Week 11, Lecture 3 – Fission Operation

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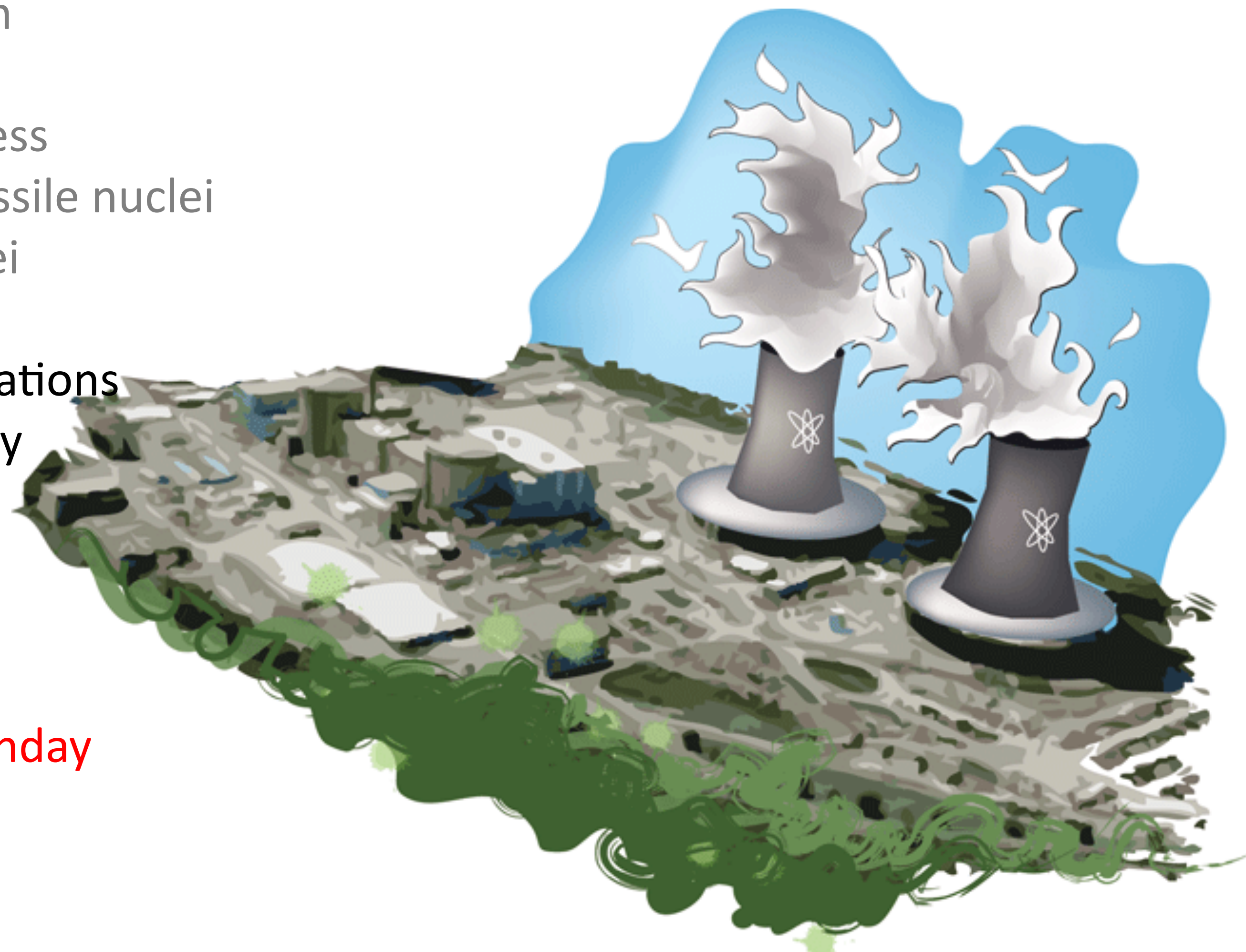
Nuclear Power, Nuclear Reactors

