Nuclear

GEOS 24705/ ENST 24705

Can nuclear be an important part of U.S. energy mix?

Only if we actually build it

Wave of construction in 1970s, tapered out by 1990

-- no new construction starts since 1977... til 2013

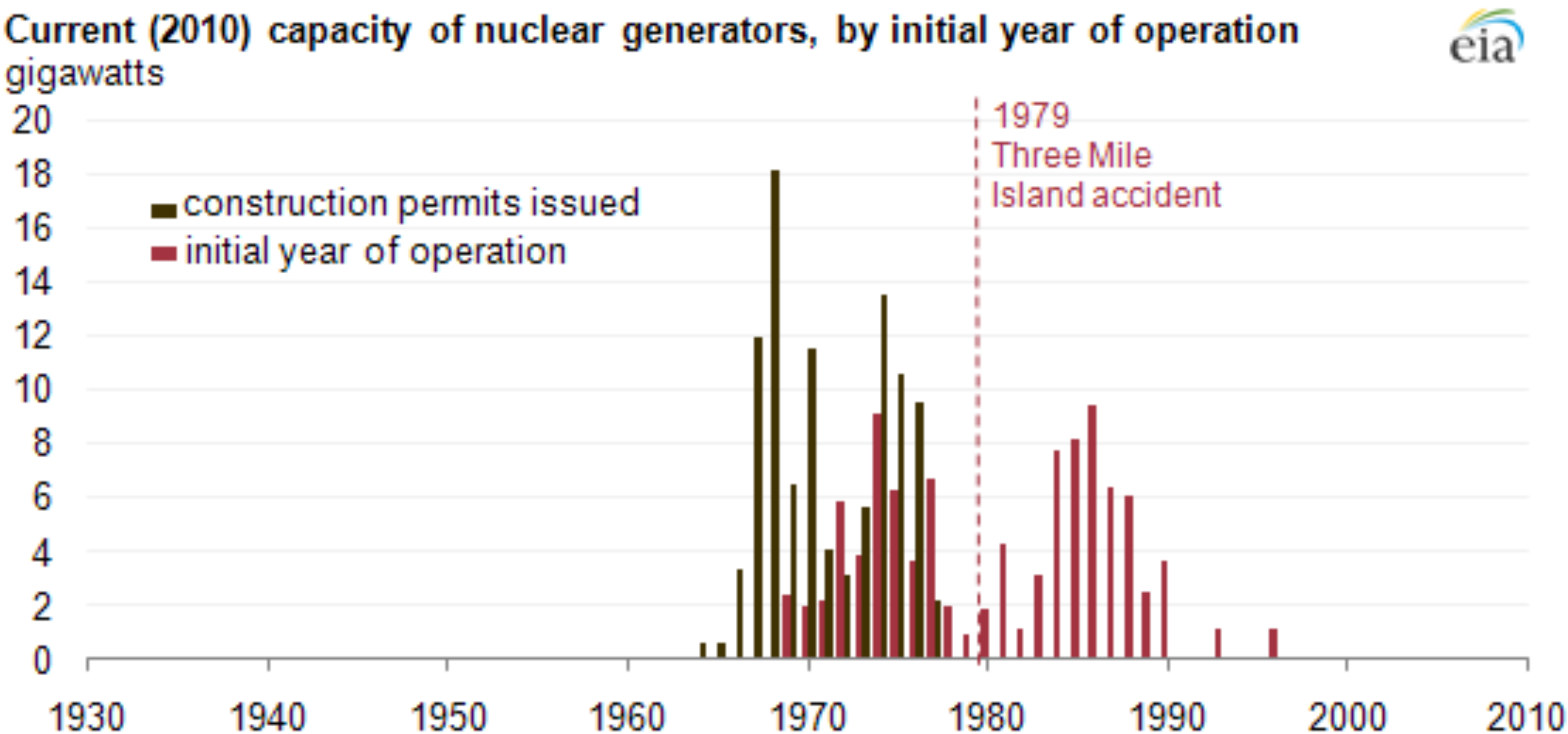


Image: Energy Information Agency

Nuclear projected to shrink in the U.S., grow worldwide

IEA projects a 60% increase in world nuclear power from 2011-2035

U.S.

