capable of holding in the ballpark of 4,250 plant-years of high-end nuclear waste.

$$\frac{85{,}000 \text{ tons}}{20 \dfrac{\text{tons}}{\text{plant-year}}} = 4{,}250 \text{ plant-years of waste}$$

As discussed previously, the United States will need about 4,200 1-GW nuclear power plants to replace fossil fuels by 2100. To permanently house the waste from these plants using underground storage, one additional Yucca Mountain-scale repository would be needed every year indefinitely. This is not practical.

— *Disposal into outer space*

Outer space disposal means placing the waste in high orbits about the Earth that will not decay for millions of years, placing the waste on the back side of the Moon in a deep crater, or launching the waste into a trajectory that will intersect the Sun—the best option. By 2100, using nuclear fission energy to replace fossil fuels will produce about 80,000 tons per year of high-end waste. To protect this during transport to space may require 5X total mass including shielding and structural protection. Thus, very roughly 400,000 tons will need to be launched into the sun each year.

A typical spaceplane payload to orbit will likely be only 20 tons. Thus, roughly 20,000 spaceplane flights per year would be needed to just reach low Earth orbit. This will not be possible with existing rockets. This will require the development of fully-reusable Transatmospheric Vehicles (TAV) capable of safely operating from runways. Additional astrologistics transport will be needed to safely move the nuclear waste into final disposition, such as disposal into the sun.

— *Concluding comments on disposal*

Reprocessing the spent fuel rods to recover usable fuel or developing new reactor designs that reduce high-end waste will reduce the storage requirements. However, should substantial additional nuclear power be built to replace fossil fuels, the long-term disposal of high-end waste will obviously present a challenge due to the sheer magnitude of waste produced each year.

It will do no good to undertake a program of expanded use of nuclear energy without addressing the storage issue first. This will require effective engineering solutions that are broadly politically acceptable. And, these solutions will need to be universally adopted to prevent high-risk disposal worldwide. Forty years after the Yucca Mountain storage project began, a political solution has yet to emerge.

18. What are the accident consequences and lessons-learned from the 2011 Fukushima nuclear accident?

Just as in all human undertakings, accidents happen at nuclear power plants. Sometimes this is a consequence of an improper human action, sometimes it is the consequence of an unforeseen limitation of technology, and sometimes it is nature acting on the power plant in an unanticipated manner. The March 11, 2011 serious nuclear accident in Japan is a very good example of the safety consequences of a major unanticipated or ignored event on a conventional nuclear fission power plant. These consequences came very close to laying waste to much of Japan.

— *Japan's historic energy insecurity*

Like many nations, Japan has limited natural resources, particularly oil. At the beginning of the last century, the world shifted from coal-fired steam power to internal combustion engines using oil. Japan aggressively turned to military conquest, as had many other nations going back to Alexander the Great, to seize needed natural resources beyond their national boundaries. By the 1930s, like many nations, Japan was almost totally dependent on the United States for oil as the United States was a primary oil exporter. The United States failed in its attempt to use an oil export embargo to influence Japan's imperialistic policies. The result was that World War II in the Pacific Theater was primarily a war to obtain or prevent Japanese control of oil and other vital industrial resources. After the Japanese surrender that ended World War II, the United States created a strong political, economic, political, and military partnership with Japan.

— *Japan's use of nuclear energy*

When civilian nuclear power became available in the 1960s, the United States promoted its use among its close allies. In part, the intent was to help prevent nuclear weapon proliferation. Japan began to build nuclear power plants using U.S. nuclear technology to reduce its dependence on imported fossil fuels. Its first plant was operating in 1966 with 53 additional plants subsequently built. Due to the mountainous nature of the country and its shape, these plants were built on the coast enabling seawater to be used for cooling. (See Figure 29.)

It is important to note that many of these plants were built in the 1970s and 1980s using what is today 50-year old nuclear energy technologies and plant design requirements. Japan is very much aware of the risk to nuclear power plants from earthquakes and tsunamis.

As scientific understanding increases, past decisions regarding the protection of older plants from damage are often viewed differently, sometimes with the conclusion by some that improvements are needed. However, opinions of what could happen are rarely unanimous making a final government or corporate decision to invest the substantial additional resources required to avoid what could happen—not what will certainly happen—politically challenging. This is a universal human trait that is often seen in divided scientific/engineering and political views on any new energy technology. It is evident in the United States, for example, with the decision not to use the Yucca Mountain nuclear waste storage site even in the absence of any Congressionally-approved alternative. Obstinance is prevalent in any open political system—often requiring a disaster to bring common sense changes.

