MANAGEMENT OF SPENT FUEL FROM HIGH-TEMPERATURE GAS-COOLED REACTORS IN THE UNITED STATES

For presentation at the IAEA Technical Meeting on the Management of Spent Fuel (Pebbles and Compacts) from High Temperature Reactors

Vienna, Austria

July 7 – 11, 2025

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Spent Fuel and High-Level Waste Disposition

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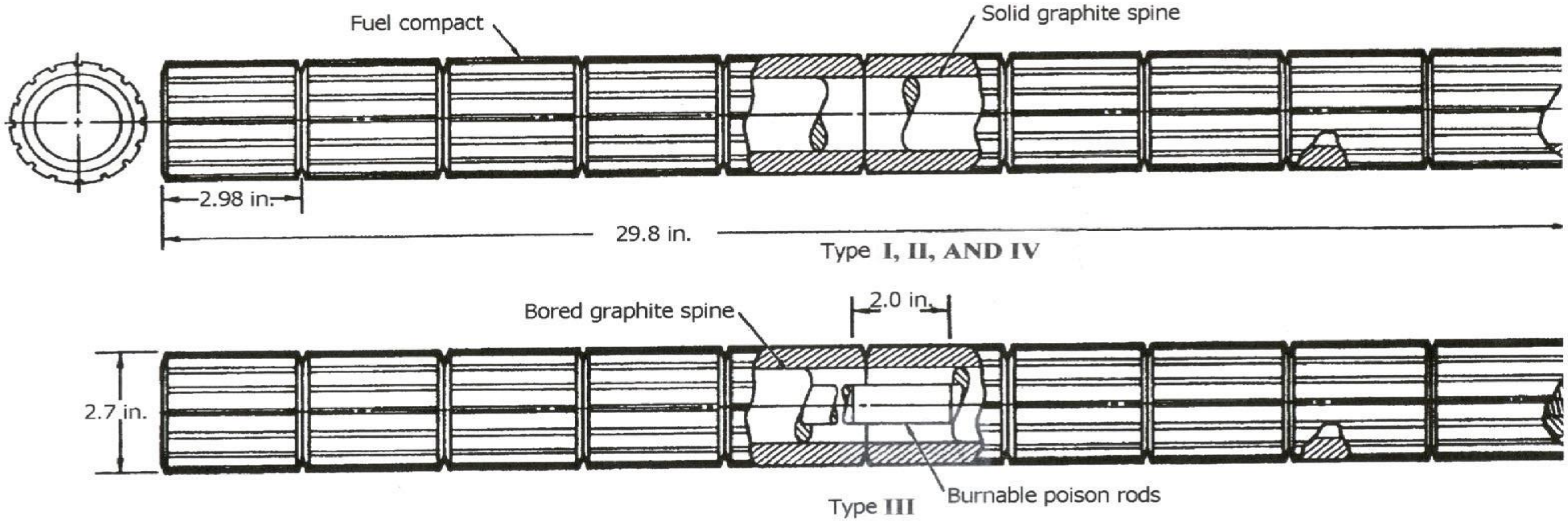
PEACH BOTTOM ATOMIC POWER STATION, UNIT 1

- First high-temperature gas-cooled reactor (HTGR) in the United States (US), Philadelphia, PA, 1966 – 1974
- Operated with two different cores
- Core 1
  - U-Th carbide fuel kernels, enriched to 93% U-235, 1.686 metric tons initial heavy metal (total)
  - Kernels 100 – 485 microns in diameter, coated with ~55 microns pyrolytic carbon, dispersed in graphite matrix
  - Annular compacts (7.6 cm long, 7 cm diameter) stacked on graphite spines, ~30 per fuel element
  - Graphite served as moderator, reflector, cladding, fuel matrix, and structure
  - Operated about half of design lifetime due to failure of fuel particle coatings, caused compacts to swell
    - Fast-neutron induced dimensional changes
    - Damage due to fission product recoil
    - Gaseous fission product release
  - Post-irradiation examination revealed >80% of coatings damaged or failed