- currently 19% of electricity (100 reactors, 65 PWRs and 35 BWRs)
- 4 new reactors under construction (+ 1 decades-old build)
  New = 2 projects, operating licenses issued 2012
  Both in regulated-utility Southeast, not competitive-generation RTO areas
- 13 likely near-term closures, all in competitive-market Northeast

World:

- currently 14% of electricity (435 reactors)
- 72 rectors under construction, most (28) in China *(followed by Russia, India, Korea)*

Image (right): existing nuclear reactors as of 2005

Image from International Nuclear Safety Center, Argonne National Laboratory

Data from World Nuclear Org. (2013) and European Nuclear Society (summarizing IAEA 2014 data)

Nuclear will still represent a small fraction of China's electricity

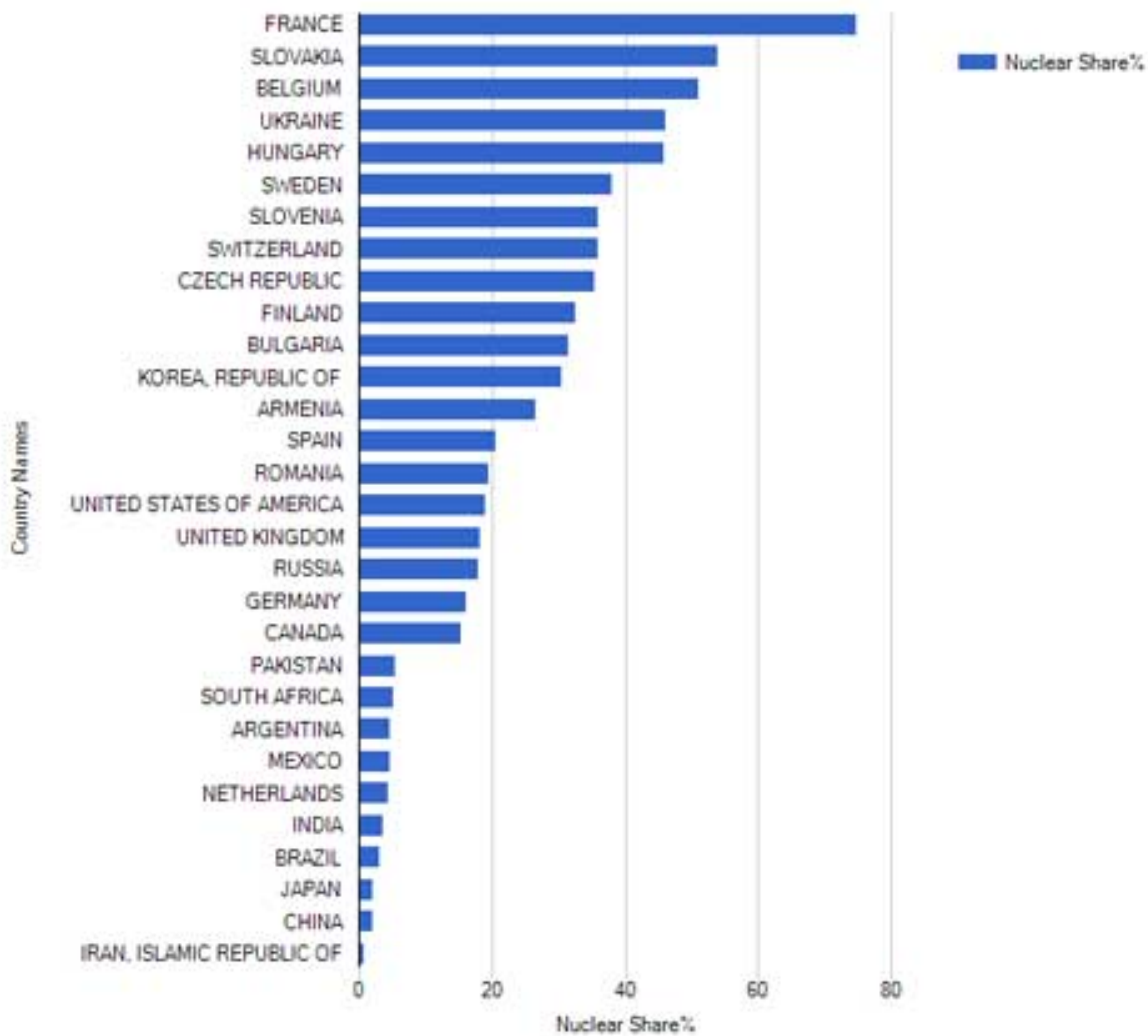
and an even smaller fraction of total power usage

Nuclear currently represents ~1% of China's electricity generation. Projected to increase by 200% in next ~ 5 years.

