U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

COMMERCIAL SPENT NUCLEAR FUEL

OVERVIEW[1]

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 United States today—boiling water reactors (BWRs) and pressurized water reactors (PWRs).[2] As of August 10, 2021, 31 BWRs and 62 PWRs were in operation in the United States, for a total of 93 operating nuclear power reactors (NRC 2021a).

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 (Figure 1). 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 cask storage systems to create space in the pools for additional SNF removed from the reactors (NRC 2021c). The casks are typically steel canisters that are either welded or bolted closed (Figure 2). Each canister is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and the public. The SNF can be transferred to dry cask storage systems once it has aged sufficiently to be cooled by natural circulation of air external to the sealed cask. The dry cask storage systems are arranged either vertically (above ground or below ground) or horizontally in concrete structures at Independent Spent Fuel Storage Installations (ISFSIs) (Figure 3). ISFSIs are used to store SNF until the SNF is removed from the site for permanent disposal in a geologic repository or is transferred to another storage facility, such as a centralized interim storage facility. As of December 2021, ISFSIs are in operation at all reactor sites, including shut down sites,[3] with the exception of the

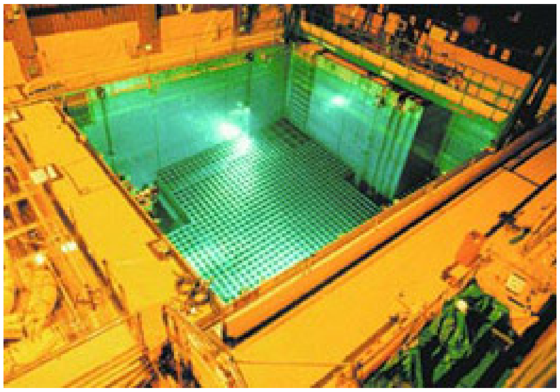

Figure 1. Example of a Spent Fuel Pool at a Reactor. Source: NRC (2021b)

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[1] Unless explicitly stated, this fact sheet does not present Board findings, conclusions, or recommendations and none should be inferred from its content.

[2] 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*.

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

Shearon Harris site.[4] The locations of U.S. ISFSIs are shown in Figure 4. Both spent fuel pools and ISFSIs are licensed to operate by the U.S. Nuclear Regulatory Commission (NRC).

COMPOSITION

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. Typically the cladding material is zirconium alloy. Fuel rods are held in a geometric array by spacer grids and other components to form a "fuel assembly." Figure 5 shows examples of PWR and BWR fuel assemblies.

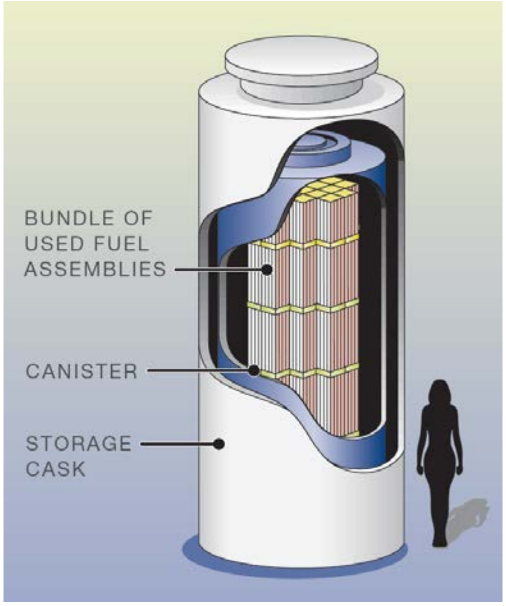

Figure 2. Spent Nuclear Fuel in a Dry Cask Storage System. Source: BRC (2012).

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 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).

(a) **(b)** **(c)**

Figure 3. Types of Dry Cask Storage Systems at Independent Spent Fuel Storage Installations: (a) Vertical, Above Ground (Maine Yankee, Wiscasset, ME), (b) Vertical, Below Ground (Humboldt Bay, Eureka, CA), and (c) Horizontal (Rancho Seco, Herald, CA). Source: Rechard et al. (2015).

