Nuclear waste

In reactors, fuel produces power but also gets converted into *high-level waste* (HLW)

The *spent* fuel rods contain unreacted $^{235}_{92}$U, $^{238}_{92}$U, *transuranic* elements including fissile $^{239}_{94}$Pu, and highly radioactive fission products

Note that Pu can be separated from the waste "relatively" easily using straightforward chemistry

Aside on implications for proliferation:

$$^{238}_{92}\mathrm{U} + \mathrm{n}^{0} \rightarrow {}^{239}_{92}\mathrm{U}$$

$$^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + \beta^{-} + \bar{\nu}_{e}^{0}$$

$$^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + \beta^{-} + \bar{\nu}_{e}^{0}$$

$$^{239}_{94}\mathrm{Pu} + \mathrm{n}^{0} \rightarrow {}^{240}_{94}\mathrm{Pu}$$

Fresh fuel produces nearly pure $^{239}_{94}$Pu, the but longer it is in the reactor the more (non-fissile) $^{240}_{94}$Pu is produced, hence less suitable for weapons

For every 1000 lbs of LEU:

Before:	After (3 years):	
967 lbs	943 lbs	$^{238}_{92}U$
33 lbs	8 lbs	$^{235}_{92}U$
	35 lbs	assorted fission products
	8.9 lbs	plutonium isotopes
	5.3 lbs	other transuranics

A 1GWe power reactor produces a few cubic yards (27 tons) of HLW each year, but very intensely radioactive

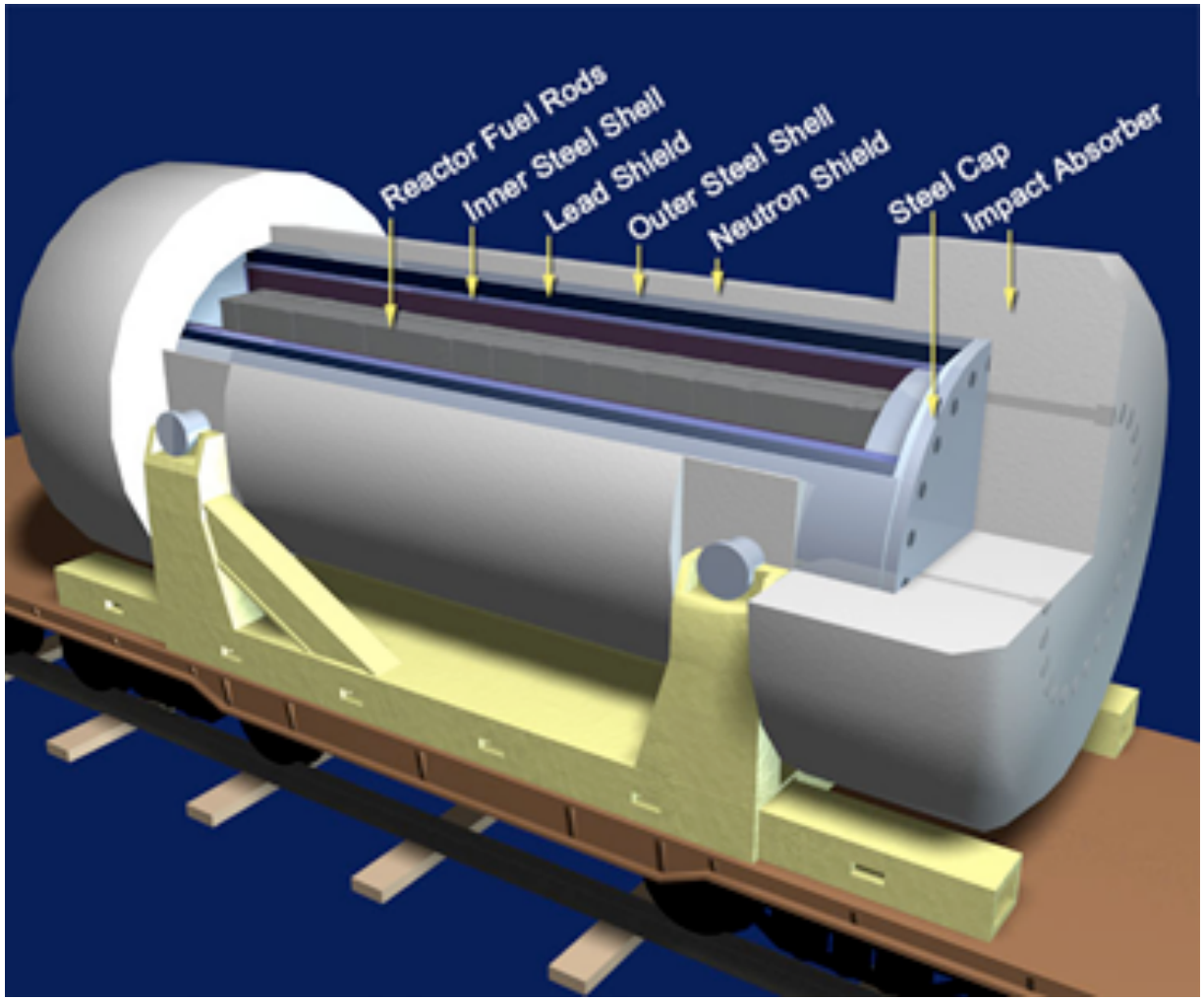
Radioactivity decays by about a factor of 10 in 10 years, another factor of 10 in 100 years, another factor of 1000 in 1000 years, then levels off due to very long lived isotopes (*e.g.*, $T_{1/2}$ for $^{239}_{94}Pu$ is 24,000 years)