But electricity generation is increasing by nearly 8%/year (50% in 5 years).

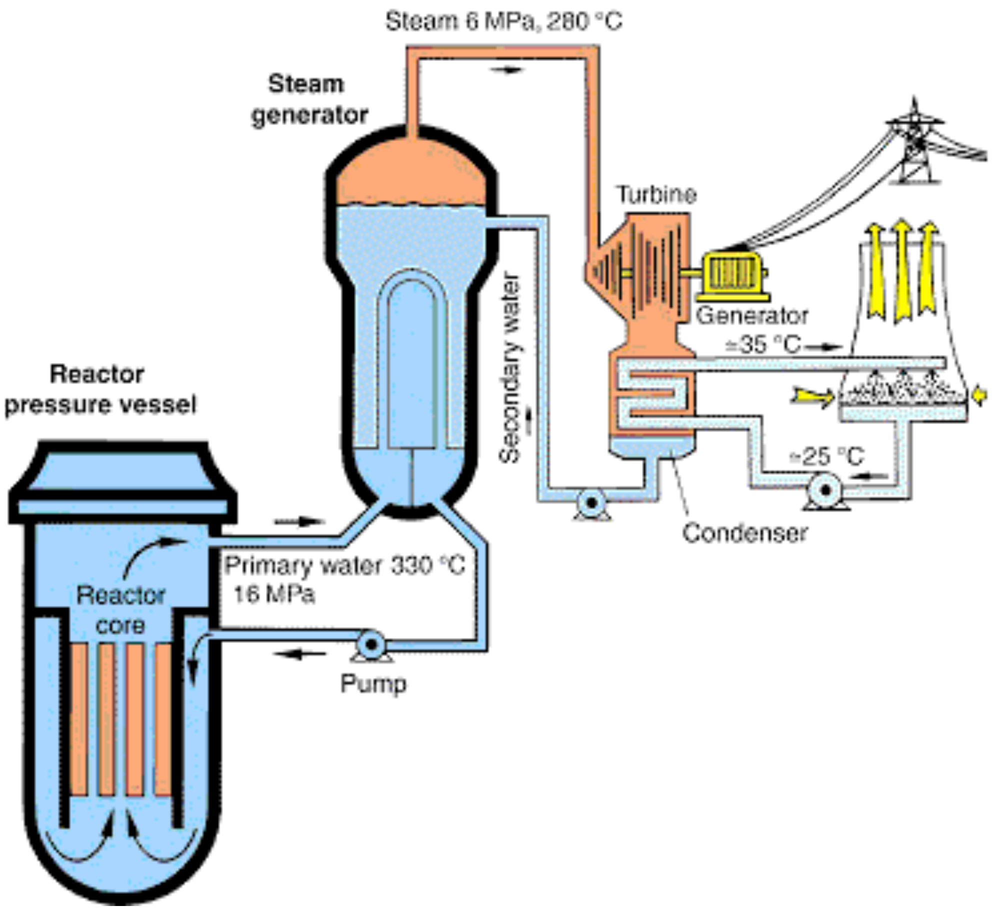
Nuclear contribution will still be ~2% even after all plants under construction are finished.