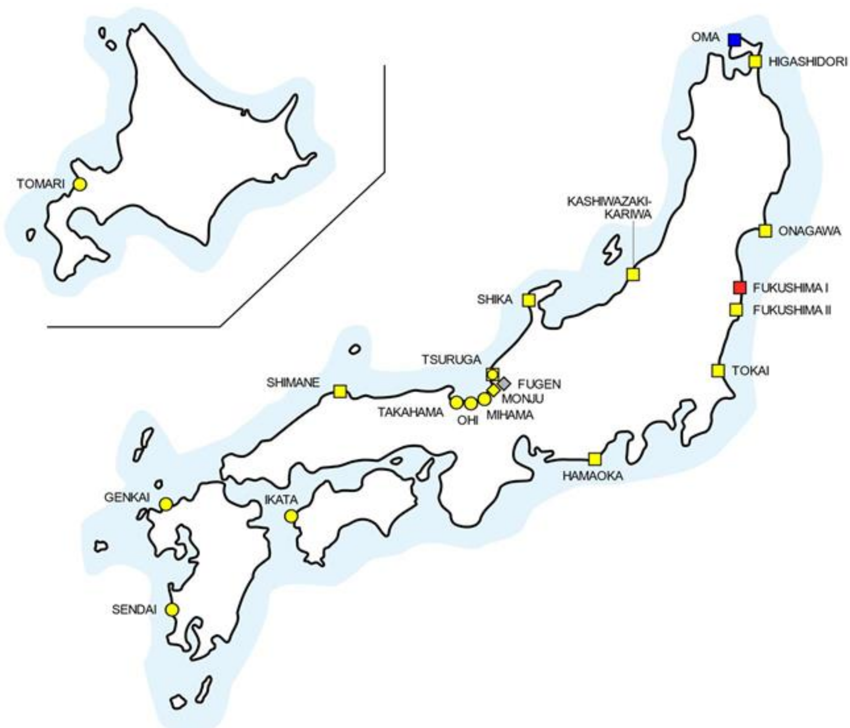


Figure 29: Locations of nuclear power plants in Japan. Most locations have multiple reactors. (Credit: kbegemot, Wikimedia Commons, public domain.)

— *Consequences of the Great East Japan Earthquake*

At 2:46 pm on March 11, 2011, the world's fourth strongest recorded earthquake—the magnitude 9.0 Great East Japan Earthquake—occurred under the seafloor 43 miles off the coast of Japan's Miyagi prefecture. The earthquake and resulting two tsunamis killed an estimated 19,000 people and damaged or destroyed about one million buildings. In Miyako, one of the two tsunamis reached a height of 133 ft. In some areas, the tsunamis flooded six miles inland.

When reviewing the consequences of the earthquake and tsunamis on the Fukushima nuclear power plants, it is important to recognize that the operating power company and Japanese government were dealing with a tremendous human tragedy.

- *Impact of the earthquake on the Fukushima nuclear plants*

Figure 30: Fukushima I nuclear power facility photograph taken prior to the 2011 accident showing the four square reactor buildings. From left-to-right, these are Units 1–4. The plant was built 10 m above sea level. (Credit: U.S. Air Force.)

The earthquake occurred off the coast of the Fukushima I and II nuclear power facilities. There were seven reactors at these facilities, with Units 1-4 shown in Figure 30. All nuclear power plants in Japan are built on rock to minimize earthquake movement. Still, the maximum horizontal ground acceleration at the Fukushima I facility was recorded to be 0.56 g's. (Nearby areas, on sediment, experienced accelerations several times greater.) The earthquake lasted for nearly three minutes. However, the nuclear power plants did <u>not</u> appear to suffer any significant damage from the earthquake.

As a normal procedure, the earthquake triggered an automatic shutdown of the operating nuclear power plants in the region. The first step of the shutdown is to "scram" the reactor by inserting control rods into the reactor. Materials in these rods capture neutrons, stopping any further U-235 chain reactions. Primary heat production stops, quickly leading to a shut-down of electricity generation. At this point, the plant is off-line. However, the reactor and its contents, with considerable thermal mass, are still quite hot with heat that must be removed. Also, the natural decay of short-lived radioisotopes, created in the fuel as the reactor operates, continue to release thermal energy for several days even though nuclear reactions have stopped. Hence, although the chain reactions stop quickly, it takes 3–4 days to complete a shutdown to the point that the residual heat in the reactor has been removed and the reactor is considered cold.

Accomplishing this shutdown requires externally-supplied electrical power to run the pumps to circulate water inside the reactor and discharge the residual heat through external heat exchangers into a lake, river, the ocean, or the atmosphere. External power is also needed to run the facility and control the shutdown. Each facility has backup emergency generators and batteries to temporarily provide this power if needed.