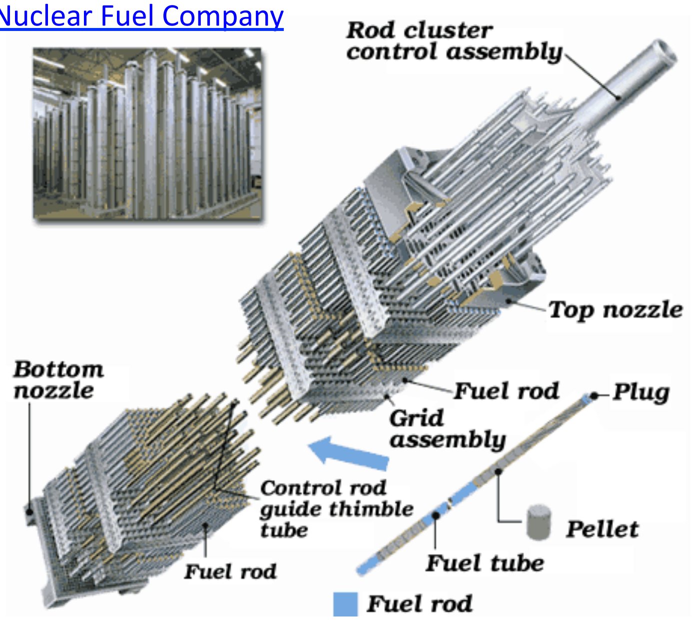
-- Overview
--- Reactor types
--- Reactors in Michigan
--- Reactors in France
-- Nuclear Fission process
--- fission energetics, fissile nuclei
--- limits to heavy nuclei
--- dynamical process
-- Nuclear Fission Operations
--- control and reactivity

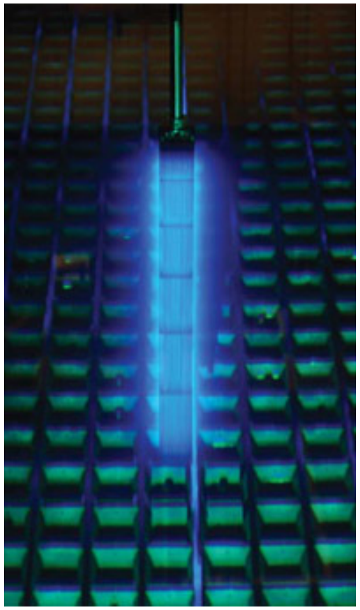


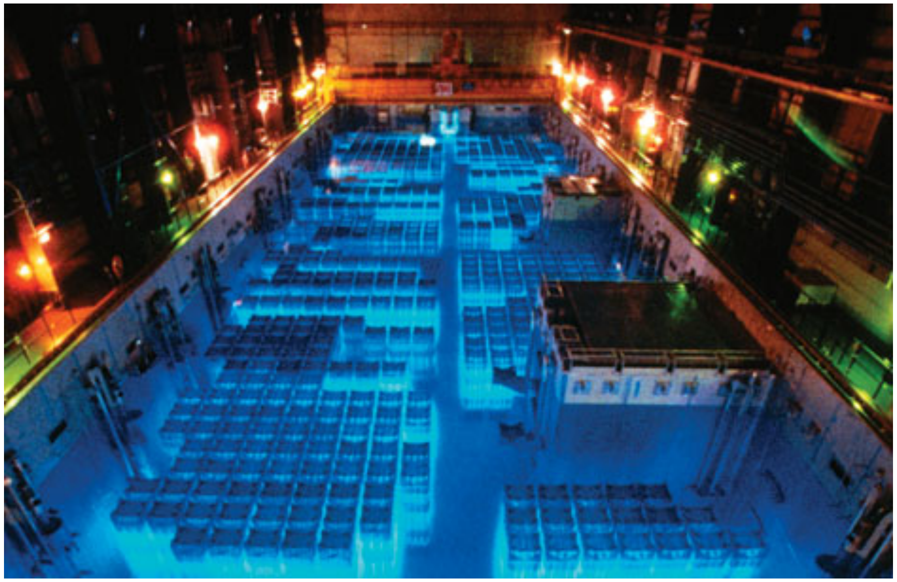
7th Homework due Monday

Nuclear Fuel Rods, Before & After

Mitsubishi Nuclear Fuel Company







Spent fuel in holding pool, before reprocessing at LaHague, France

Temporary storage in the US

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[NRC Website on Storage]

"Fuel that has been stored for at least five years in water has cooled sufficiently, and its radioactivity decreased enough, for it to be removed from the spent fuel pool and loaded into casks to free up additional space in the pool for storing spent fuel newly removed from the reactor."