Source: Kingrey 2003

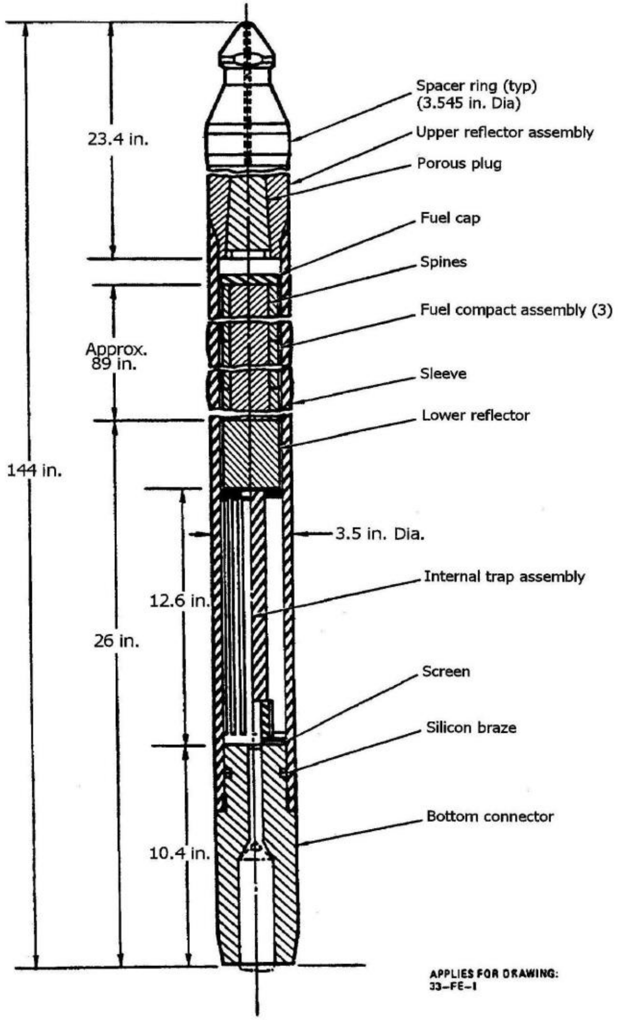
PEACH BOTTOM CORE 1 ANNULAR COMPACTS

Fuel Type	Number of elements required
I	54
II	564
III	84
IV	102
	804



Source: Kingrey, 2003

PEACH BOTTOM CORE 1 FUEL ELEMENT



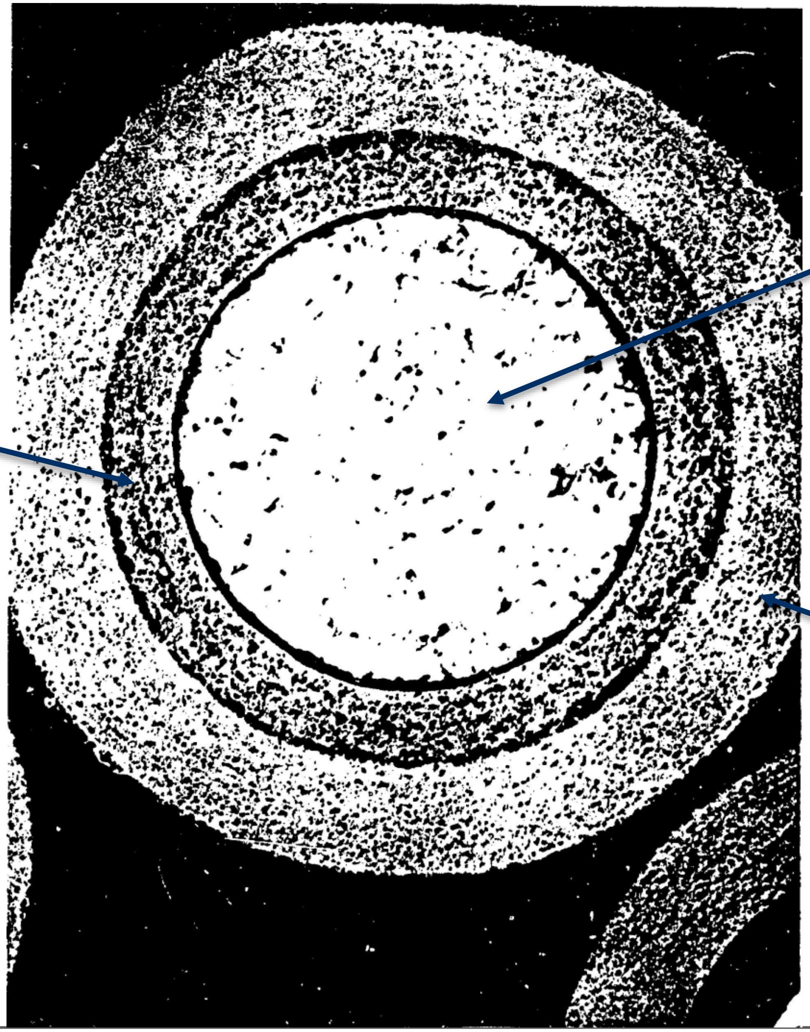
Source: Kingrey 2003

PEACH BOTTOM UNIT 1, CORE 2

- Core 2 fuel particles were slightly different from Core 1 fuel
  - Used two layers of carbon coating, instead of one: low-density “buffer” carbon layer was coated onto the kernel first and then a high-density, isotropic pyrolytic carbon coating was fabricated over the buffer coating; called BISO, “buffer isotropic”
  - Low-density buffer layer protected the outer layer from damage due to fission product recoil and gaseous fission product release. Under irradiation, the buffer material would shrink providing volume to accommodate fission product accumulation
  - Better performance was achieved – 3.4% of fuel particles failed; operated entire design lifetime
  - Initial heavy metal loadings were lower per kernel, but still enriched to 93% U-235
  - 1.419 metric tons initial heavy metal (total Core 2)