The sudden vertical movement of the ocean floor due to an earthquake can produce a large surface wave called a tsunami. As a result of the 2011 earthquake, two tsunamis hit the facility within an hour, as the shut-down process was underway. Tsunamis produced by large seafloor earthquakes near Japan are common and precautions are taken in the form of a seawall. Due to this extremely large earthquake, the unusually high 15 m (49 ft) tsunami wave height at this location breached the 10 m seawall intended to protect the plant from such an occurrence. As seen in Figure 31, the damage in nearby areas caused by the tsunamis was extensive.

Figure 31: Aftermath of the March 11, 2011 Japanese earthquake and tsunamis. (Credit: Lance Cpl. Gary Welch, U.S. Marine Corps, public domain.)

- *Consequence of inadequate flooding protection*

As the automatic and orderly shutdown of the three operating nuclear plants was underway—Units 1–3— two earthquake-created tsunamis reached the shore only eight minutes apart. (Three other plants in the facility were already shutdown for refueling.) The tsunamis breached the protective seawall to flood the facility, cutting-off the emergency backup generators and destroying the emergency batteries. Further, the earthquake and tsunamis destroyed much of the region's electrical transmission and distribution system preventing outside power from being used.

Tsunamis in the 1980s and 1990s in other parts of Japan exceeded the height of the seawall protecting the Fukushima plants. Hence, the inadequate elevation of the backup generators and batteries and the failure to properly seal the buildings from water intrusion were recognized weaknesses prior to the accident. However, consensus could not be reached to invest the funds needed to address these weaknesses. This failure to undertake common sense precautions precipitated the subsequent events.

- *Consequence of loss of cooling in the reactors*

The design used in the Fukushima plants is shown in Figure 32. The steel reactor is contained within a heavy concrete housing. A large open space under the reactor, called the "dry well", is intended to contain melted nuclear fuel during a loss of containment within the reactor itself. This central concrete housing sits on top of a toroidal shaped "wet well" containing water to help cool down the reactor during an emergency shutdown. Steam produced in the reactor during an emergency shutdown is vented into the sealed wet well where it condenses when it comes into contact with concrete and any liquid water in the well. This is intended to contain any radioactive materials within the overall containment building.

Heroic efforts were undertaken, at serious personal risk, by plant personnel to maintain cooling at the plant. However, radiation levels climbed to the point that evacuation was necessary. In addition to three reactors being without cooling, two fuel storage ponds were without the power needed to circulate water to remove the heat being continuously released within the stored spent fuel rods.

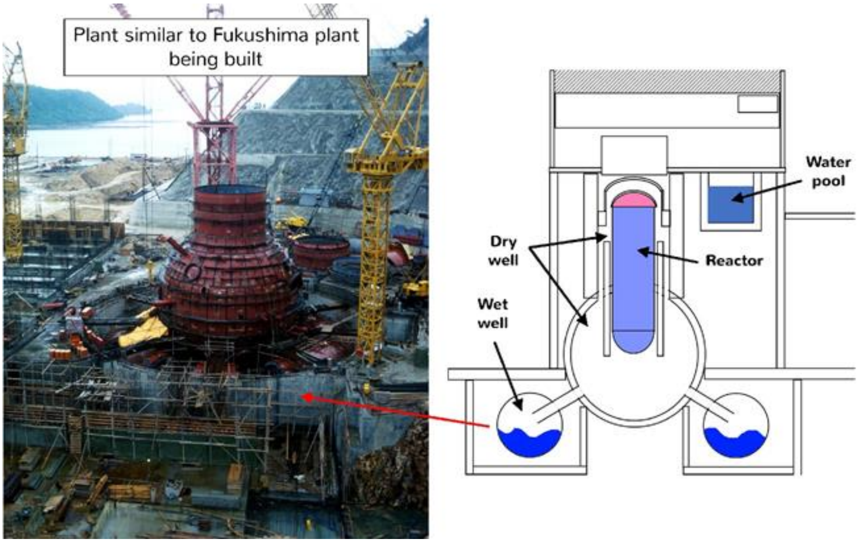


Figure 32: Diagram of the nuclear plant design used in the Fukushima plants. (Left photograph credit: U.S. Government work. Right original diagram credit: 84user, Wikimedia Commons, public domain. Modified right image credit: J. M. Snead.)

Without electricity to circulate water through the reactor, the residual heat in the fuel boils any water remaining in the reactor into steam which is, if the controls are operating, vented into the wet well. As the liquid water level drops, fuel assemblies are uncovered causing their temperature to rise. Temperatures in the reactor can climb to an estimated 5000°F (2800°C). Quickly, all liquid water cooling is lost. The fuel assemblies and control rods melt, falling to the bottom of the reactor while continuing to release heat. In several units, the molten fuel melted through the steel reactor shell and fell into the dry well. (See Figure 32.) There it cooled and solidified.