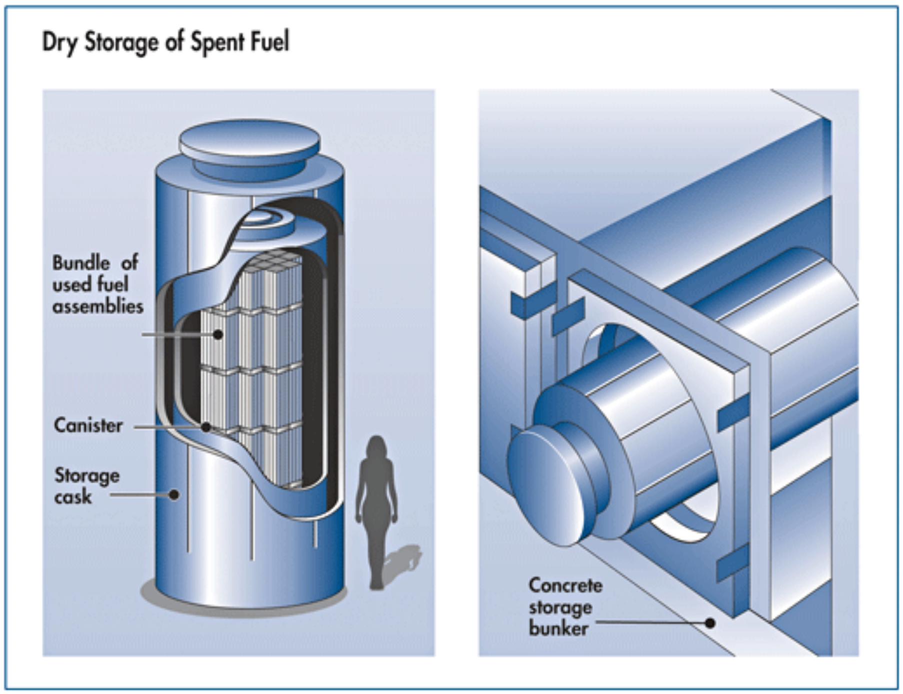
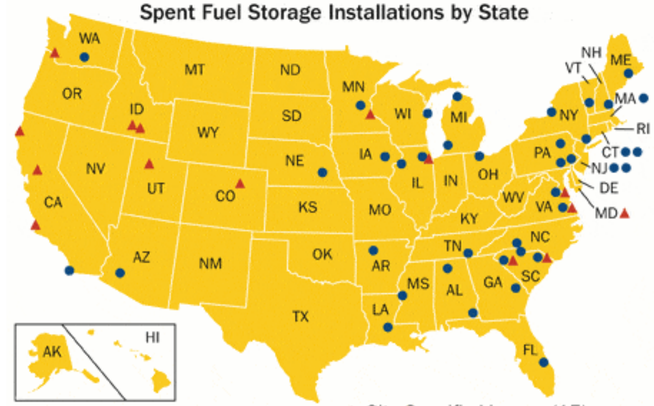


Figure 44. Licensed/Operating Independent Spent Fuel Storage Installations by State



▲ Site-Specific License (15)
● General License (39)

