Views on Nuclear Fuel in Dry Storage

Dave Lochbaum

In 1986, I descended a temporary ladder about twenty feet to the bottom of a concrete pit at the Grand Gulf Nuclear Station in Port Gibson, Mississippi. I wore neither protective clothing nor a respirator. Stepping off the ladder, I knelt down on the concrete floor to look beneath the bottom of a metal storage rack. The rack had a thick metal frame and sheet metal walls. On the other side of the thin metal walls – mere inches from my shoulders, neck and head – rested the nearest of several dozen nuclear fuel bundles in dry storage. The sheet metal walls shielded beta emissions, but afforded scant protection against gamma and neutron emissions. Several minutes later, I climbed the ladder and exited the pit.

New Fuel Vault at Grand Gulf with the lid covering the far end removed and the lids covering the near end installed.

The primary hazard I faced during my excursion into the dry storage pit was not radiation but gravity. Had I fallen off the ladder, I might have been injured.

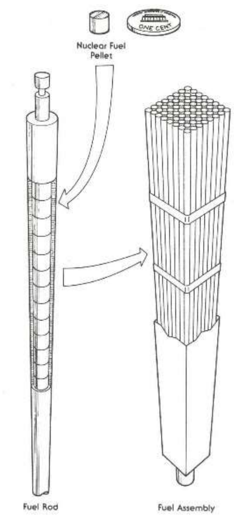
Radiation posed little hazard because nearly no radioactivity was being emitted. The pit stored new fuel bundles that had not yet been inside an operating reactor. The new fuel bundles would be transferred from the new fuel vault into the spent fuel pool, and then transferred into the reactor core to replace 264 irradiated fuel bundles being discharged after the first cycle of operation.

Nuclear fuel in dry storage poses risks. When those risks are properly understood and managed, nuclear fuel in dry storage can be acceptably safe.

Nuclear Fuel

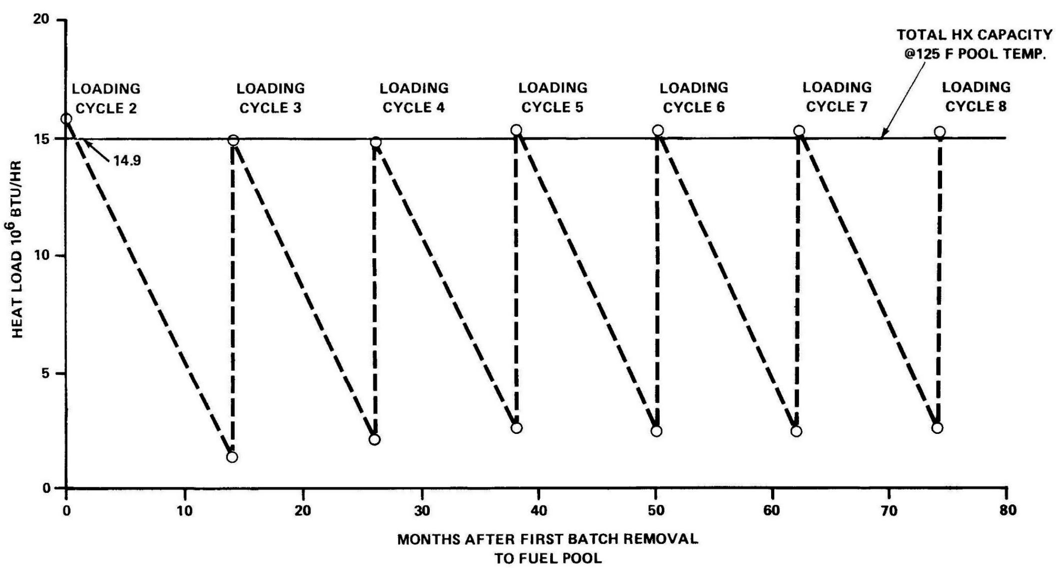
U.S. nuclear power reactors utilize fuel in the form of ceramic pellets of uranium dioxide. The uranium content is a mixture of two isotopes: Uranium-238 (U-238) and Uranium-235 (U-235). U.S. reactors are designed to split U-235 isotopes; U-238 isotopes also fission, but to a significantly lower rate.

Fuel pellets are loaded like peas in a pod into hollow metal tubes called fuel rods. Fuel rods are installed in square arrays called fuel bundles, or fuel assemblies. Fuel assemblies are transported to nuclear power plants for placement in reactor cores.