- Minor differences in fuel elements (no axial grooves, added slots on the ends)

Source: Kingrey 2003

BISO FUEL PARTICLE



Source: Kingrey 2003

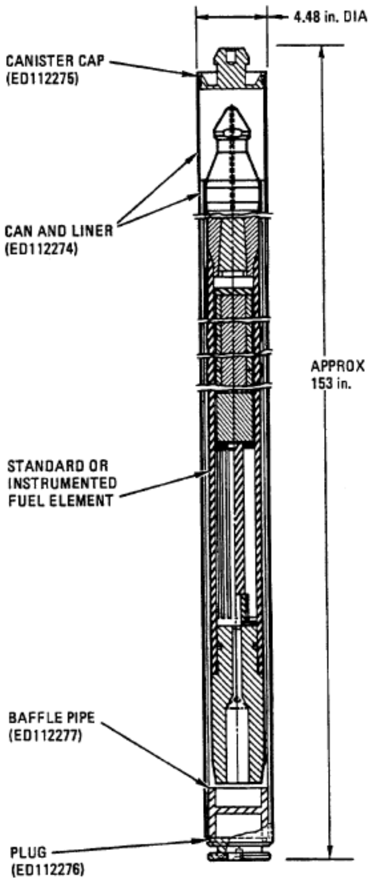
STORAGE – PEACH BOTTOM CORE 1

- Individual Core 1 fuel elements were placed in a double O-ring sealed aluminum (6061) canister with a stainless-steel liner at the reactor after removal from the HTGR
  - Failed fuel elements (i.e., those with cracked sleeves) were removed from the reactor with a stainless-steel failed fuel element tool; tool emplaced in the canister with the element
  - Leaking canisters were placed in salvage canisters
  - The tool and the stainless-steel liner add weight (reducing buoyancy) and absorb neutrons
  - 813 canisters total, 21 different canister types; 11.4 cm – 12 cm in diameter, 3.9 m – 4.0 m tall
  - Volume of canisters containing Core 1 spent fuel is about 32 m^3
  - Decay heat of each element at time of canning was ~20 watts
  - Filled in a helium atmosphere
  - After filling, stored underwater at the Peach Bottom fuel storage pool
  - Production of flammable organic compounds from carbide fuel reacting with water, humid air was a concern