33 States have at least one ISFSI

ALABAMA
- ● Browns Ferry
- ● Farley

ARIZONA
- ● Palo Verde

ARKANSAS
- ● Arkansas Nuclear

CALIFORNIA
- ▲ Diablo Canyon
- ▲ Rancho Seco
- ● San Onofre
- ▲ Humboldt Bay

COLORADO
- ▲ Fort St. Vrain

CONNECTICUT
- ● Haddam Neck
- ● Millstone

FLORIDA
- ● St. Lucie

GEORGIA
- ● Hatch

IDAHO
- ▲ DOE: TMI-2 (Fuel Debris)
- ▲ Idaho Spent Fuel Facility

ILLINOIS
- ▲ GE Morris (Wet)
- ● Dresden
- ● Quad Cities

IOWA
- ● Duane Arnold

LOUISIANA
- ● River Bend

MAINE
- ● Maine Yankee

MARYLAND
- ▲ Calvert Cliffs

MASSACHUSETTS
- ● Yankee Rowe

MICHIGAN
- ● Big Rock Point
- ● Palisades

MINNESOTA
- ● Monticello
- ▲ Prairie Island

MISSISSIPPI
- ● Grand Gulf

NEBRASKA
- ● Ft. Calhoun

NEW HAMPSHIRE
- ● Seabrook

NEW JERSEY
- ● Hope Creek/Salem
- ● Oyster Creek

NEW YORK
- ● Indian Point
- ● FitzPatrick

NORTH CAROLINA
- ● McGuire

OHIO
- ● Davis-Besse

OREGON
- ▲ Trojan

PENNSYLVANIA
- ● Limerick
- ● Susquehanna
- ● Peach Bottom

SOUTH CAROLINA
- ● ▲ Oconee
- ● ▲ Robinson
- ● Catawba

TENNESSEE
- ● Sequoyah

UTAH
- ▲ Private Fuel Storage

VERMONT
- ● Vermont Yankee

VIRGINIA
- ● ▲ Surry
- ● ▲ North Anna

WASHINGTON
- ● Columbia

WISCONSIN
- ● Point Beach

Note: Data are current as of June 2009
NRC-abbreviated unit names used
Source: U.S. Nuclear Regulatory Commission

Reactor Startup Neutrons

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Q: Recall that our reaction needs a neutron to get going, where do they come from?
A: You have to make them in another nuclear reaction!

$^{238}Pu_{144} \rightarrow {}^{234}U_{142} + {}^{4}He_2 + Q_\alpha$

$^{4}He_2 + {}^{9}Be_5 \rightarrow ({}^{13}C_7)^* \rightarrow {}^{12}C_6 + {}^{1}n + Q$

$^{1}n + {}^{235}U \rightarrow ({}^{236}U_{144})^* \rightarrow ({}^{A1}Z_1)^* + ({}^{A2}Z_2)^* + Q_f$

Make an alloy of Pu and Be metal (ugh) and some of the alpha's will react with the beryllium and the metal will be a source of neutrons.

Note that you won't be able to turn this source off once you have mixed the metals. An alternative that is controllable is to use deuterons from a small accelerator in a reaction:

$^{2}H_1 + {}^{9}Be_5 \rightarrow ({}^{11}B_6)^* \rightarrow {}^{10}B_5 + {}^{1}n + Q'$

Better reaction from nuclear reactor standpoint but messier target:

$^{2}H_1 + {}^{7}Li_4 \rightarrow ({}^{9}Be_5)^* \rightarrow ({}^{8}Be_4) + {}^{1}n + Q''$

$\searrow {}^{4}He_2 + {}^{4}He_2 + 0.092\ MeV$

Prompt & Delayed Neutrons

Q: We said we have ~2.5 n/fission, where do the subsequent neutrons come from?

A: The fission fragments have internal excitation and promptly emit about 1 n /fragment AND a few of the fission fragments are so unstable that they emit a neutron after β-decay

$$^{1}n + {}^{235}U \rightarrow ({}^{236}U_{144})^* \rightarrow ({}^{A1}Z_1)^* + ({}^{A2}Z_2)^* + Q_f$$

$${}^{A1-1}Z_1 + {}^{1}n + {}^{A2-1}Z_2 + {}^{1}n$$ (promptly emitted, high energy)

$${}^{A1-1}(Z_1+1)^* + \beta^- + \bar{\nu} + Q_\beta$$

$${}^{A2-1}(Z_2+1)^* + \beta^- + \bar{\nu} + Q_\beta$$

$${}^{A2-2}(Z_2+1) + {}^{1}n + Q_n$$ (after decay)

The first nuclear reactor was built and studied by Enrico Fermi at the Univ. of Chicago.

"The neutron source was the beryllium target of the University of Chicago cyclotron struck by a beam of up to 20 microA of 8 MeV deuterons. Near the target was placed a hollow shell made of tinned iron and containing 106 lbs. of U_3O_8. This was surrounded by about 2" of paraffin. The interior of the shell was filled with paraffin, except for an axial hole which accommodated a BF_3- filled proportional counter. The counter was connected through an amplifier to a scaling circuit ('scale of 64') equipped with interpolating lights and a Cenco impulse counter. A tenth-second timer, driven by a synchronous motor, and hundredth-second stop watch were mounted on the panel of the scaler, close to the interpolating lights and impulse counter. This group of dials and lights was photographed at an appropriately varying rate by a Sept camera which was actuated by hand. The result was a record on movie film of times and counts, from which the decay curves were plotted."