	
Nuclear Fuel Pellets	Nuclear Fuel Pellets

Nuclear Fuel in Wet Storage

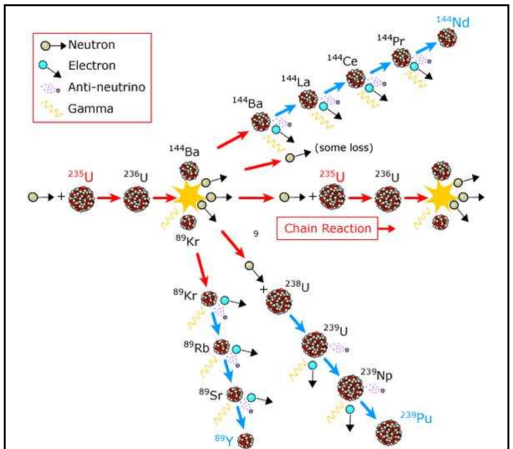
After residing in the reactor core for three operating cycles of 18 to 24 months in length, fuel assemblies are discharged from the reactor core into the spent fuel pool. Placing irradiated fuel assemblies into the spent fuel pool increases the heat load in the pool. During the 18 to 24 months that the reactor operates, the heat load in the spent fuel pool decreases to less than one-third of its initial level. Periodic discharge of fuel assemblies from the reactor core “recharges” the heat load in the spent fuel pool.



Spent Fuel Pool Heat Load

Nuclear Fuel Fission, Radioactive Emissions and Decay Heat

The source of the heat from irradiated fuel assemblies is the radioactive decay of fission byproducts. An isotope fissions into two smaller isotopes, but not always the same two byproducts. Subatomic particles called neutrons released by a fission may cause other isotopes to fission in a nuclear chain reaction. Many of the fission byproducts are unstable and at varying rates by different means seek stability through radioactive decay – emission of particles or energy rays. These radioactive emissions generate thermal energy, called decay heat. Sometimes, a single radioactive emission results in a stable isotope. Other times, multiple emissions through a chain of daughter products are needed to obtain a stable isotope.



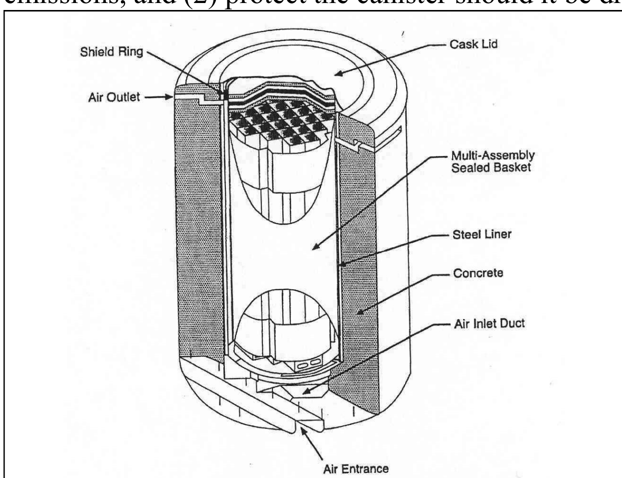
Nuclear Fission

In essence, heat load corresponds to hazard level. The worker holding the nuclear fuel pellets in the picture above is wearing a glove; not for protection from decay heat or radioactive emissions but to protect the fuel pellets from degradation by human skin oils. Unirradiated fuel emits radioactivity, but in forms and rates that pose little hazard to workers handling it.

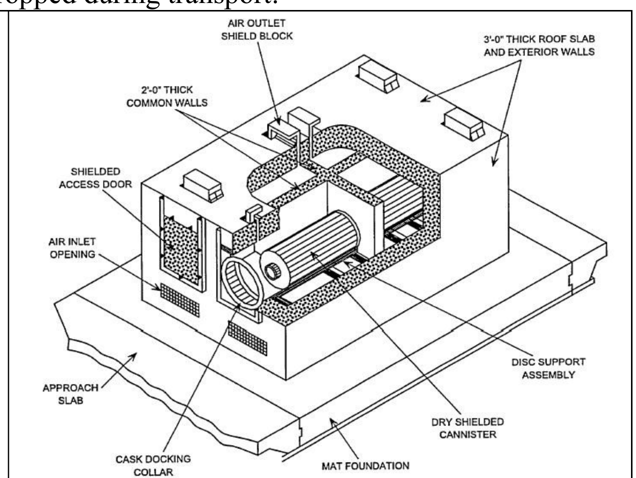
As illustrated in the spent fuel pool heat load graphic, the recurring placement of freshly discharged irradiated fuel into the spent fuel pool keeps its heat load, and radiation hazard level, relatively high. The spent fuel pool water has two important roles. The water circulating through a cooling system prevents the water from boiling. And the water attenuates radioactivity emitted from the spent fuel assemblies to protect workers from unacceptable radiation exposures.