The loss of the integrity of the fuel rod assemblies prevents the use of traditional methods to remove the assemblies from the reactor. Also, radiation measurements determined that the solidified fuel was still producing extreme radiation levels within the reactor.

Personnel attempting to maintain cooling at the Fukushima plants were forced to evacuate as the radiation levels increased.

Figure 33: Unmodified March 16, 2011 image of the Fukushima I nuclear facility taken by Digital Globe showing the damage to the reactor buildings due to hydrogen explosions. The two long, white buildings at the bottom of the image are not the reactor buildings. The reactor buildings are above these long, white buildings. On two reactor buildings, the exterior siding has been blown off. (Credit: Digital Globe, Wikimedia Commons, used as permitted under the image's stated Creative Commons Attribution-Share Alike 3.0 Unported license.)

As the temperature in the Fukushima reactors and containment structures climbed, water's molecular bonds broke, releasing free hydrogen into the reactor. Hydrogen appears to have escaped into the reactor buildings, mixed with air, and exploded, severely damaging the reactor buildings making access difficult and dangerous and further hindering efforts to contain the release of radioactive materials. (See Figure 33.) A consequence of the hydrogen explosions is that radioactive materials were dispersed downwind of the facility.

- *Consequence of the loss of cooling to the storage ponds*

Each nuclear reactor building contained a concrete water pool located in the reactor building to hold new and used fuel assemblies underwater to remove heat produced by the natural decay of the radioisotopes in the fuel. These pools are not at the ground level as they are in most plant designs but are high up in the reactor building. (See Figure 32.) This elevated location made the pool more vulnerable to loss of water from earthquake-induced damage. Without continuously circulating water through the pool, the trapped water will boil away. Once the fuel assemblies are uncovered, their temperature will climb until they fail due to melting, likely enabling dangerous radioisotopes to escape into the air.

Structural damage to one of these pools and the containment building, the loss of power to pumps, and the damage to the buildings due to hydrogen explosions combined to reduce the water level to a dangerously low level before an emergency source of water was provided. A concrete pump with a 190-ft boom was used as a makeshift water canon to direct water through the damaged walls into the pool. Had water cooling not been restored in time, escaping airborne iodine-131, cesium-137, and cesium-134 radioisotopes could have contaminated a much larger geographic area than occurred. These elements are readily absorbed within tissue. While iodine-131 has a short half-life of only eight days, the half-life of Cesium-137 is 30 years making contamination a prolonged event. Cesium-137 decays with a strong gamma radiation emission making it particularly hazardous to live tissue.

The Fukushima facility also contained a large ground-level storage pond outside the reactor buildings. While the internal storage pond was designed to hold a full core load of around 548 fuel assemblies, the outside pond held about 6,375 fuel assemblies, usually containing spent fuel. This means that this pond may have held several tonnes of U-235 and Pu-239.

Power was lost to the water pumps keeping these pools cool when the plant lost external power. When power was restored after two weeks, the water temperature had climbed to 193°F. While it is reasonable that priority was given to using available resources to address the disabled and heavily damaged reactors and inside water ponds, the secondary storage pond also presented a likely more serious threat had circumstances not enabled power to be restored.

- *Post-accident radioactive soil removal*

By the end of 2012 operations at the Fukushima facility turned to cleanup and remediation. Roughly 5,000 square miles of the surrounding area was monitored for radioactive contamination, primarily from cesium-137. Despite the apparently limited radiation release, one report states that millions of cubic meters of contaminated soil have been removed and placed into temporary storage at the Port of Okuma within the Fukushima prefecture. However, the Japanese government has only promised to remove the soil by 2045—a quarter century in the future—provided they find a location to permanently store it.

- *Post-accident radioactive surface water containment and remediation*

Damage to the reactors and loss of containment is enabling surface water to become contaminated with radioisotopes. Extensive efforts are underway to limit, trap, and contain the contaminated surface water. These include building a permanent metal seawall facing the reactors; surrounding the reactors on the land side with a subsurface frozen wall to limit subsurface water penetration; sealing the surface with concrete; pumping contaminated water into storage tanks; diverting surface water; pumping out subsurface water outside the frozen wall before it can be contaminated; and, treating contaminated seawater with special filters. (See Figure 34.) However, these efforts are not permanent solutions with their long-term practicality questionable. As of 2017, the rate of trapping and containment of contaminated surface water was still 220 metric tonnes per day, about 40 percent of the 2014 rate despite these prevention efforts. What to do with the contained contaminated surface water has yet to be determined.