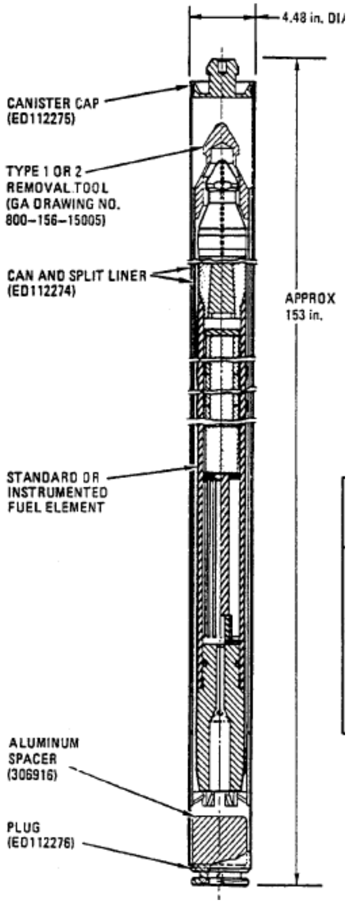
Source: Kingrey 2003

PEACH BOTTOM CORE 1 FUEL ELEMENT CANISTERS

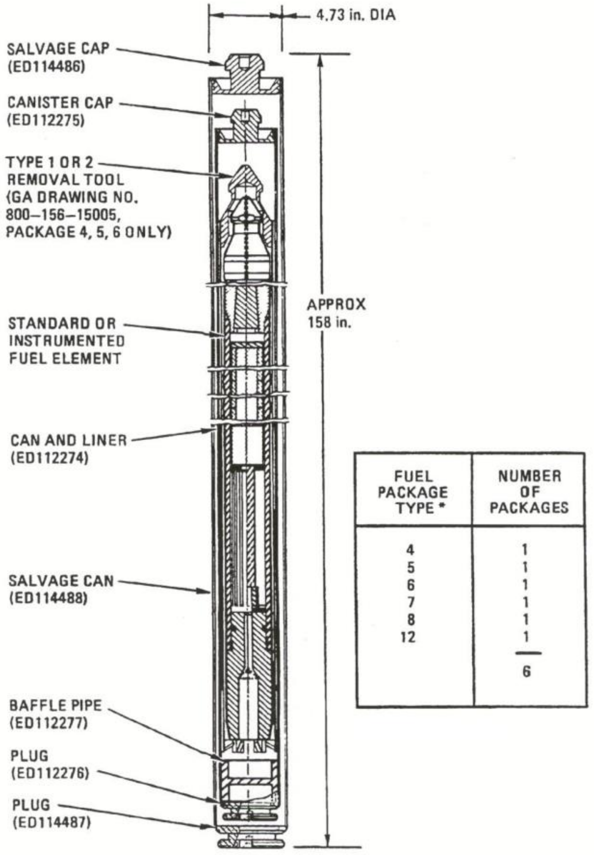
Without removal tool



With removal tool



Salvage canister



Salvage canister surrounding a leaking canister with a removal tool.

Source: Kingrey 2003

TRANSPORTATION AND SUBSEQUENT STORAGE – PEACH BOTTOM CORE 1

- Shipped (probably via truck) to Idaho National Laboratory in two Peach Bottom-1 fuel shipping casks from 1971 to 1973
- Each cask could hold 18 spent fuel canisters; 46 shipments
- Placed in dry, outdoor 30-inch diameter wells at the Idaho Nuclear Technical and Engineering Center
- Tubes installed in the vaults take gas samples and remove water if needed
- Helium and krypton have been detected
    - Some of the canisters have been breached
    - Water has contacted the fuel elements
    - Gas samples analyzed for volatile organics to determine if corrective action is needed
- Some of the Core 1 spent fuel was moved to dry storage (where Core 2 spent fuel is stored) because of water intrusion

Source: Kingrey 2003; NWTRB 2017

STORAGE, TRANSPORTATION, AND SUBSEQUENT STORAGE – PEACH BOTTOM CORE 2

- In 1974, 804 Core 2 fuel elements were placed in the same sealed steel-lined aluminum canister used for the Core 1 elements; no failed fuel tools or additional salvage canisters were needed; canister volume is about 32 m^3
- In 1975, they were shipped by truck in the Peach Bottom-1 fuel shipping casks and in single-element Hallam fuel shipping casks.
  - 44 shipments in the Peach Bottom-1 shipping casks to Idaho National Laboratory
  - 27 shipments in Hallam fuel shipping casks to other locations for post-irradiation examination
- Once at Idaho National Laboratory, elements were removed from the single-element canister, the top 18 inches of reflector was cut off, and the remaining part was placed in 18-inch diameter stainless-steel canister with 11 other elements
- Canisters placed in the Irradiated Fuel Storage Facility, a dry vault-type storage facility in a building