Nuclear Fuel in Dry Storage

The heat load of irradiated fuel assemblies decreases with time. At some point, the reduced heat load permits transfer of irradiated fuel assemblies from the spent fuel pool into dry storage. Workers lower an empty metal canister into the spent fuel pool, move irradiated fuel assemblies one at a time into the canister, and lift the loaded canister from the spent fuel pool. The loaded canister is sealed and its water replaced with an inert gas like helium or nitrogen. The canister is placed inside a cask for transport to the onsite dry storage facility. The cask serves two protective roles: (1) protect workers from radioactive emissions, and (2) protect the canister should it be dropped during transport.



Vertical Dry Storage Cask



Horizontal Dry Storage Cask

Dry storage systems feature vertical or horizontal casks. In either system, the decay heat generated by the spent fuel passes through the metal walls of the canister by a heat transfer process called conduction. The "chimney effect" pulls air into the cask that gets warmed by heat conducted through the canister walls and exhausts through outlets. This heat transfer process is convection. The dry storage system designs limit the decay heat load from spent fuel assemblies placed into the canister based on the conductive and convective heat transfer rates.

The conductive heat transfer rate depends on factors such as temperature inside the canister, temperature outside the canister, and physical properties of the canister (e.g., type of metal, thickness of metal wall, etc.). Heat generated by the radioactive decay of fission byproducts passes through the pellets, through any gas in the gap between the pellets and the fuel rod, through the fuel rod, through the gas inside the canister and finally through the metal canister wall.

The convective heat transfer rate depends on factors such as the outside surface temperature of the canister, ambient temperature of the outside air, and size of the air inlet and outlet ports.

The dry storage systems design limit the temperature of the fuel rods to below the temperature experienced during operation in the reactor core (around 750°F). [Federal regulations require core cooling systems that keep the fuel rod temperatures below 2,200°F during design basis events.]

Nuclear Fuel in a Leaking Dry Storage Canister

If a crack or hole developed through a canister's wall, it would be more like poking a hole in a deflated balloon than popping an inflated balloon. The contents of the canister would not rapidly rush out through the opening. The pressure inside the canister decreases as the contents leak out through the opening. As the canister's internal pressure drops, the release rate through the opening decreases.

For radioactive gases and particles to escape from a leaking canister in appreciable amounts, fuel rods must also be leaking. Otherwise, these gases and particles would be largely contained within the intact fuel rods.