Figure from European Nuclear Society (summarizing IAEA 2014 data)



Nuclear power just another way of making steam

A nuclear plant is a big tea-kettle driving a steam turbine

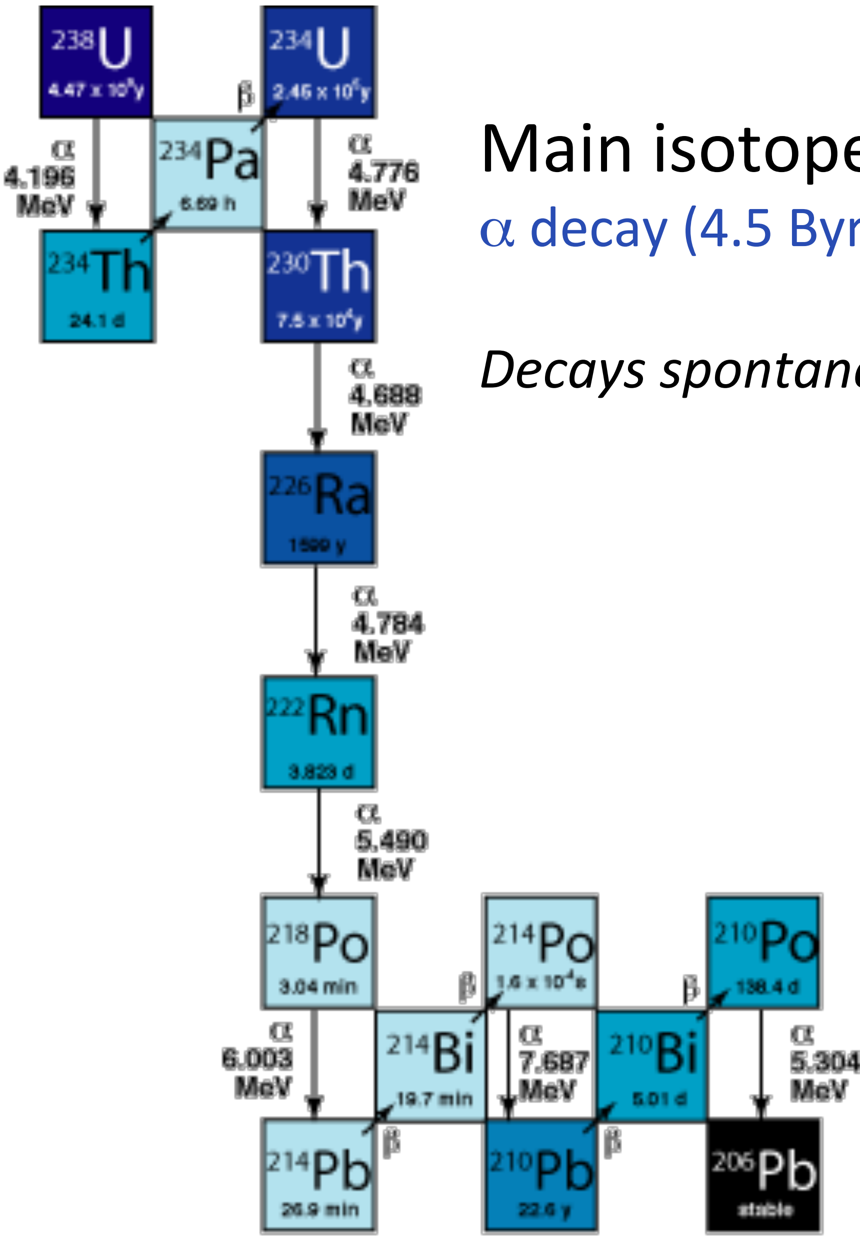


Nuclear engineering is all about keeping the system in the Goldilocks condition – not too cold and not too hot.

Most of it is thermal management

Images: copyright unknown

Uranium: two most common isotopes radioactively decay



Main isotope is ^{238}U (99.28%)

α decay (4.5 Byr half-life)