Irradiated Fuel Storage Facility

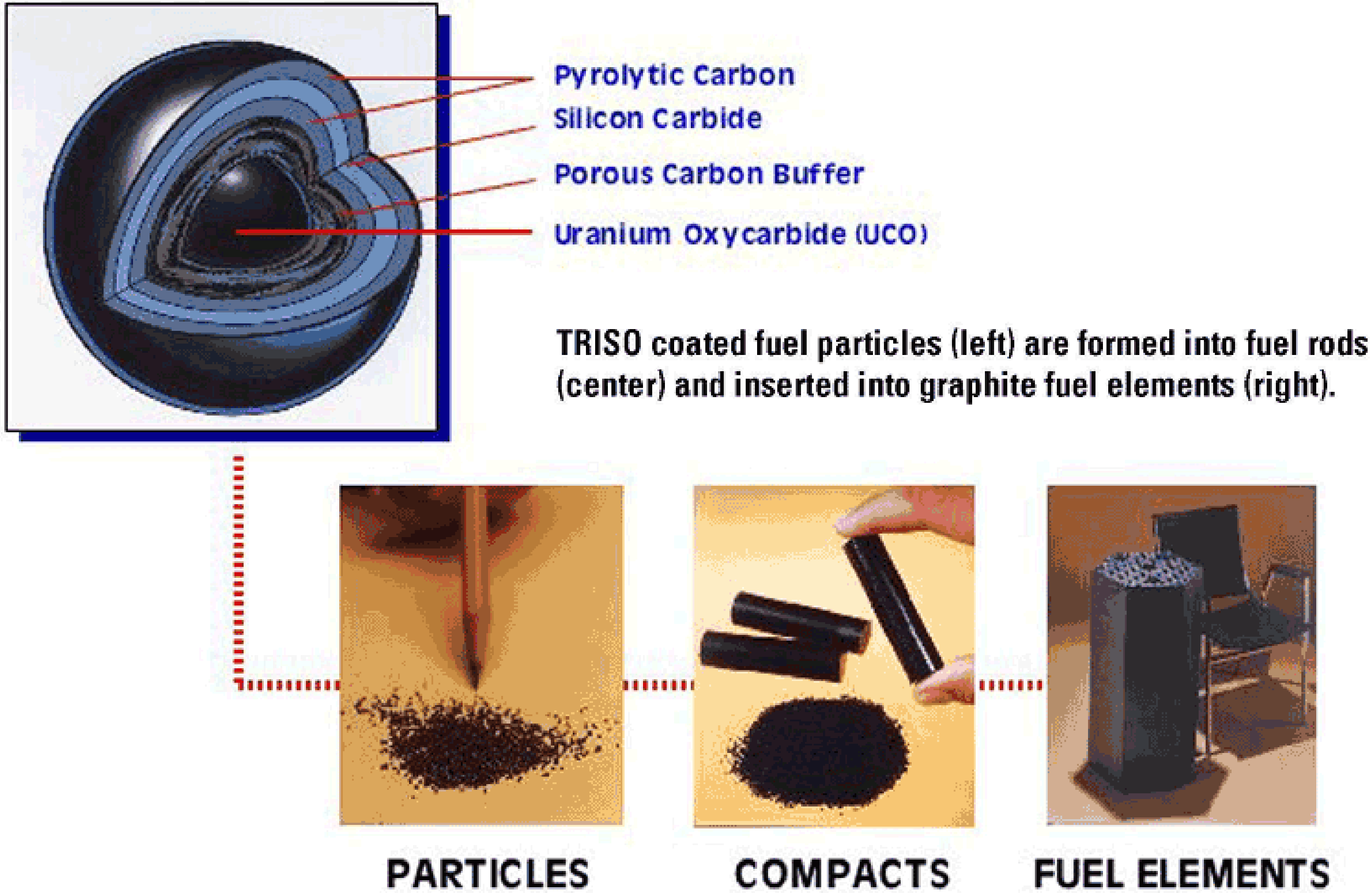
Source: Kingrey 2003; NWTRB 2017

FORT SAINT VRAIN

- Second HTGR in the U.S.; Colorado; 1979 – 1989.
  - Fissile U-Th carbide particles, enriched to 93% U-235; also fertile Th-only particles
  - Kernels are similar in size to those from Peach Bottom but have four layers of three distinct materials (tristructural isotropic, TRISO):
    - Porous buffer carbon layer
    - High-density isotropic pyrocarbon layer
    - Silicon carbide (SiC) layer
    - High-density Isotropic pyrocarbon layer
  - Particles dispersed in graphite matrix compact, which is placed in fuel channels in hexagonal fuel elements, 35.6 cm across the flats and 78.7 cm high
  - Particles are similar to the particles currently proposed to be used in advanced reactors, except for enrichment level
  - Observed failure fractions on the order of 1×10^{-4}