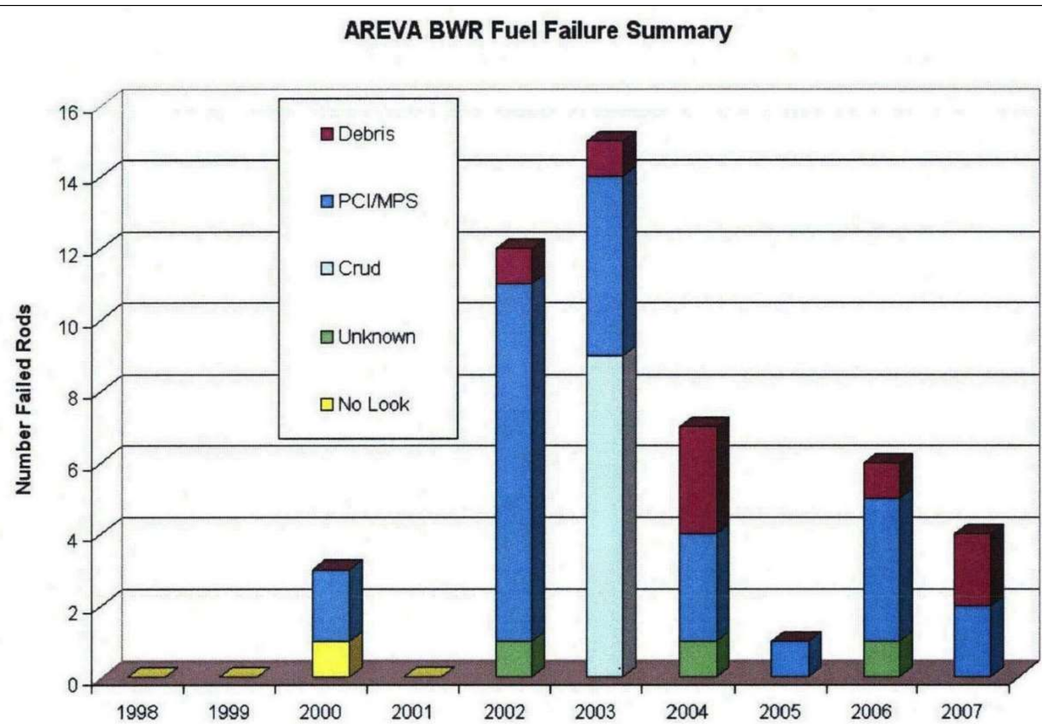
Nuclear fuel performance improved over the years as experience taught fuel vendors and plant owners how to manage the factors causing damage. In the early days, hundreds of failed fuel rods were discharged into spent fuel pools each year. Over time, the rate dropped to dozens of failed fuel rods each year. Vendors modified fuel pellet, fuel rod, and fuel assembly designs to lessen vulnerabilities. And plant owners improved water chemistry control and implemented other steps to minimize the chances of fuel rod damage during reactor operation.

Rod Failures During Reactor Operation: BWR Data

	A	B	C	D	E	F	G	H	I	J	K	L
1	file = Rod-Initial-C.xls, Sheet = Reactor F							file = Rod-Initial-C.xls			Sheet = Reactor F	
2	BWR Data											
3	YEAR	BWR (Total discharged)	BWR, Assembly damaged	% Assembly Damaged/yr	% of Total Assembly Damaged	Rods/ Assembly	Total Number Rods	Failed Rods	% FAILED Rods/yr.	Number of WPs/yr	% of Total BWR WPs	Source for Column C
4	1969	96	32	33.33	0.05	49	4704	70.4	1.497	2.18	0.15	A
5	1970	29	29	100.00	0.04	49	1421	63.8	4.490	0.66	0.04	A
6	1971	413	87	21.07	0.13	49	20237	191.4	0.946	9.39	0.64	A
7	1972	801	68	8.49	0.10	49	39249	149.6	0.381	18.20	1.24	A
8	1973	564	323	57.27	0.50	49	27636	710.6	2.571	12.82	0.87	A
9	1974	1290	671	52.02	1.04	49	63210	1476.2	2.335	29.32	1.99	A
10	1975	1223	463	37.86	0.71	49	59927	1018.6	1.700	27.80	1.89	A
11	1976	1666	297	17.83	0.46	49	81634	653.4	0.800	37.86	2.57	A
12	1977	2047	108	5.28	0.17	56	114632	237.6	0.207	46.52	3.16	A
13	1978	2239	119	5.31	0.18	56	125384	261.8	0.209	50.89	3.46	A
14	1979	2131	124	5.82	0.19	56	119336	272.8	0.229	48.43	3.29	A
15	1980	3330	112	3.36	0.17	56	186480	246.4	0.132	75.68	5.14	A
16	1981	2467	42	1.70	0.06	62	152954	92.4	0.060	56.07	3.81	A
17	1982	1951	59	3.02	0.09	62	120962	129.8	0.107	44.34	3.01	A
18	1983	2698	26	0.96	0.04	62	167276	57.2	0.034	61.32	4.16	A
19	1984	2735	81	2.96	0.13	62	169570	178.2	0.105	62.16	4.22	A
20	1985	2928	99	3.38	0.15	62	181536	217.8	0.120	66.55	4.52	A
21	1986	2551	41	1.61	0.06	62	158162	90.2	0.057	57.98	3.94	B
22	1987	3316	24	0.72	0.04	62	205592	52.8	0.026	75.36	5.12	B
23	1988	2956	64	2.17	0.10	62	183272	140.8	0.077	67.18	4.56	B
24	1989	4020	57	1.42	0.09	62	249240	125.4	0.050	91.36	6.21	C
25	1990	3759	15	0.40	0.02	62	233058	33.0	0.014	85.43	5.80	C
26	1991	2872	24	0.84	0.04	62	178064	52.8	0.030	65.27	4.43	C
27	1992	4150	12	0.29	0.02	62	257300	26.4	0.010	94.32	6.41	C
28	1993	3974	16	0.40	0.02	62	246388	35.2	0.014	90.32	6.13	C
29	1994	3893	15	0.39	0.02	62	241366	33.0	0.014	88.48	6.01	C
30	1995	4684	4	0.09	0.01	62	290408	8.8	0.003	106.45	7.23	C
31												
32	sum	64783	3012		4.65		3878998	6626.4		1472.34	100.00	
33					% Rods failed, all years			0.170828				
34					% Rod failed through 1985			0.37				
35		A: Bailey and Wu 1990, Table 30, B: Polls and Proebsle 1994, pTable 2, C: Yang 1997, Table 2										