Figure 34: Contaminated surface water holding tanks constructed at the Fukushima facility. (Credit: International Atomic Energy Agency, CC BY-SA 2.0, www.flickr.com/photos/iaea_imagebank/8547334045/in/photolist-e2ijCn, unmodified.)

- *Evacuation due to the threat of radiation release*

All nuclear power plants have emergency evacuation plans to address actual or potential radiation hazards. At 7 pm on March 11, 2011, the first 2-km evacuation order was issued as the initial consequence of the loss of power and lack of cooling became apparent. In Unit 1, by 7 pm the fuel assemblies in the reactor were almost uncovered with cooling water. By the next day, the fuel assemblies began to melt. The evacuation order was extended to 30 km (19 miles) from the plants. (See Figure 35.) Large portions of these areas were already devastated by the earthquake and tsunami indicating that many were likely already absent.

Reports place the number evacuated between 170,000–200,000; perhaps 300,000. The initial order only impacted about 2,000 people but as the threat of loss of containment mounted, the expanded evacuation order impacted a much larger number of people.

What is interesting is the post-accident response to the evacuation order and their consequences. Due to heroic efforts, containment of the radioactive materials was mostly maintained in the first days. It appears that only the hydrogen explosions released radioactive materials. No immediate deaths in the general population appear to have resulted from this release. Yet, one survey indicates that roughly 1,600 people prematurely died due to the stress of the relocation on their physical and mental health. Some draw the conclusion that the broad evacuation was unneeded and that a shelter in place order would have sufficed. However, had containment not been maintained, then would a shelter in place order have been appropriate? In testimony before Congress immediately after the general evacuation order, the chairman of the U.S. Nuclear Regulatory Commission stated: "We would recommend an evacuation to a much larger radius than has currently been provided by Japan." The need to be cautious and evacuate may, unavoidably, be as dangerous as the potential of direct deaths should a serious radiation release or threat of a release occur.

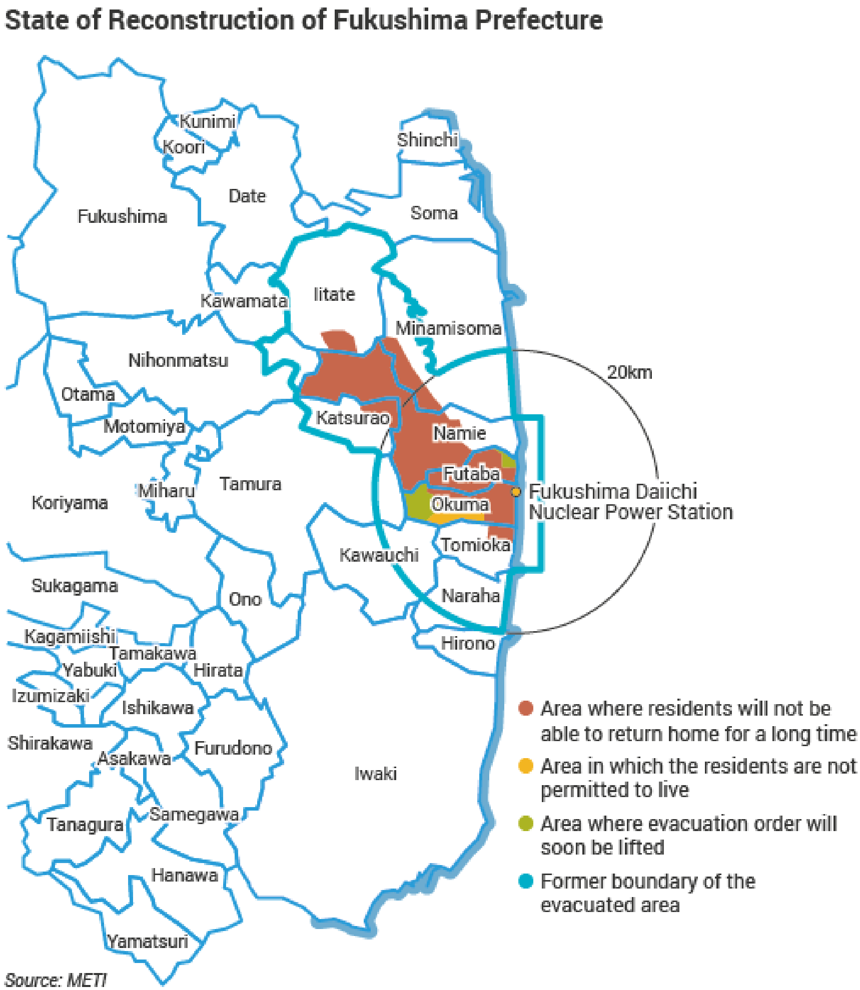


Figure 35: Area adjacent to the Fukushima Daiichi facility that will not be reopened to permanent occupation. (Credit: Japanese Ministry of Economy, Trade and Industry from a World Nuclear Association webpage as of April 11, 2019.)