[4] In December 2021, workers at Three Mile Island began loading SNF into dry cask storage systems for the first time. Dry storage loading activities at the Wolf Creek Generating Station began on January 2, 2022 (UxC 2022). The Shearon Harris Nuclear Power Plant will not require dry storage of SNF before the end of its current license (Peters et al. 2021; UxC 2022).

[5] Fuel burnup is a measure of the thermal energy generated in a nuclear reactor per unit mass of nuclear fuel as initially loaded in the reactor and is typically expressed in units of gigawatt-days per metric ton of uranium (GWd/MTU).

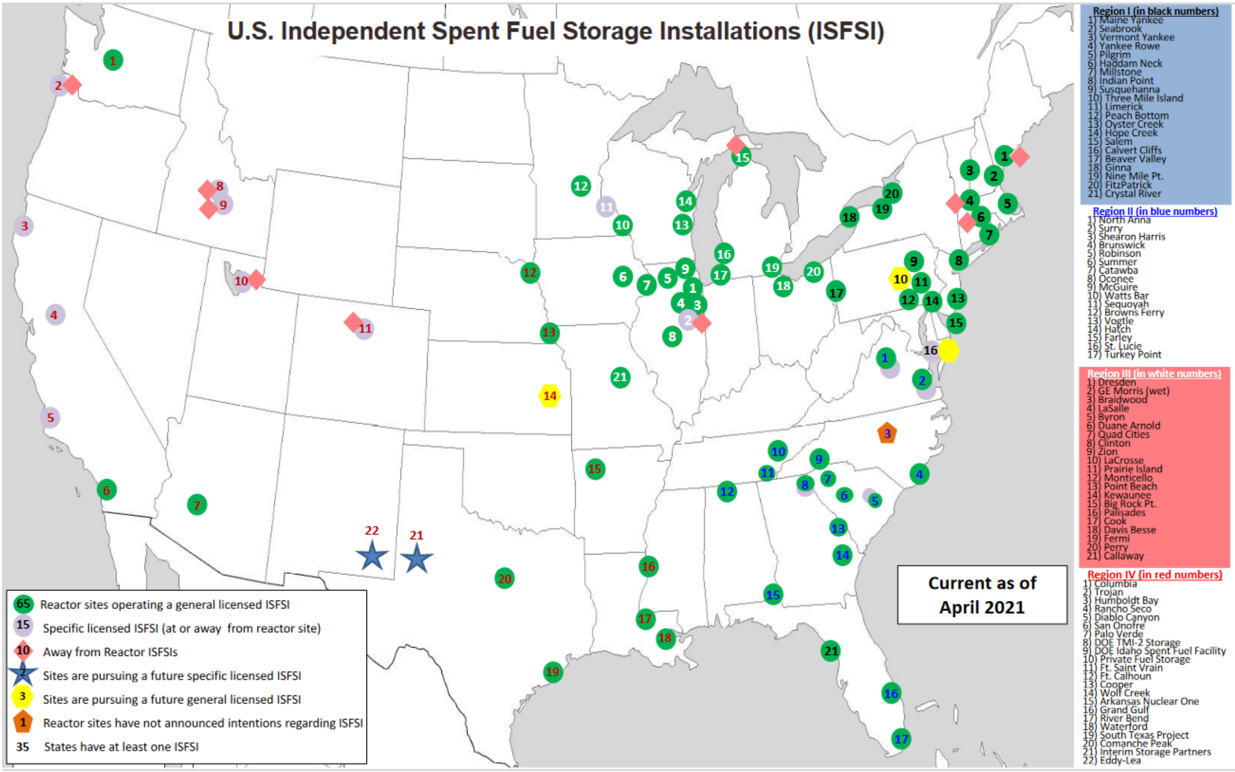

Figure 4. Locations of U.S. Independent Spent Fuel Storage Installations. Source: NRC (2021d).

