U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

COMMERCIAL SPENT NUCLEAR FUEL

OVERVIEW

Commercial spent nuclear fuel (SNF) is nuclear fuel that has been removed from a commercial nuclear power reactor following irradiation and that is no longer intended for use in producing power. The United States first began using nuclear power to produce electricity in 1957. This fact sheet focuses on SNF from the two types of commercial nuclear power reactors operating in the U.S. today—boiling water reactors (BWRs) and pressurized water reactors (PWRs).[1] As of May 2017, 34 BWRs and 65 PWRs were in operation in the U.S., for a total of 99 operating nuclear power reactors (NRC 2017).

STORAGE AND LOCATION

When SNF is first removed from a nuclear reactor, it is intensely radioactive and thermally hot due to radioactive decay (the heat generated is called decay heat), which decreases over time. Until the radioactivity has subsided sufficiently, the SNF must be stored underwater in a spent fuel pool adjacent to the reactor to dissipate the decay heat. The water in the spent fuel pool also provides shielding to protect plant operators and equipment from the SNF radiation.

Because spent fuel pools have limited capacity, beginning in the 1980s, nuclear utilities began to transfer SNF to dry-storage systems to create space in the pools for additional SNF removed from the reactors. Dry-storage systems provide radiation shielding, as well as natural circulation air cooling to dissipate decay heat. The SNF can be transferred to dry-storage systems once it has aged sufficiently to be cooled by passive air ventilation—generally after about five years or longer. The dry-storage systems are arranged either vertically on concrete pads or horizontally in concrete structures at Independent Spent Fuel Storage Installations (ISFSIs). ISFSIs are designed to store SNF for several decades until the SNF is permanently disposed of in a geologic repository or is transferred to a centralized storage facility. ISFSIs are in operation at the majority of reactor sites, including 13 shut down sites.[2] Both spent fuel pools and ISFSIs are licensed to operate by the U.S. Nuclear Regulatory Commission.

Figure 1 shows the estimated distribution of the PWR and BWR SNF inventory in wet and dry storage, based on Vinson and Metzger's (2017) projections of SNF

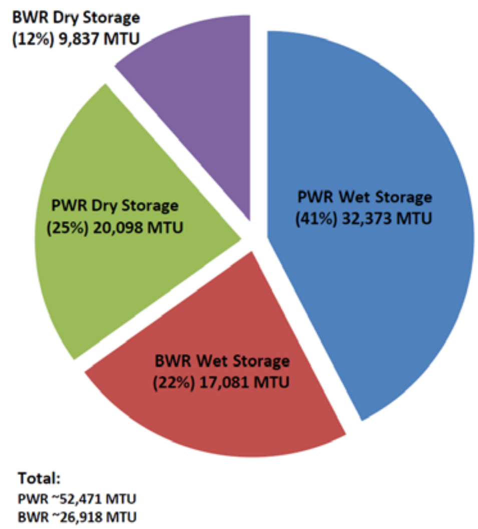

Figure 1. Distribution of Commercial Spent Nuclear Fuel Inventory in Wet and Dry Storage, Projected to December 31, 2017.
Note: Data from Vinson and Metzger (2017).

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[1] The U.S. Department of Energy (DOE) manages SNF from some early commercial reactors, including from gas-cooled reactors such as at the former Fort St. Vrain (Colorado) commercial nuclear power plant (see fact sheet on *Department of Energy-Managed Spent Nuclear Fuel at Fort St. Vrain*). An overview of DOE-managed SNF is provided in the fact sheet on *DOE-Managed Spent Nuclear Fuel*.

[2] Shut down sites are commercial nuclear power reactor sites where all the reactors have been shut down and the site has been decommissioned or is undergoing decommissioning.

inventory (in metric tons of uranium, MTU)[3] through the end of 2017. Approximately two thirds of the total mass of commercial SNF stored at that time will be in spent fuel pools, whereas the remainder will be in dry storage at ISFSIs. Figure 2 shows the locations in the U.S. of wet storage (spent fuel pools) and dry storage (ISFSIs) of commercial SNF.[4]

COMPOSITION

Nearly all commercial reactor fuel is composed of small (approximately the size of a fingertip) ceramic pellets of uranium dioxide sealed inside 12- to 15-foot-long (3.7- to 4.6-meter-long) metal tubes, referred to as cladding, to form fuel rods. Some early fuel used stainless steel cladding, but most cladding used now is fabricated from zirconium alloys. Fuel rods are held in a geometric array by spacer grids and other components to form a "fuel assembly." Figure 3 shows typical PWR and BWR fuel assemblies.