So where does HLW go? Right now it stays on the site of the reactor. It is stored in pools of water that provide shielding and cooling. Most people feel this is not a safe long-term disposal strategy partly because it was not planned this way and sites were not chosen for long-term disposal.

Two issues for off-site disposal: safe transportation and safe disposal

How to safely transport?

Start with specially designed transportation *casks*



http://mcnucprojects.com/corridors.htm

Crash Testing

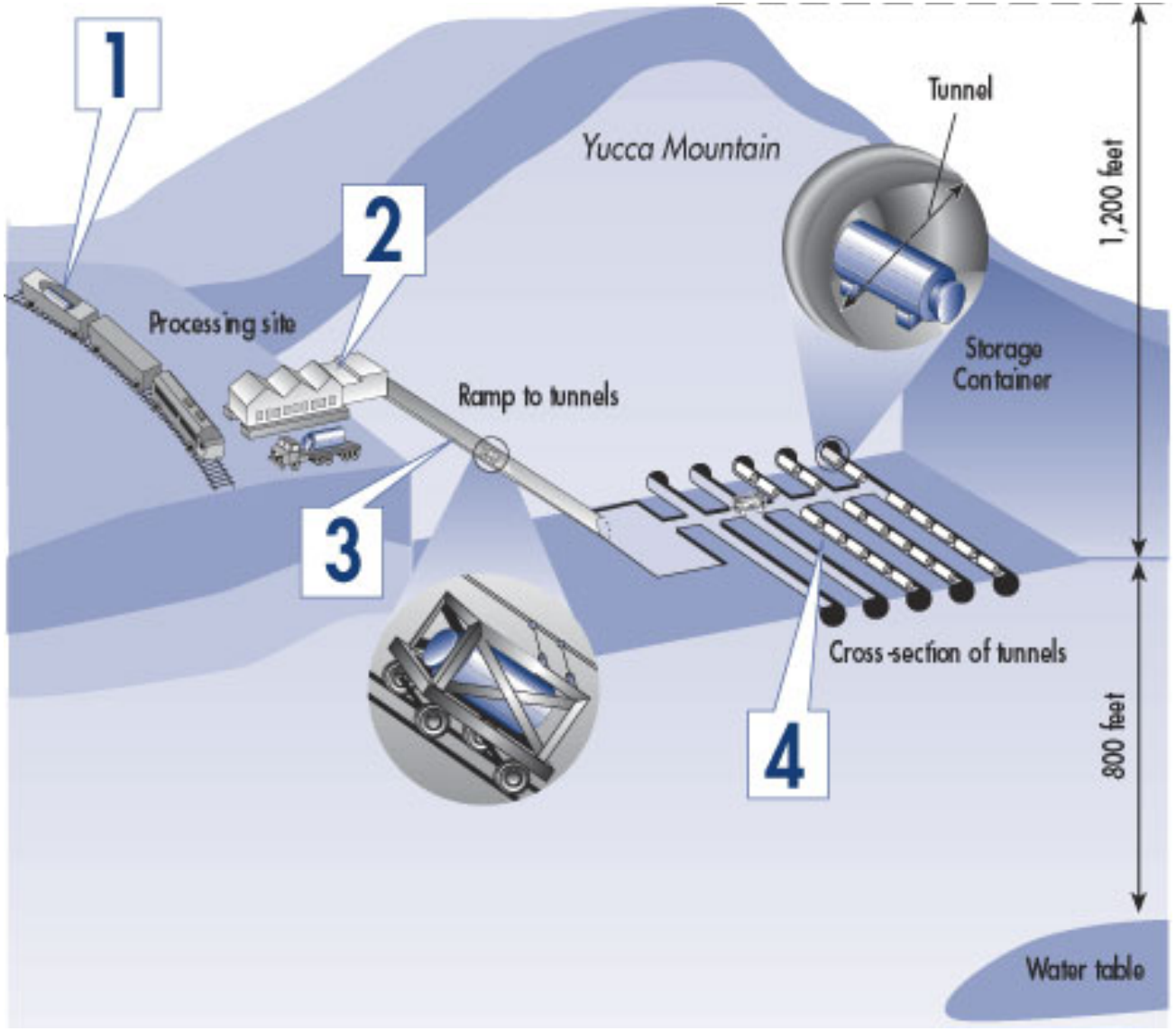
https://www.youtube.com/watch?annotation_id=annotation_3583941997&feature=iv&src_vid=N_JhruRobRI&v=hlextDSoVkQ
https://www.youtube.com/watch?v=VzupfyrWiew