Boiling Water Reactor Fuel Performance, 1969-1995 (Pressurized Water Reactor Fuel Performance Similar)

Over more time, the number of failed fuel rods dropped lower and lower to handfuls or less.



AREVA Boiling Water Reactor Fuel Performance, 1998-2007 (Pressurized Water Reactor Fuel Performance Similar)

The amount of radioactivity escaping from a leaking canister containing failed fuel rod(s) is reduced by the dwindling inventory of unstable isotopes. Even with one or more failed fuel rods, a canister's leakage could contain no Iodine-131, Strontium-91, Xenon-135 or other short-lived isotopes because these isotopes would have long since decayed away.

	Time After End of Reactor Operation											
Radionuclide	**0 days**	**1 day**	**1 month**	**3 months**	**6 months**	**1 year**	**2 years**	**3 years**	**4 years**	**5 years**	**10 years**	**100 years**
Beryllium 10	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Calcium 41	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%
Niobium 94	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.7%
Carbon 14	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	98.8%
Molybdenum 93	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	99.9%	99.8%	98.3%
Silver 108m	100.0%	100.0%	100.0%	100.0%	99.9%	99.8%	99.7%	99.5%	99.3%	99.2%	98.4%	84.7%
Nickel 59	100.0%	100.0%	100.0%	99.9%	99.8%	99.7%	99.3%	99.0%	98.7%	98.3%	96.7%	71.5%
Nickel 63	100.0%	100.0%	99.9%	99.8%	99.7%	99.3%	98.6%	97.9%	97.3%	96.6%	93.3%	50.0%
Cesium 137	100.0%	100.0%	99.8%	99.4%	98.9%	97.7%	95.5%	93.3%	91.2%	89.1%	79.4%	9.9%
Strontium 90	100.0%	100.0%	99.8%	99.4%	98.8%	97.6%	95.3%	93.0%	90.8%	88.7%	78.6%	9.0%
Hydrogen 3	100.0%	100.0%	99.5%	98.6%	97.3%	94.5%	89.3%	84.5%	79.8%	75.4%	56.9%	0.4%
Krypton 85	100.0%	100.0%	99.5%	98.4%	96.9%	93.7%	87.9%	82.3%	77.2%	72.3%	52.3%	0.2%
Barium 133	100.0%	100.0%	99.5%	98.4%	96.8%	93.6%	87.7%	82.1%	76.9%	72.0%	51.8%	0.1%
Cobalt 60	100.0%	100.0%	98.9%	96.8%	93.7%	87.7%	76.9%	67.4%	59.1%	51.8%	26.8%	0.0%
Cesium 134	100.0%	99.9%	97.3%	92.2%	85.0%	71.9%	51.7%	37.2%	26.7%	19.2%	3.7%	0.0%
Manganese 54	100.0%	99.8%	93.6%	81.9%	67.0%	44.4%	19.8%	8.8%	3.9%	1.7%	0.0%	0.0%
Cerium 144	100.0%	99.8%	93.0%	80.3%	64.5%	41.1%	16.9%	7.0%	2.9%	1.2%	0.0%	0.0%
Zinc 65	100.0%	99.7%	91.8%	77.4%	60.0%	35.5%	12.6%	4.5%	1.6%	0.6%	0.0%	0.0%
Cobalt 58	100.0%	99.0%	74.6%	41.5%	17.2%	2.8%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Yttrium 91	100.0%	98.8%	69.7%	33.8%	11.4%	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Strontium 89	100.0%	98.6%	66.2%	29.1%	8.5%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iron 59	100.0%	98.5%	62.7%	24.6%	6.1%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Barium 140	100.0%	94.7%	19.7%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iodine 131	100.0%	91.7%	7.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Xenon 133	100.0%	87.6%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iodine 132	100.0%	80.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Tellurium 132	100.0%	80.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Molybdenum 99	100.0%	77.7%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Yttrium 90	100.0%	77.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Lanthanum 140	100.0%	66.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iodine 133	100.0%	44.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Strontium-91	100.0%	17.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iodine 135	100.0%	8.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Technetium 99	100.0%	6.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Krypton 88	100.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Manganese 56	100.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon 41	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Krypton 87	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Iodine 134	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Tellurium 134	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Bromine 84	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Xenon 135	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rubidium 88	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Praseodymium 144	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rubidium 89	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Xenon 138	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Depletion of Isotopic Inventory due to Radioactive Decay