The uranium in PWR and BWR fuel is comprised mostly of the uranium-238 isotope. Typically, the fuel is enriched in the fissile uranium-235 isotope to about 3 to 5% by mass (natural uranium contains only

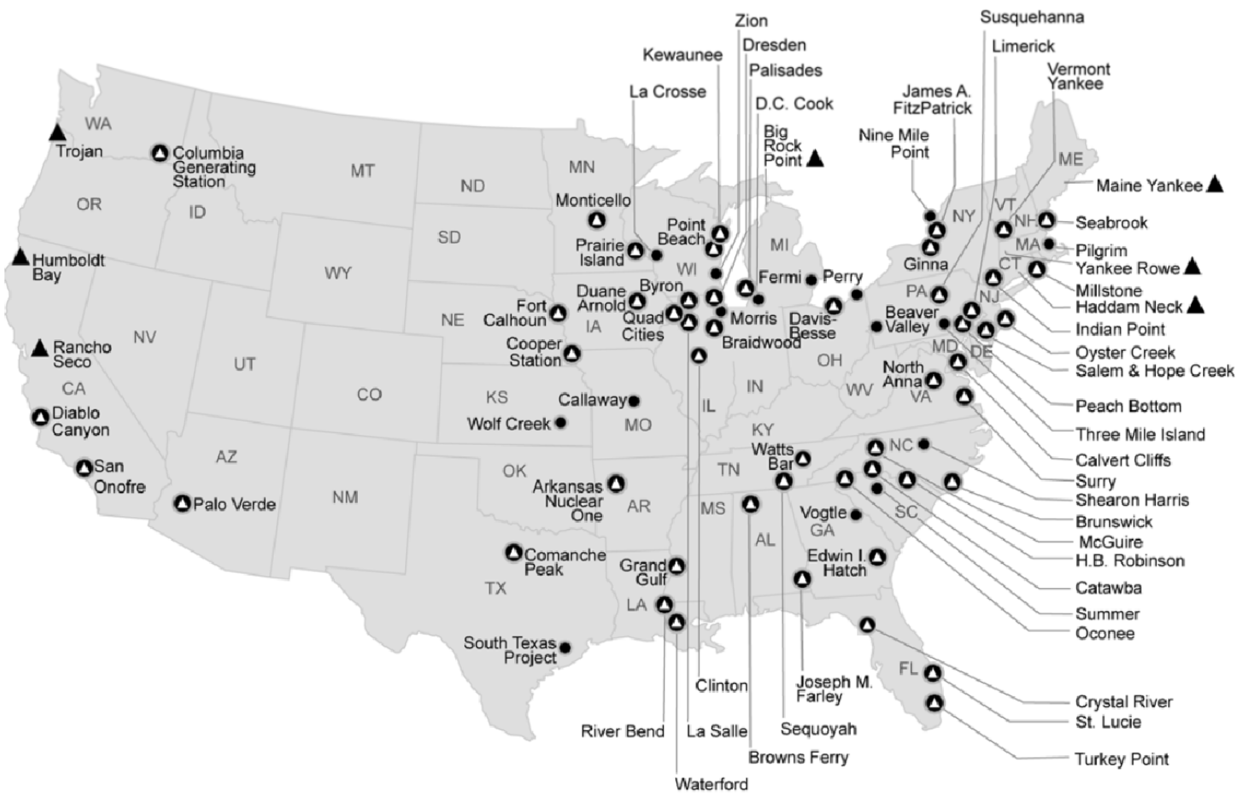

Figure 2. U.S. Locations Where Commercial Spent Nuclear Fuel Is Stored in Spent Fuel Pools (Wet Storage) or in Dry-Storage Systems at Independent Spent Fuel Storage Installations. Modified from GAO (2012) and Updated with Information from UxC (2017).