How about theft/hijacking/terrorism?

If nuclear becomes bigger part of electrical power generation do additional transportation risks due to more material transport outweigh benefits?

High level waste disposal

~~Current plan~~ is to ship HLW to Yucca Mountain, Nevada for shallow burial



Big question: How far into the future do we need to guarantee safety?

Yucca Mountain Event Timeline

1957 – National Academy of Sciences recommends deep geologic storage as safest alternative
1978 – Department of Energy begins evaluation of Yucca Mountain
1984 – DOE studies 10 sites in six states
1985 – using studies, DOE selects three sites (Yucca Mountain, Nevada Hanford, Washington, and Deaf Smith County, Texas) for intensive "site characterization"
1987 – Congress directs DOE to only consider Yucca Mountain. If Yucca Mountain is found unsuitable, then stop process. Yucca Mountain is deemed suitable
1998 – Yucca Mountain was to to begin accepting waste by law, but could not due to legal challenges, project underfunding
2002 – Congress again authorizes Yucca Mountain
2006 – Harry Reid (D, NV) becomes Senate Majority Leader, declares project "dead"; Nuclear Regulatory Commission (NRC) objects
2008 – Obama elected, stops work on Yucca Mountain

Cost to date $9 billion, but $30 billion was collected from nuclear power industry over the years. Planned capacity will be exceeded by 2014

Legal basis for opposition

EPA determined standards that for 10,000 years, members of the public would receive no more than 15 mrem/year off-site. Groundwater protection was to be consistent with EPA's current Safe Drinking Water Act.

In 2004, US Court of Appeals finds that EPA's 10,000 year time limit was not consistent with law that stated that that guidelines should be consistent with National Academy of Science recommendations. NAS guidelines call for timeline of up to 1 million years.

EPA changes guidelines to allow exposures of up to 100 mrem/year from 10,000 to 1,000,000 years. Analyses must account for possibility of earthquakes, volcanic activity, climate change, and container corrosion

Can anyone provide assurances over such long periods of time? What standards of care do we owe to people further into the future than civilization has existed on Earth? What are the risks of NOT approving Yucca Mountain or an alternative?

HLW disposal in other countries

France (59 reactors, 75% electricity) Reprocesses HLW. *Expects* (2025*)* to store HLW in deep geologic disposal site. Note also reprocesses HLW for other countries, but requires those countries to dispose of HLW.
Germany (17, 30%) No long term plan. Recently resolved to end nuclear power generation.
Russia (31, 16%) Plans deep geologic storage, but no site selected.
Switzerland (5, 43%) Intends deep geologic storage, but no site selected
United Kingdom (19, 20%) Reprocesses HLW. Plans deep geologic storage, but no site selected
Japan (55, 29%) Reprocesses HLW. Deep geologic disposal site selection in 2023-2027
China (10 with 5 under construction, 2%) Deep geologic site selection expected in 2020 with disposal planned for 2050
Canada (18, 16%) Deep geologic disposal with siting expected to take 10 years or more
US (104, 20%) Deep geologic disposal. Yucca Mountain rejected. No plans for new site

No one has currently operating site or has even definitely selected a site.

Other disposal ideas:

deep burial (under water table. *C.f.,* fracking)
"salt domes"
subduction zones
deep seabed disposal
ship to outer space
freeze in polar ice
dilute and put into old uranium mines

Stabilization ideas:

vitrification: seal waste into glass
incorporate into artificial minerals

Burn up idea:

Bombard with neutrons or protons until long-lived isotopes are broken down into shorter lived isotopes