The Japanese government expects that a large area immediately adjacent to the Fukushima facility will not be habitable for a long time. (See Figure 35.) In the adjacent town of Okuma, part of the town was opened for the return of residents. Of 10,341 registered residents, only 367 indicated a desire to return. Most appear to have moved on with their lives. The rest of Okuma is still unsafe.

- *Cost of the Fukushima accident*

Recognizing that remediation cost estimates are challenging to make, in 2016 the Japanese government estimated its future financial assistance to the company responsible for the Fukushima site at $188 billion which would appear to include indirect costs. The direct facility decommissioning costs were estimated to be $70 billion. These efforts will likely take 3-4 decades to complete.

It is also appropriate to note that melted and solidified fuel remains at the bottom of the damaged reactor buildings. These cost estimates may not fully reflect removal of this highly radioactive material.

- *Lessons-learned regarding siting new nuclear power plants in proximity to central U.S. population centers*

With a U.S. population expected to grow to 500 million by 2100, a substantial use of nuclear power plants to replace fossil fuels will require that plants be located in proximity to population centers. Further, for non-coastal locations, this will require locating these plants on major rivers or lakes.

The Fukushima accident apparently released only a modest amount of radioactive cesium-137 into the atmosphere. Yet, a substantial adjacent land area remains uninhabitable and will likely remain this way for a long time.

Of additional concern at the Fukushima site has been the inability to contain contaminated ground water since radioactive materials attributable to the accident have now been detected across the Pacific Ocean. In the central United States, a similar uncontrollable discharge of contaminated water would likely enter fresh water lakes or rivers or the subsurface fresh water supply. This would create a substantial hazard to nearby and downstream population centers.

19. How will new plant designs impact safety concerns?

The United States has nearly one hundred aging nuclear power plants that will need to be decommissioned. Some may be replaced by new plants using improved designs and different fuel cycles.

— *Improved current designs*

In the 1990s, a new generation of commercial nuclear power plants began to be built, although only a handful have so far become operational. The intent of this generation—referred to as Generation III—was to evolve the earlier designs to increase safety, especially passive procedures to cool the reactor, to increase standardization to minimize construction costs, and to decrease the overall burden of operating the plant.

The Fukushima plant failures identified further improvements in the Generation III plants that are being incorporated. Within the United States, safety regulatory approval is undertaken by the Nuclear Regulatory Commission. It has so far approved a few Generation III designs.

— *Next generation designs*

An entirely new generation of fission plants—Generation IV—is under development. These may, as examples, incorporate thorium-based breeding, nuclear waste burnup to minimize waste disposal needs, and extreme high-temperature operation to use heat, rather than electricity, to produce hydrogen from water directly. These are not expected to become ready for commercialization for a generation. Fueling these plants will likely require breeding.

— *Small nuclear power plants*

Advocates of conventional fission nuclear power are exploring the design of nuclear power plants producing less than 300 MW of electrical power. The goal is to develop designs that can be produced at a manufacturing plant and transported to the operational site as a single unit or as major modules. (See Figure 7 for a small reactor that, decades ago, was transported to the site as a single unit.) A single reactor could be used, or several could be housed together to provide a combined output to replace a current larger commercial nuclear plant or coal-fired power plant.

Serial production, it is argued, would reduce costs, increase uniformity of design, and increase quality and safety. Designers are exploring ways to increase plant safety with respect to safe scram shutdown in the absence of external power and water, eliminate on-site refueling, reject waste heat to the atmosphere, and, even, run without on-site human control. In some designs, the reactor would be buried for increased protection from external threats and containment of the radioactive materials. Despite the smaller size, key siting considerations, including the proximity to population centers, would be the same. Waste disposal would also remain an important issue needing an acceptable solution.

Extra small nuclear power plants, perhaps as small as producing 15 MW of electrical power, may be attractive in some circumstances such as remote locations having modest populations, and energy-intensive industries such as steel and aluminum production. The first nuclear submarine, the *U.S.S. Nautilus*, had a 10 MW nuclear power reactor.

20. Is there risk of nuclear plant abandonment?

The Japanese power company that owns Fukushima is facing a significant cost for cleanup and demolition of the damaged reactors. The Japanese government intends to financially support the power company. With the broad expansion of nuclear power to replace fossil fuels, presumably worldwide, private companies and the insurance market may need to assume greater financial risk. Governments may encourage private investment through regulatory reform and reduced government oversight, especially outside the United States.