The observed activities had half-lives of 2, 7, 24 and 57 seconds …

Delayed Neutrons Moderation & Control

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We can have a sustained chain reaction if one of the product neutrons can find its way to another ^{235}U nucleus BEFORE it is lost. Seems easy, but:

Loses: Leak out from region with fuel; Absorption by another nucleus (i.e., ^{238}U)
Mitigation strategies: Careful design of reactor core; Increase fraction of ^{235}U (typical is ~5%)
Moderate energy of neutrons (increase σ); Use water moderator, heavy water is better
Control: physically add or remove neutron absorbing material to the core

Notice that even 1 eV neutrons travel at ~10^7 m/s so it is unlikely that you could control the rate of production … good for explosions, not good for controlled reactions. The delayed neutrons provide the time needed to control the system.

$$^{1}n + {}^{235}U \rightarrow ({}^{236}U_{144})^* \rightarrow ({}^{A1}Z_1)^* + ({}^{A2}Z_2)^* + Q_f$$

A1 ~ 140 , A2~96 – common e.g.,

$^{137}I_{84} + {}^{97}Y_{58}$ → → → $^{97}Mo_{55}$

$T_{½}$ = 24s

$({}^{135}Xe_{83})^* \rightarrow {}^{1}n + {}^{136}Xe_{82}$ (stable)

$^{87}Br_{52} + {}^{147}Pm_{86}$ → $^{147}Sm_{85}$ (106 Gyr)

$T_{½}$ = 56s

$({}^{87}Kr_{51})^* \rightarrow {}^{1}n + {}^{86}Kr_{50}$ (stable)

Another influence of the nuclear shells on fission.

Xenon Poisoning & Accidents

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A few of the fission products on the opposite side of the neutron shells have the opposite effect on the number of neutrons available for fission. These nuclei have an insidious behavior if a reactor has been run, stopped, and then restarted because they are radioactive, their number can change with time…

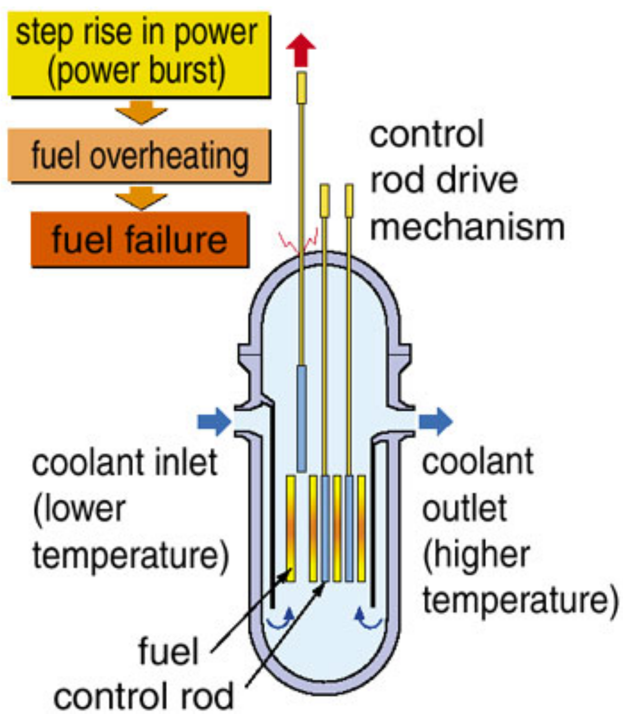
$$^{1}n + {}^{235}U \rightarrow ({}^{236}U_{144})^* \rightarrow ({}^{A1}Z_1)^* + ({}^{A2}Z_2)^* + Q_f$$

A1 ~ 140 , A2~96 – common e.g., $^{135}I_{82} + {}^{99}Y_{62}$ → → → → $^{99}Ru_{55}$

$^{135}I_{82}$ → ($T_{½}$ =6.6 hr) → $^{135}Xe_{81}$

$\sigma(n,\gamma)$= 2.6 Mb $^{135}Xe_{81} + {}^{1}n \rightarrow {}^{136}Xe_{82}$ (stable)

$^{135}Xe_{81}$ → ($T_{½}$ =9.1 hr) → $^{135}Cs_{80}$ ($T_{½}$ = 2.3 Myr)



There have been two fatal accidents with nuclear reactors, both light-water moderated BWR, in both cases the operators were standing on top of the core and physically removed the control rods. Mostly likely removed too much due to poisoning. Fission rate takes off, water boils, steam explosion, and then fuel melts.

SL-1 (1961) a small test reactor in Idaho, 3 dead

Chernobyl-4 (1986) a large power reactor in Ukraine, >30 dead