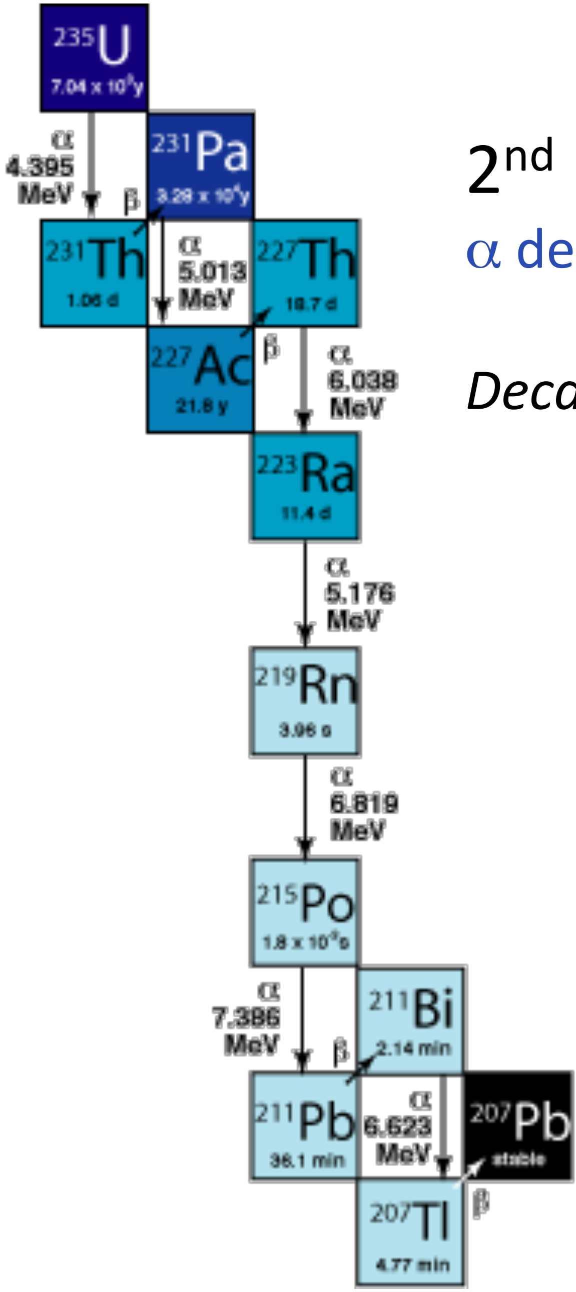
Decays spontaneously

^{238}U -- > α + ^{234}Th

...eventually -- > ^{206}Pb

Image: Macquarie University

Uranium: two most common isotopes radioactively decay



2nd most abundant is ^{235}U (0.72 %)

α decay (700 Myr half-life)

Decays spontaneously

$^{235}U \;\text{-- >}\; \alpha + {}^{231}Th$

...eventually -- > ^{207}Pb

Image: Macquarie University

How can you get heat from something with a 700 My half-life?

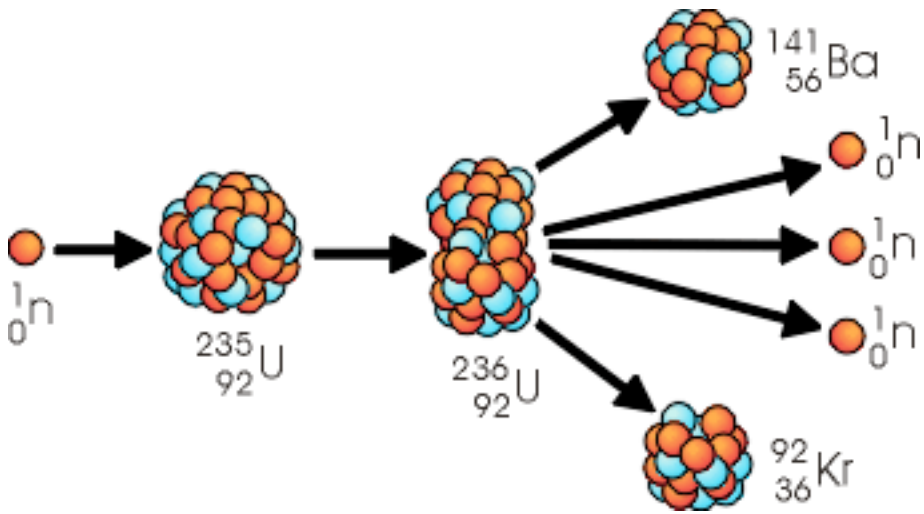
Bypass natural radioactive decay: induce nuclear fission