The wind power industry is starting to see abandonment of broken wind turbines. Not replacing a broken turbine or simply shutting down the company may become preferred to investing the funds needed to repair or replace broken, out-of-warranty turbines. Property owners that leased land for the turbines may be left with non-functioning turbines without legal recourse to have the original owners pay for removal and site remediation. Being a commercial agreement and lacking any safety risk to the general public, the government may choose not to be involved. The broken turbines would become relics.

It is possible that a new small nuclear power industry may try to emulate the wind power industry by purchasing small nuclear power plants from the manufacturer and entering into power supply contracts with local utilities or industries. Government regulation and oversight may be reduced to promote private investment and increased financial returns. Private nuclear power companies, perhaps experiencing financial problems because their primary commercial customer closes or out-of-warranty repairs or regulatory changes are too expensive could simply walk away, abandoning their nuclear plants. However, unlike the benign giants of broken wind turbines, these buried power plants could contain radioisotopes—e.g., plutonium and cesium—emitting intense radiation or other residual sources of radiation. Local or state governments would likely inherit primary legal responsibility for the abandoned reactors much as has happened with toxic chemical dumps.

As mentioned, some small reactors are being designed to be buried at the site. While the plant was not a radioactive hazard when first transported; after becoming operational, it would be. In some plants, such as molten salt reactors, the radioactive solid salt may not be readily removed should a normal shutdown procedure not be used, such as would happen with an accident. Simply digging up the once-operated plant and transporting it to a disposal site would possibly become a significant safety problem and cost burden. Land, water, and rail transport of the radioactive reactor may not be safe or even possible.

While it is easy to think of small nuclear power plants as a simple solution for the issues facing large nuclear power plants, simply being smaller does not necessarily resolve any of these issues. Small nuclear fission power plants may find a useful niche, perhaps as clusters to replace aging GW-class plants. The notion, however, of thousands of neighborhood nuclear fission power stations powering America does not appear to be practical.

21. What would be the consequence of an EMP attack on nuclear power plants?

When detonated at the correct high altitude, a nuclear explosion will create a massive pulse of electromagnetic energy. Propagating down into the atmosphere, the pulse creates powerful voltage and amperage surges in unshielded electrical equipment and electrical transmission lines. The surges can create electrical arcs, start fires, melt power lines, and render equipment, especially safety monitoring equipment, inoperable.

While a nuclear EMP attack would create substantial devastation, the dependence of nuclear power plants on secondary external power to maintain cooling for years after the reactor is shut down creates an especially dangerous situation. Even if the local plant is sufficiently EMP hardened to enable the reactor to be scrammed with battery or generator power providing cooling, these will not provide power for years.

Without external power, core and fuel assemblies stored in cooling ponds would melt down. Hydrogen explosions may occur, damaging critical containment structure and dispersing radioactive materials into the air, contaminating a large area downwind. Surface water contamination would further spread the radioactive materials. Each nuclear power plant would become a prolonged nuclear radiation hazard that, in a post-EMP attack environment, may be impossible to detect or end once containment is lost.

22. What are the prospects for nuclear fusion energy?

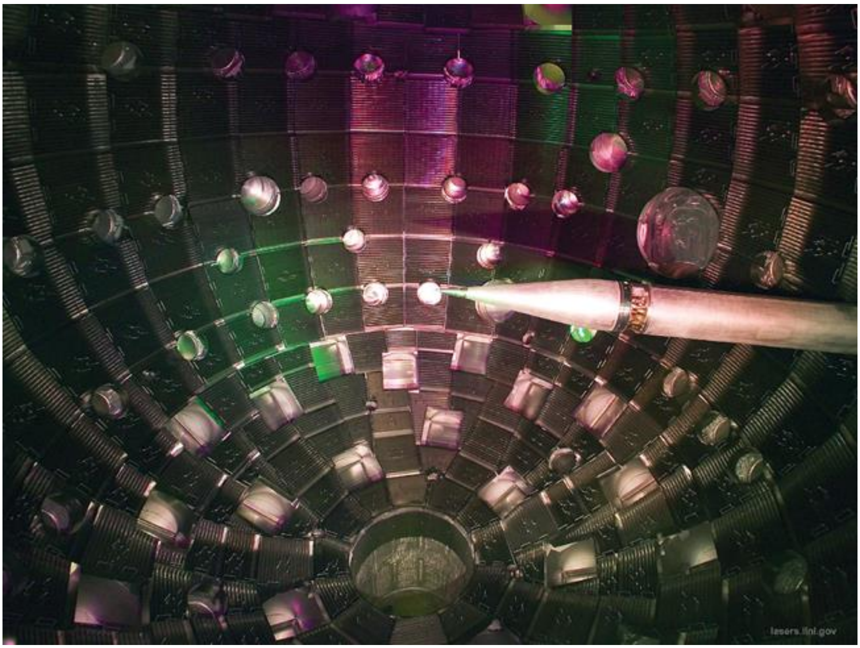


Figure 36: Experimental U.S. laser-initiated fusion facility. Multiple lasers, entering through the portholes, converge on the target held at the tip of the probe. (Credit: U.S. Government work.)