Isotopes with longer half-lives (e.g., Cesium-137, Strontium-90, Krypton-85, and Cobalt-60) might be released from a leaking canister holding damaged fuel rod(s). Such a release would pose more of a contamination and cleanup problem than immediate public health hazard. Strontium-90 fires its "radioactive bullets" sporadically and sparsely while Krypton-87 fires "radioactive bullets" like a machine gun, fast and furious.

A release of radioactivity from a dry canister would not be legal, because federal regulations require that all radioactivity released to the air or water be controlled and monitored. Any such release would likely not be lethal, because it would most likely be considerably below the amounts released from the nuclear plant during routine reactor operation as permitted by federal regulations.

Nuclear Fuel Relative Risk

Risk is the product of the probability of something happening and its consequences. An event that occurs once every 25 years that harms 100 people poses a risk of 4 persons annually. Another event that occurs once every 3 months that harms one person (hopefully not the same person every time) has the same risk of 4 persons per year.

The probability of an event involving nuclear fuel depends on a number of factors, with the energy or power level of the nuclear fuel being a key factor. The higher the energy level, the less time one has to intervene to prevent fuel damage. This table shows the maximum power levels of nuclear fuel in the reactor core, spent fuel pool, and dry cask at three nuclear reactors.

Reactor	Reactor Core Maximum Power	Spent Fuel Pool Maximum Power	Dry Canister Maximum Power
Indian Point Unit 2	87,154	63	1
Pilgrim	54,959	206	1
San Onofre Unit 2	93,171	196	1

The power levels are normalized to the maximum power level in a single dry storage canister (36.9 kilowatts in this case for a Hi-Storm 100S design). The maximum power level in the spent fuel pool at Pilgrim was 206 times greater than the maximum power level in one of its dry canisters. The maximum power level in the reactor core at Indian Point Unit 2 when it operated was 87,154 times greater than the maximum power level in one of its dry canisters.

The consequences from an event involving nuclear fuel also depends on a number of factors, with the amount of fuel that can be damaged in the event being a key factor. This table shows the maximum number of nuclear fuel bundles that could be placed in the reactor core, spent fuel pool, and dry canister at three nuclear reactors.

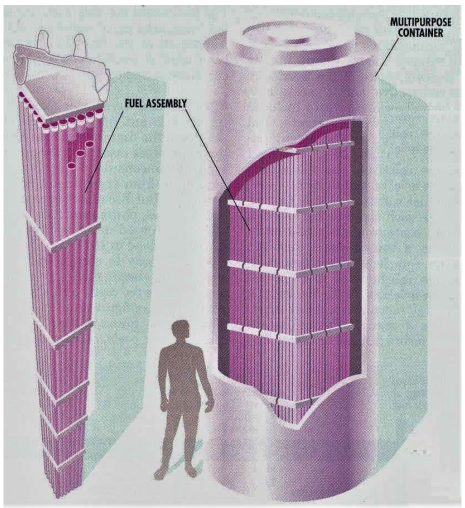
Reactor	Reactor Core Maximum Bundles	Spent Fuel Pool Maximum Bundles	Dry Canister Maximum Bundles
Indian Point Unit 2	6	43	1
Pilgrim	9	53	1
San Onofre Unit 2	7	90	1

The maximum number of bundles is normalized to the maximum capacity in a single dry storage canister (32 for pressurized water reactor spent fuel or 68 for boiling water reactor spent fuel in a Hi-Storm 100S design). It would take damage to the spent fuel bundles in 53 dry canisters to match the number of spent fuel bundles damaged in a spent fuel pool event at Pilgrim. Spent fuel bundles in seven dry canisters would need to be damaged to match the number of fuel bundles damaged in a reactor core event at San Onofre Unit 2.