Force uranium to break apart by bombarding it with a neutron
(^{235}U "fissions" spontaneously only one in 14 billion decays)

add a neutron to make a new element: $^{235}U + n \rightarrow\ ^{236}U$

… which then falls apart into big chunks…. *(for example)*

$$^{236}U \rightarrow\ ^{141}Ba + ^{92}Kr + 3n$$



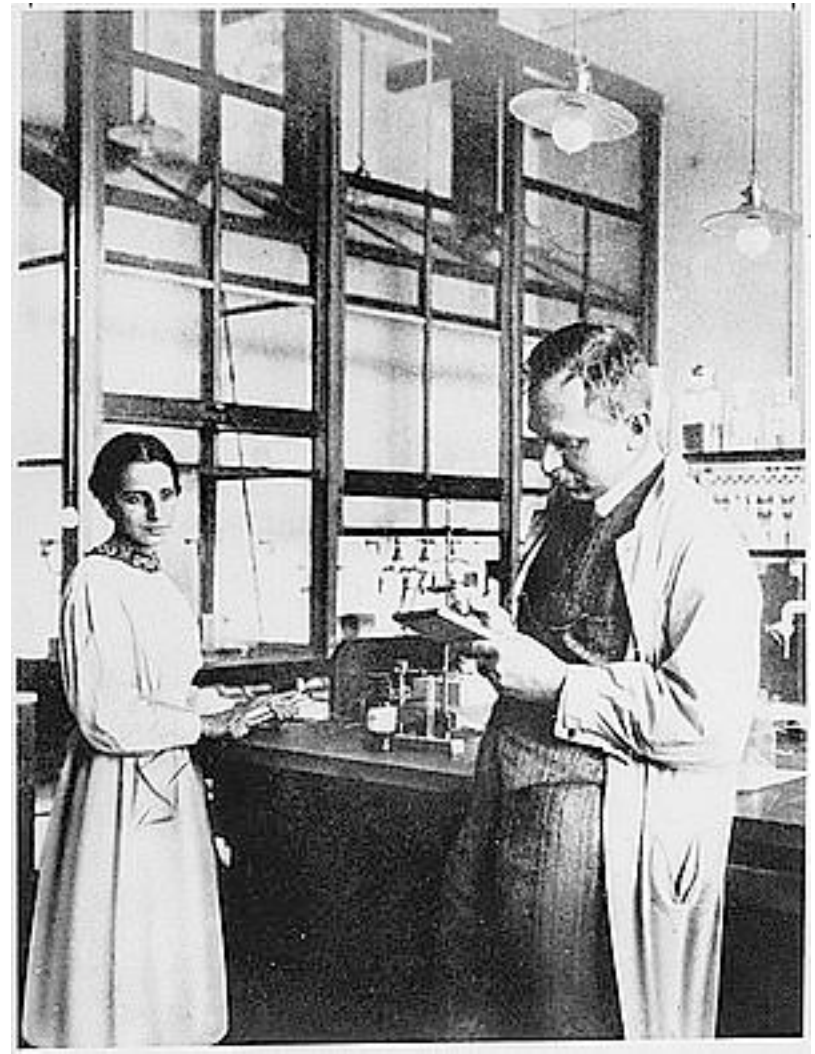
^{235}U is "fissile": multiple neutrons produced in turn make multiple new decays: a chain reaction.

Fission products themselves are highly radioactive: decay by β emission. Short half-life: spent fuel is "hot".