Whereas nuclear fission divides a single nucleus into two to liberate nuclear energy, nuclear fusion combines multiple nuclei into one to liberate nuclear energy. Stars use fusion to produce solar energy. Humans first demonstrated the ability to produce fusion energy using nuclear weapons. Since then, scientists have been trying to produce sustained nuclear fusion as a commercial power source to replace nuclear fission.

Producing nuclear fusion in a laboratory has been accomplished using laser methods, as shown in Figure 36, and electromagnetic containment methods. In fact, achieving fusion is not that difficult as even desktop fusion devices have been built—some as high school science fair experiments. What has not yet been achieved is producing more useful electricity than is being consumed by the fusion device. When this is achieved, the nuclear fission reactor could be replaced with a nuclear fusion device.

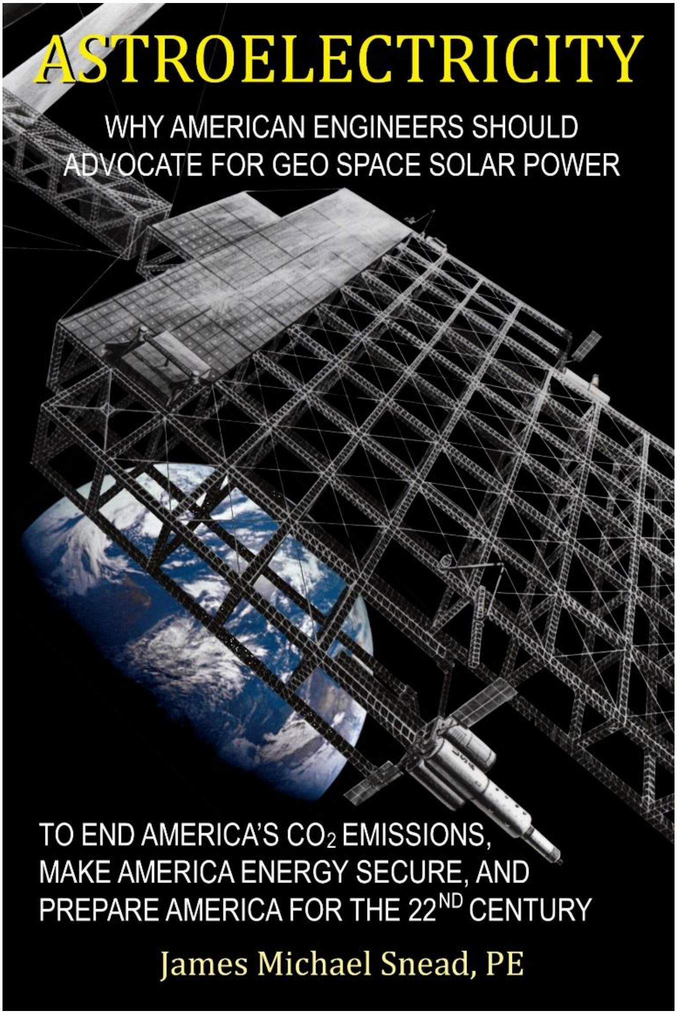
Heat produced in some manner will still likely be the means of generating electricity. This means that nuclear fusion plants will likely be thermal plants where only 30–40 percent of the nuclear energy becomes electricity with the remainder becoming waste heat at the plant site. Thus, utility-scale (GW) nuclear fusion power plants will still likely require external cooling like that needed by nuclear fission plants today.

Most fusion approaches produce free neutrons. Thus, fusion energy may still enable nuclear weapon proliferation through the covert breeding of U-233 or Pu-239. To limit or avoid issues related to the production of neutrons, researchers are trying to develop a form of fusion called aneutronic fusion. Little or no free neutrons are released as the target nuclei fuse. Also, theoretically, the released nuclear energy can be directly converted into electricity

All types of nuclear fusion remain in the early research phase of development seeking needed breakthroughs to proceed to engineering development. Thus, while a future aneutronic fusion device may one day provide a compact electrical power source, there is still no demonstrated technological path to a practical implementation.

23. What sustainable power source can replace fossil fuels?

Geostationary Earth orbit space solar power—astroelectricity.



Corrections & Updates

- *20190418: Minor typo correction on page 22.*

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