Risk of a dry cask event involving nuclear fuel damage is certainly not zero — but it is considerably closer to zero than when the nuclear fuel is in a spent fuel pool or reactor core.

Nuclear Fuel in Dry Storage Risk

A dry canister breach becomes dangerous when it enables spent fuel to heat up and catch on fire and/or allows spent fuel to achieve a nuclear chain reaction (i.e., go critical.) Fire or criticality can damage fuel rods and propel the radioactivity released from damaged fuel rods out the canister's breach. Malicious action, such as using explosive force to rupture a canister, can also damage fuel rods and result in significant releases of radioactivity.



Dry Cask Release Barriers

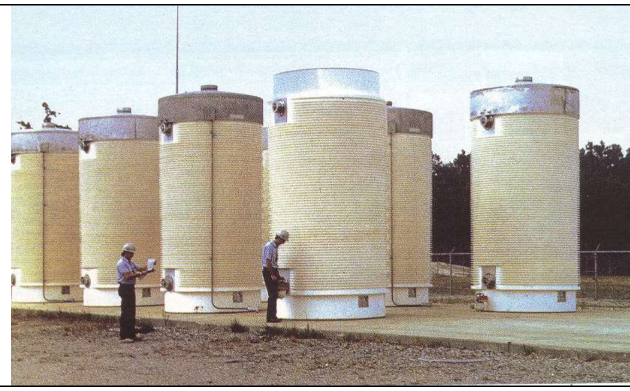
For spent fuel inside a breached canister to catch on fire, there needs to be sufficient openings (e.g., one large opening or multiple smaller openings) for air to feed the fire and for smoke to be exhausted. If air cannot enter in sufficient amounts, the fire will burn itself out. If smoke is not vented, it will smother and extinguish the fire. Sizeable openings can serve to prevent a spent fuel fire by essentially promoting convective heat transfer by the larger "chimney," thus cooling the spent fuel rods and averting overheating damage.

For a nuclear chain reaction to occur inside a breached canister, a critical mass must form. Spent fuel assemblies are inside the dry storage canister because their reactivity levels have decreased to the point where they are only wasting space inside the reactor core. Their reactivity "octane" is certainly lowered, but not to benign levels. Nuclear chain reactions within canisters are prevented by geometry (i.e., spacing between adjacent assemblies) and anti-criticality measures (i.e., neutron absorbers). A canister is loaded by placing it inside the spent fuel pools and transferring one spent fuel assembly at a time into it. The loaded canister does not experience a nuclear chain reaction due to the criticality prevention features. Thus, even if a breached canister allowed water to enter, the spent fuel inside should not sustain a nuclear chain reaction.

In my opinion, the primary safety hazard of dry storage involves dropping a loaded canister, especially while being transported over the edge of a spent fuel pool wall or wall of the opening used to lower the canister to ground level. Dropping a canister on the top edge of a wall enables the canister to tilt and fall further to impact the floor at a vulnerable angle. While dry canisters have been analyzed for drops, the safety margins are minimized, or compromised, when challenged. The drop could dislodge fuel rods, defeating the anti-criticality protection from geometry. The drop could breach a canister, providing a pathway for release of radioactivity from damaged fuel inside.

The primary security hazard of dry storage involves saboteurs who use force to breach one or more canisters in the Independent Spent Fuel Storage Installation (ISFSI).

I believe the security hazard is the larger of these two threats. The Federal Building in Oklahoma City was not destroyed because it lacked a chain-link fence around it. Similarly, the World Trade Center towers did not fall because they were not surrounded by chain-link fences.

Chain-link fences may adequately protect postal carriers from fierce dogs, but they provide scant protection for dry casks from fierce malevolent actors. Perhaps, sadly, the U.S. Nuclear Regulatory Commission thinks the only security threat to dry casks in an ISFSI is from fierce dogs. If they are right, millions of Americans are adequately protected from the ISFSIs in their communities. If the NRC is mistaken, … .

“Who Let the Dogs Out?” must be become “Who Let the Bad Guys In?” That’d be a sad song and even sadder moment.