Fission of uranium discovered by Lise Meitner from Otto Hahn's data in 1939

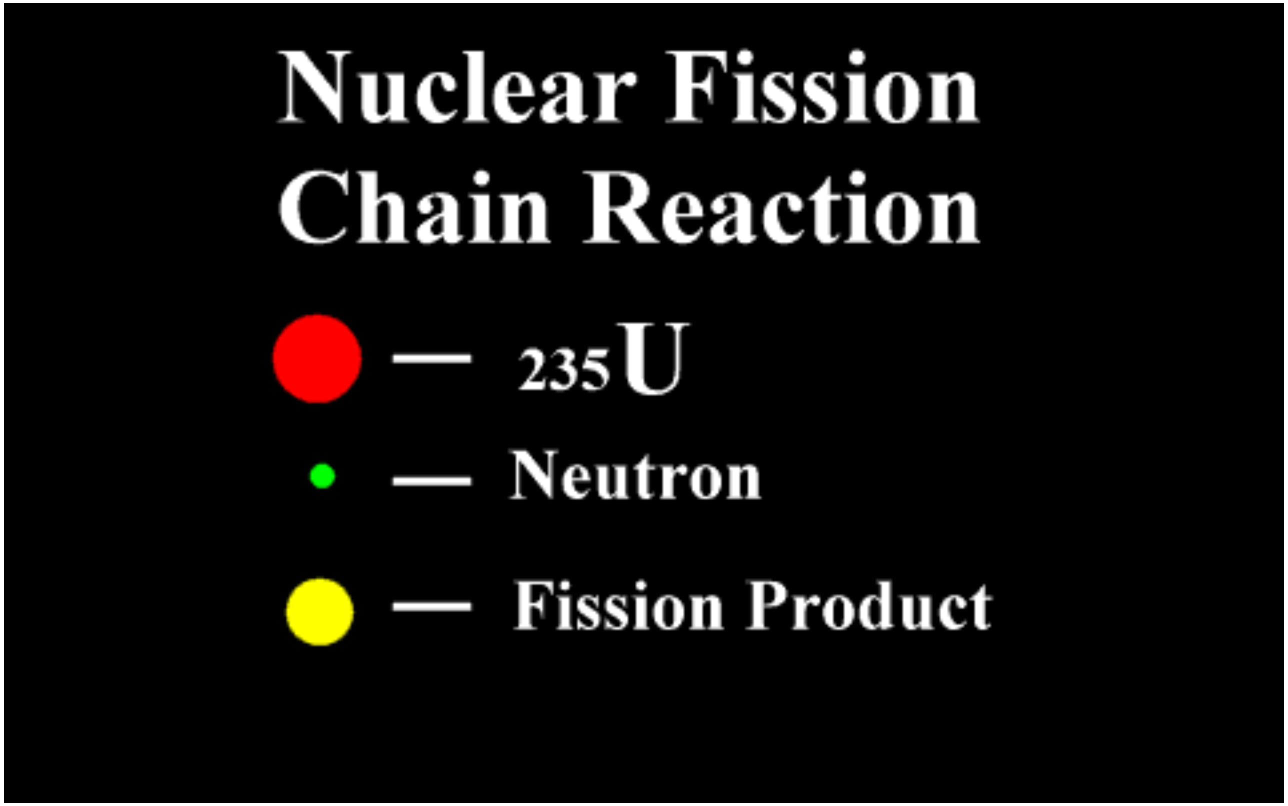
Hahn was trying to make heavier elements by neutron bombardment – didn't understand his results.

But only Hahn got the Nobel prize…



Hahn and Meitner in the laboratory, Berlin, ca. 1925
Image: Technische Universitat Munchen

Get the most out of your neutrons with a chain reaction



Each fission event makes more fission events.
And each event produces heat….

Animation: http://library.thinkquest.org/17940/texts/fission/fission.html

Two main types of nuclear reactor

In a **power reactor** you just want heat produced in nuclear decay.

Here the goal is to control the rate of heat production.
Not too cool (low power) or too hot (meltdown).

In a **"breeder" reactor** the only purpose is transmutation, turning one element into another.

Here the goal is to control the daughter product.
(Generally make plutonium out of uranium). Can use breeders to reprocess spent nuclear fuel, but then you're left with fuel that contains dangerous plutonium. Reactor meltdowns are worse if using reprocessed fuel.

Many possible design choices for reactor

- Moderator and therefore fuel type

  Moderator makes neutrons more useful by slowing them down.
  If using a great moderator can use natural abundance uranium with < 1% ^{235}U. If no moderator must enrich to > 20% ^{235}U.

- Composition of fuel

  Choices: include U in oxide, metal alloy, or non-oxide ceramic.
  Most fuel is oxide (UO_2) which cannot burn.

- Size/shape/arrangements of fuel rods or pellets

- Cladding / control rods that separate fuel from coolant, absorb some neutrons

Reactor management

"Goldilocks" heat production: want a chain reaction but not a bomb

- Need a coolant to transfer heat from reactor to turbine

  Often water. If not enough transfer, could melt fuel.