MASS AND RADIOACTIVITY

The U.S. inventory of commercial SNF (in metric tons of uranium, MTU) as of December 31, 2020 was estimated to be 86,584 MTU (Peters et al. 2021, Table 2-5). This inventory has been increasing by approximately 2,200 MTU per year since 2012 (Freeze et al. 2021). The estimated total radioactivity of the SNF inventory in 2012 (~70,100 MTU) was 23 billion curies (Carter et al. 2013).

Figure 6 shows the distribution of the PWR and BWR SNF inventory in wet and dry storage at nuclear power reactor sites as of the end of December 2020 (Peters et al. 2021, Table 2-6). Just over half the total mass of commercial SNF is stored in spent fuel pools, with the remainder in dry storage at ISFSIs.

As noted above, radioactivity decreases with time and, therefore, the associated radiological risk to the public and the environment also 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 7 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-lived fission product radionuclides also are present in the SNF, such as technetium-99 (210,000 years), chlorine-36 (301,000 years), 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-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 7, 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.

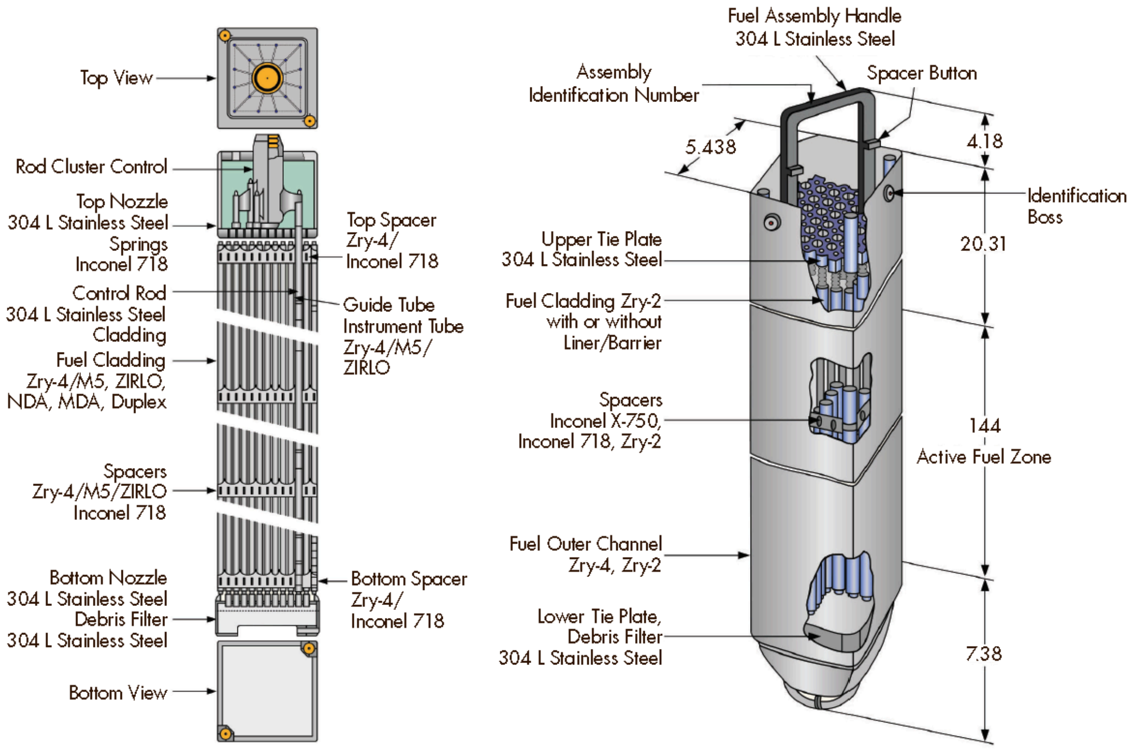

Figure 5. Examples of (a) Pressurized Water Reactor and (b) Boiling Water Reactor Fuel Assemblies (Strasser et al. 2014). Provided by Courtesy of ANT International. Dimensions in Inches.