Source: Copinger and Moses, 2003; Demkowicz 2023; Demkowicz et al., 2015; Gibboney, 2022; Westinghouse, 2024

FORT SAINT VRAIN FUEL



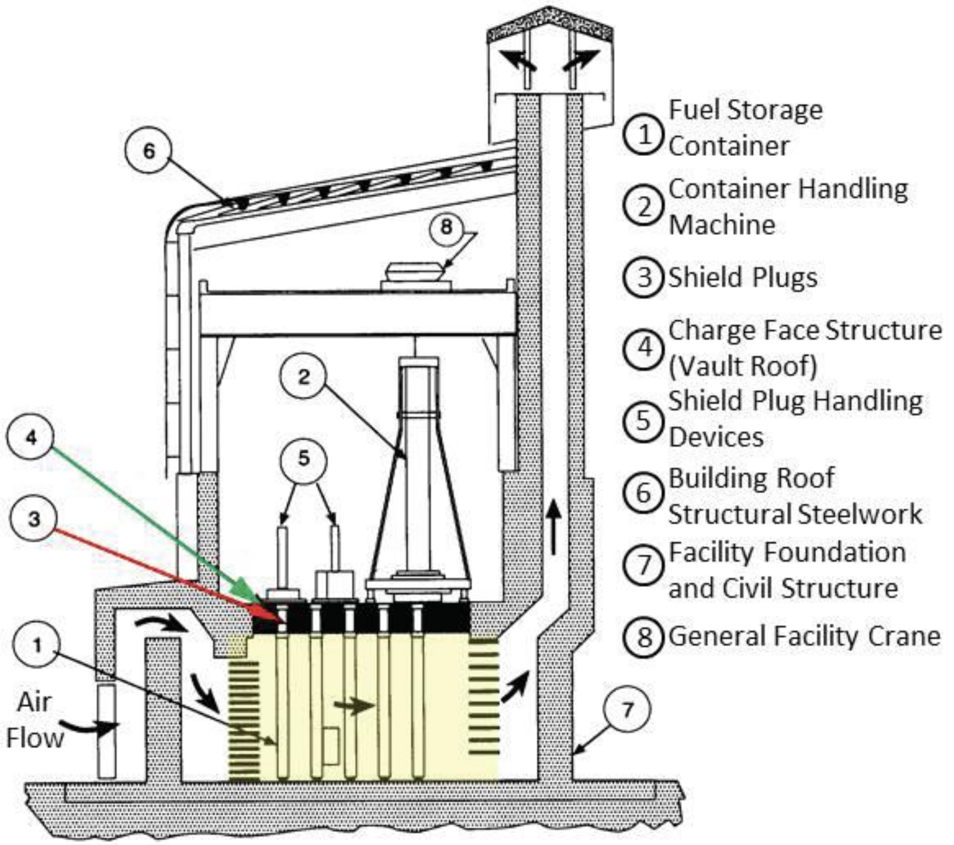
Source: Peterson 2006

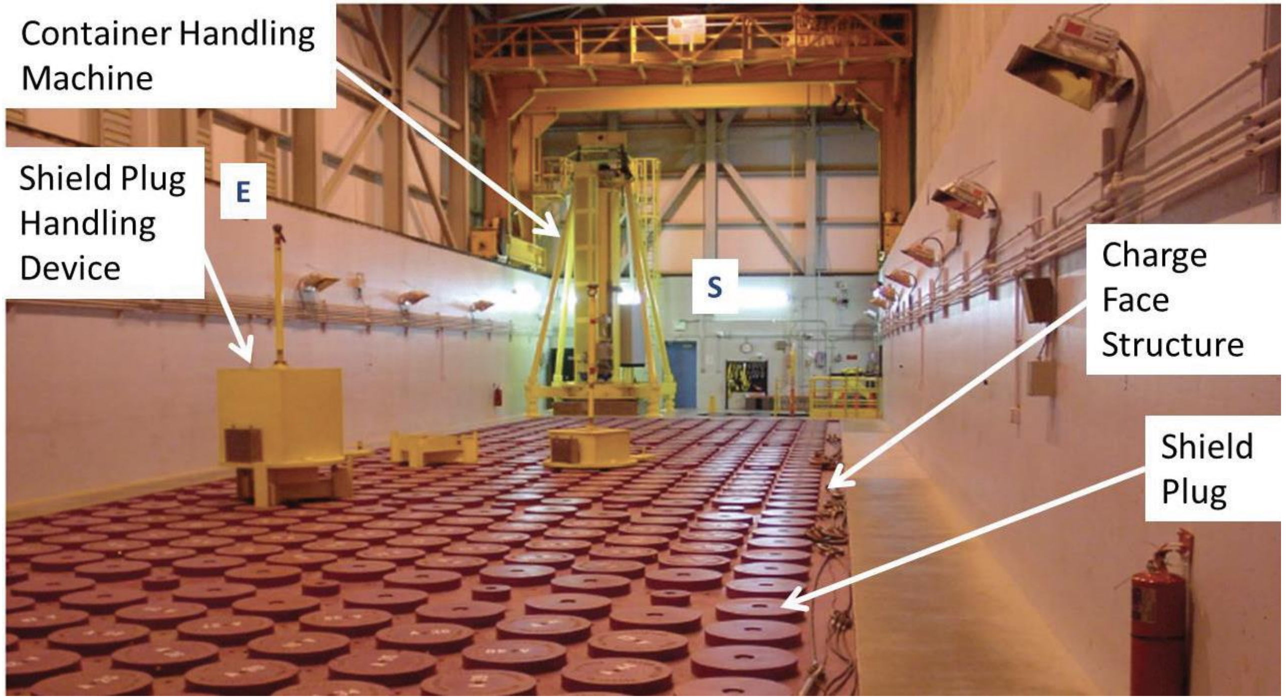
STORAGE – FORT SAINT VRAIN SPENT FUEL

- Stored in carbon-steel Fuel Storage Containers in two places
  - Independent Spent Fuel Storage Installation in Colorado (15 metric tons of heavy metal)
  - Idaho National Laboratory Irradiated Fuel Storage Facility (~8.6 metric tons of heavy metal)
  - Containers are not filled with inert gas; total container volume is about 295 m^3
- Colorado Facility
  - Stored in 244 Fuel Storage Containers, placed there between Dec. 1991 and June 1992.
  - Container is 4.9 m long, shell is 1.27 cm thick, container lid is 3.8 cm thick; bolted closed, sealed with double metal O-rings; holds up to six elements
  - Exterior of shell coated with flame-sprayed aluminum
  - Six containers are leak-tested every five years in accordance with American National Standards Institute
  - Modular vault dry storage system;
  - Maximum element decay heat 600 days after removal from the reactor is 85 watts; temperature at Fuel Storage Canisters is about 74ºC
  - Licensed by the U.S. Nuclear Regulatory Commission (NRC)
- Idaho Facility
  - Stored in the same place as Peach Bottom Core 2 spent fuel, 186 clamped Fuel Storage Containers

Source: NWTRB 2017, NRC 2011, DOE 1997

FORT SAINT VRAIN INDEPENDENT SPENT FUEL STORAGE INSTALLATION





Source: NWTRB 2017

FORT SAINT VRAIN INDEPENDENT SPENT FUEL STORAGE INSTALLATION