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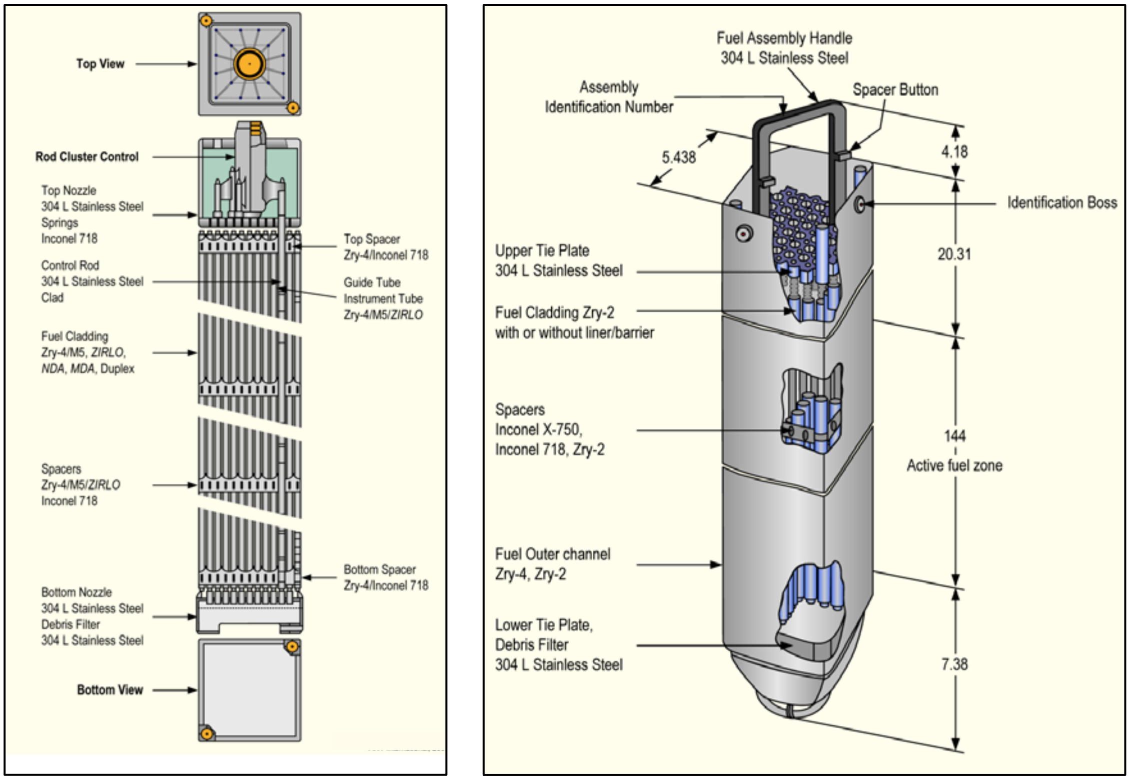
[3] Unit of measurement for the mass of commercial SNF. It refers to the mass of uranium that is contained in a fuel assembly before irradiation in a nuclear reactor. A metric ton is 1,000 kg, which is equal to about 2,200 lb.

[4] The ISFSI in Morris, Illinois, shown in Figure 2 is an away-from-reactor facility that stores SNF in a spent fuel pool.



(a) (b)

Figure 3. Typical (a) Pressurized Water Reactor and (b) Boiling Water Reactor Fuel Assemblies (Strasser *et al.* 2014). Provided by Courtesy of ANT International. Dimensions in Inches.

about 0.71% by mass uranium-235). The composition of commercial SNF removed from a reactor depends on the fuel burnup.[5] SNF with a burnup of 50 GWd/MTU consists of about 93.4% uranium (~0.8% of which is uranium-235), 5.2% fission products, 1.2% plutonium, and 0.2% other transuranic elements (neptunium, americium, and curium) (Feiveson *et al*. 2011).

MASS AND RADIOACTIVITY

The U.S. inventory of commercial SNF was projected to be 79,389 MTU by the end of 2017 (Vinson and Metzger 2017). The estimated total radioactivity of the SNF inventory in 2012 was 23 billion curies (Carter *et al*. 2013). The commercial SNF inventory is expected to increase by 2,000 MTU each year (GAO 2011), increasing the inventory to 142,000 MTU and 33 billion curies by 2048.

As noted above, radioactivity decreases with time. After 10,000 years, commercial SNF will be about ten thousand times less radioactive than it is one month after it is removed from the reactor. After many hundreds of thousands of years, the radioactivity in SNF will become equivalent to that in the original mined uranium ore (Bruno and Ewing 2006). Figure 4 illustrates the major contributors to commercial SNF radioactivity as a function of time. Initially, the radioactivity is dominated by short-lived fission products, such as cesium-137 and strontium-90, which have half-lives of ~30 years. However, long-half-lived fission product radionuclides also are present in the SNF, such as technetium-99 (210,000 years),

[5] Burnup is the amount of energy extracted per unit mass of the fuel. Typical units for burnup of commercial SNF are gigawatt-days per metric ton of uranium originally contained in the fuel (GWd/MTU) or megawatt-days per metric ton of uranium (MWd/MTU).

selenium-79 (1.1 million years), cesium-135 (2.3 million years), and iodine-129 (16 million years). After several hundred years, the total radioactivity is dominated by long-half-lived actinides, including uranium-238 (4.5 billion years), uranium-235 (0.70 billion years), neptunium-237 (2.1 million years), and plutonium-239 (24,100 years). As illustrated in Figure 4, the radioactivity of some isotopes can increase with time for a while, the result of a parent isotope decaying and producing daughter isotopes at a rate faster than the decay rate of the daughter isotopes.