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 if 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 cesium-135, chlorine-36, iodine-129, selenium-79, and technetium-99 (Fanghänel et al. 2013). However, most of the radionuclides (over 90%) are embedded within the

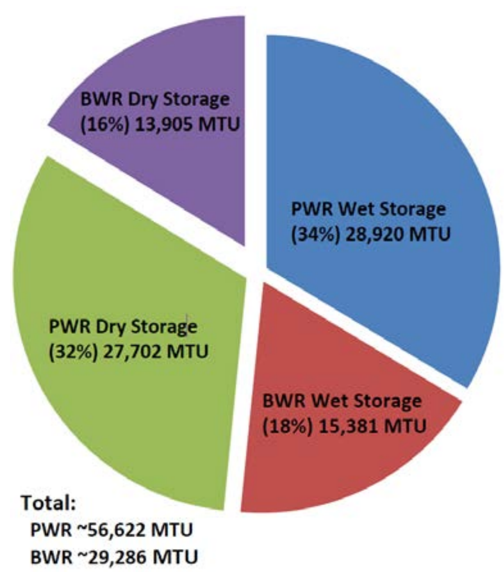

Figure 6. Distribution of Commercial Spent Nuclear Fuel Inventory in Wet and Dry Storage at Nuclear Power Reactor Sites, as of December 31, 2020. Note: Data from Peters et al. (2021, Table 2-6). Excludes the Inventory Stored at the Morris, IL Away-from-Reactor Independent Spent Fuel Storage Installation.

uranium dioxide fuel matrix and are released later when the matrix is eventually dissolved by groundwater (Shoesmith 2000).

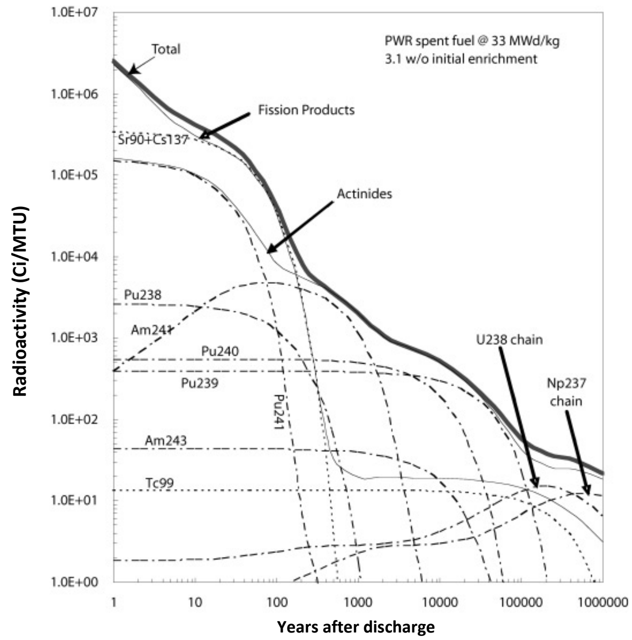

Figure 7. Radioactivity (Curies per Metric Ton of Uranium) *vs*. Time for Pressurized Water Reactor Spent Nuclear Fuel. Reproduced from Xu et al. (2005) with Permission from the American Nuclear Society, La Grange Park, Illinois.

At the depths of mined geologic repositories, such as the Onkalo repository under construction in Finland, 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 ions and hydrogen gas, that result from corrosion of the SNF waste package (Jerden et al. 2019). Thus, the radiolytic effect on SNF dissolution may not be significant.

REFERENCES

BRC (Blue Ribbon Commission on America's Nuclear Future). 2012. *Report to the Secretary of Energy*. https://www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf. [Accessed December 29, 2021].