Source: NWTRB 2017

FORT SAINT VRAIN SPENT FUEL TRANSPORTATION

- 744 Fort Saint Vrain spent fuel elements were transported from Colorado to Idaho National Laboratory in 1989 via truck using the Transnuclear-Fort Saint Vrain (TN-FSV) cask
- The TN-FSV cask was a NRC-certified cask specifically designed to transport Fort Sain Vrain spent fuel; it holds one fuel storage container

TN-FSV Cask with impact limiters

Source: Hall et al. 2020

DISPOSAL OF HTGR SPENT FUEL

- For HTGR spent fuel, heavy metal mass per volume is ~10 - 20x less than that for typical light-water reactor spent fuel => treat spent fuel to reduce its volume?
- Accordingly, the low heavy metal mass per volume for HTGR spent fuel results in low heat per volume
- Deep geologic repositories designed to date are for typical light-water reactor spent fuel that generates a lot of heat per volume
  - Waste packages are spaced far apart
  - Small percentage of excavated rock is used for emplacement of waste packages (~1% to 5%)
- Analyses currently in progress indicate that disposing of HTGR spent fuel in a repository designed for a low-heat-generating spent fuel would be more cost-effective than disposing of it in a repository designed for a high-heat-generating spent fuel
  - Waste packages could be stacked next to and on top of each other
  - A larger percentage of excavated rock is used for emplacement of waste packages (~25%)
  - Could remove the perceived need to treat the TRISO fuel to reduce its volume

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