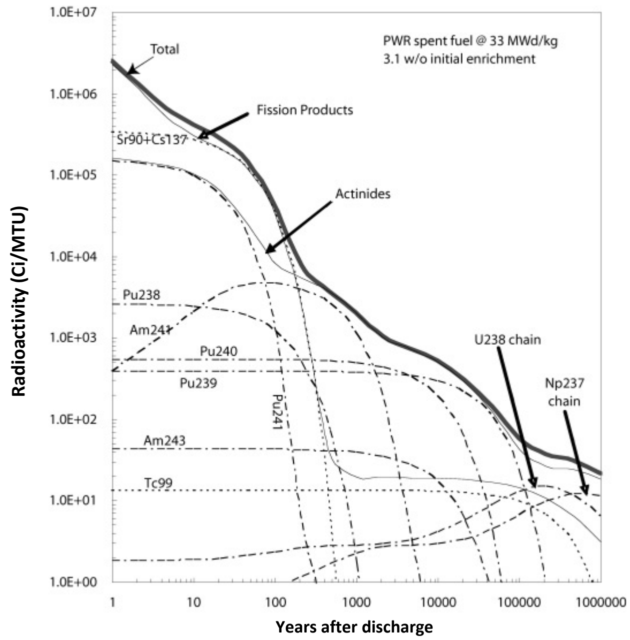


Figure 4. Radioactivity (Curies per Metric Ton of Uranium) *vs*. Time for Pressurized Water Reactor Spent Nuclear Fuel. Reproduced From Xu *et al.* (2005) with Permission from the American Nuclear Society, La Grange Park, Illinois.

STABILITY AND RADIONUCLIDE RELEASE IN A GEOLOGIC REPOSITORY

In a geologic repository, commercial SNF will be disposed of inside corrosion-resistant metal waste packages to delay or prevent groundwater from reaching the SNF. Commercial SNF has two stages of degradation once groundwater breaches the waste package and the fuel cladding. A fraction of the SNF radionuclide inventory is susceptible to prompt, or "instantaneous," release when the SNF is first exposed to groundwater. This fraction includes mainly the radionuclides that migrated between the fuel grains in the fuel pellet and between the fuel pellet and the fuel cladding during reactor operation and, to a lesser degree, during SNF storage, including long-lived, highly mobile radionuclides such as chlorine-36, selenium-79, technetium-99, iodine-126, and cesium-135 (Fanghänel *et al*. 2013). However, most of the radionuclides (over 90%) are embedded within the uranium dioxide fuel matrix and are released later when the matrix is dissolved by groundwater (Shoesmith 2000).

At the depths of mined geologic repositories, such as the KBS-3 repository described in the fact sheet, *Spent Nuclear Fuel and High-Level Radioactive Waste in the United States* (NWTRB 2017), the groundwater is inevitably oxygen-free. Under this condition, uranium dioxide is very insoluble and the radionuclide release from the SNF will be very slow, with fractional release rates of 10^{-6} to 10^{-8} per year (Werme *et al*. 2004). When oxygen is present in groundwater, uranium dioxide is much more soluble and the radionuclide release from the SNF will be much faster compared to oxygen-free conditions. The solubility of uranium dioxide is further increased by the presence of certain dissolved chemical species, such as carbonate ions, in groundwater. But even if the groundwater that contacts the SNF is oxygen-free, the radiation from decaying radionuclides will break down water molecules and produce a variety of chemical species, including oxidants such as hydrogen peroxide, that could enhance the dissolution of the uranium dioxide fuel matrix. However, this radiolytic enhancement of SNF dissolution could be offset by the presence of oxidant scavengers, such as ferrous ion and hydrogen gas, that results from corrosion of the SNF waste package. Thus, the radiolytic effect on SNF dissolution may not be significant.

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The U.S. Nuclear Waste Technical Review Board is an independent federal agency established in the 1987 amendments to the Nuclear Waste Policy Act (NWPA).

The Board evaluates the technical and scientific validity of U.S. Department of Energy activities related to implementing the NWPA and provides objective expert advice on nuclear waste issues to Congress and the Secretary of Energy.

The eleven Board members are nominated by the National Academy of Sciences and are appointed by the President.

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