Bruno, J. and R.C. Ewing. 2006. "Spent Nuclear Fuel." *Elements*, Vol. 2, pp. 343–349.

Carter, J.T., A.J. Luptak, J. Gastelum, C. Stockman, and A. Miller. 2013. *Fuel Cycle Potential Waste Inventory for Disposition*. FCRD-USED-2010-000031, Rev. 6. Washington, D.C.: U.S. Department of Energy. July.

Fanghänel, T., V. Rondinella, J.-P. Glatz, T. Wiss, D. Wegen, T. Gouder, P. Carbol, D. Serrano-Purroy, and D. Papaioannou. 2013. "Reducing Uncertainties Affecting the Assessment of the Long-Term Corrosion Behavior of Spent Nuclear Fuel." *Inorganic Chemistry*, Vol. 52, pp. 3491–3509.

Feiveson, H., Z. Mian, M.V. Ramana, and F. von Hippel. 2011. *Managing Spent Fuel from Nuclear Power Reactors—Experience and Lessons from Around the World*. International Panel on Fissile Materials. September.

Freeze, G., E. Bonano, P. Swift, E. Kalinina, E. Hardin, L. Price, S. Durbin, R. Rechard, and K. Gupta. 2021. *Integration of the Back End of the Nuclear Fuel Cycle*. SAND2021-10444. Albuquerque, New Mexico: Sandia National Laboratories. August.

Jerden, J., E. Lee, V. Gattu, and W. Ebert. 2019. *Fuel Matrix Degradation Model Development Update: Alloy Corrosion Rates and Hydrogen Generation*. ANL/CFCT-19/12. Argonne, IL: Argonne National Laboratory. September.

NRC (U.S. Nuclear Regulatory Commission). 2021a. *NRC 2021–2022 Information Digest*. NUREG-1350, Volume 33. Washington, D.C.: U.S. Nuclear Regulatory Commission. October.

NRC. 2021b. "Spent Fuel Pools." https://www.nrc.gov/waste/spent-fuel-storage/pools.html [Accessed December 29, 2021].

NRC. 2021c. "Dry Cask Storage." https://www.nrc.gov/waste/spent-fuel-storage/dry-cask-storage.html [Accessed December 29, 2021].

NRC. 2021d. "Locations of U.S. Independent Spent Fuel Storage Installations." https://www.nrc.gov/docs/ML2111/ML21116A041.pdf [Accessed December 29, 2021].

Peters, S., D. Vinson, and J. Carter. 2021. *Spent Nuclear Fuel and Reprocessing Waste Inventory*. FCRD-NFST-2013-000263, Rev. 8d. July.

Rechard, R.P., L.L. Price, and E.A. Kalinina. 2015. *Integrating Management of Spent Nuclear Fuel from Generation to Disposal*. SAND2015-5503. Albuquerque, New Mexico: Sandia National Laboratories. June.

Shoesmith, D.W. 2000. "Fuel Corrosion Processes Under Waste Disposal Conditions." *Journal of Nuclear Materials*, Vol. 282, pp. 1–31.

Strasser, A., P. Rudling, and C. Patterson. 2014. *Fuel Fabrication Process Handbook, Revision I.* Mölnlycke, Sweden: Advanced Nuclear Technology International. February.

Werme, L.O., L.H. Johnson, V.M. Oversby, F. King, K. Spahiu, B. Grambow, and D.W. Shoesmith. 2004. *Spent Fuel Performance Under Repository Conditions: A Model for Use in SR-Can*. Technical Report TR-04-19. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. September.

UxC. 2022. *StoreFUEL and Decommissioning Report*. Vol. 24, No. 281. January 4, 2022. Roswell, GA: UxC, LLC.

Xu, Z., M.S. Kazimi, and M.J. Driscoll. 2005. "Impact of High Burnup on PWR Spent Fuel Characteristics." *Nuclear Science and Engineering*, Vol. 151, pp. 261–273.

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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