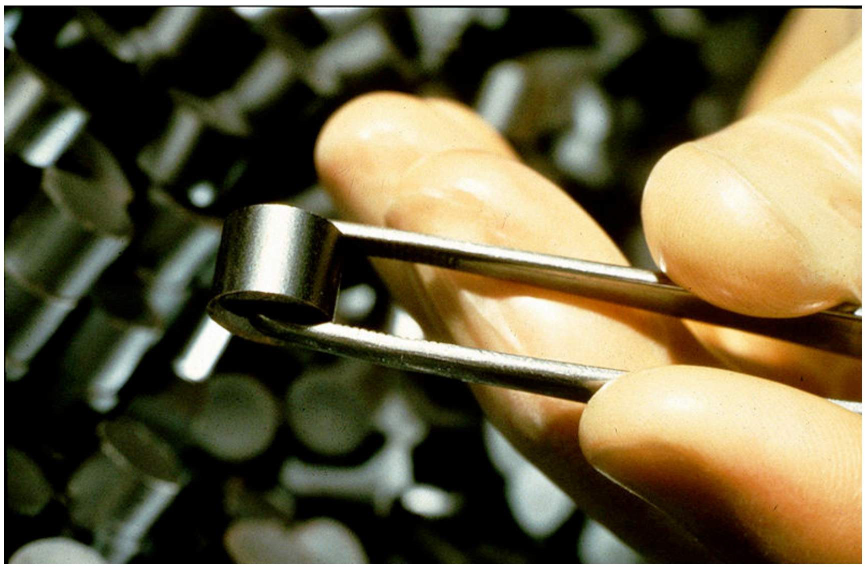
- If reactor gets too hot anyway, need emergency option

  Keep fuel in distinct units that can be separated

  In emergency, separate fuel rods or pebbles

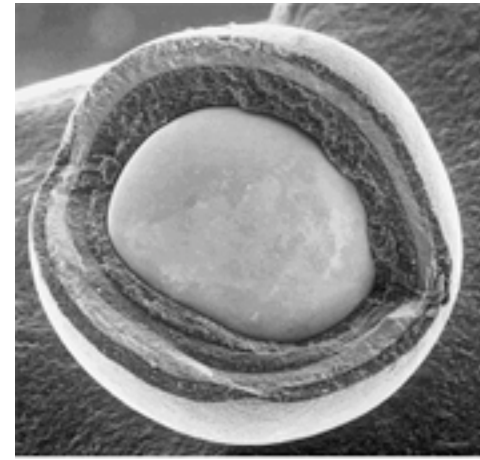
Nuclear power reactor fuel options

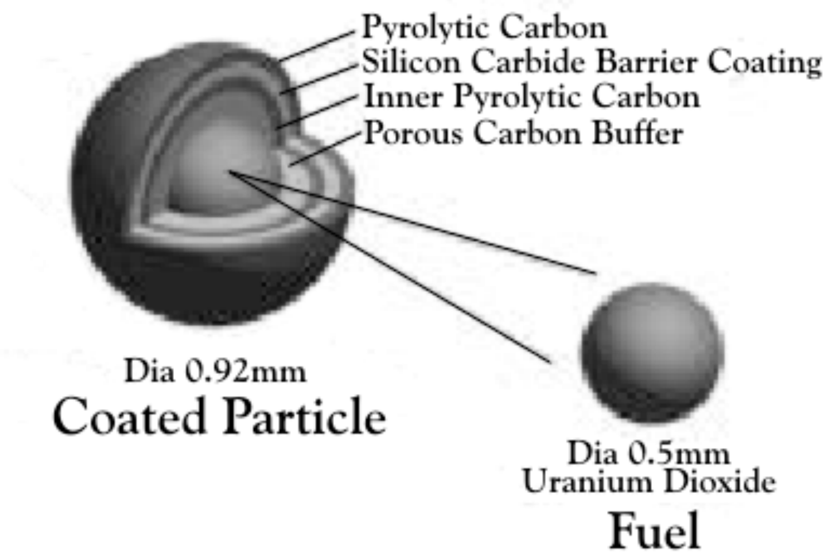
Uranium oxide = UO_2 = semiconducting solid



Uranium oxide fuel pellet

Image: Nuclear Regulatory Council

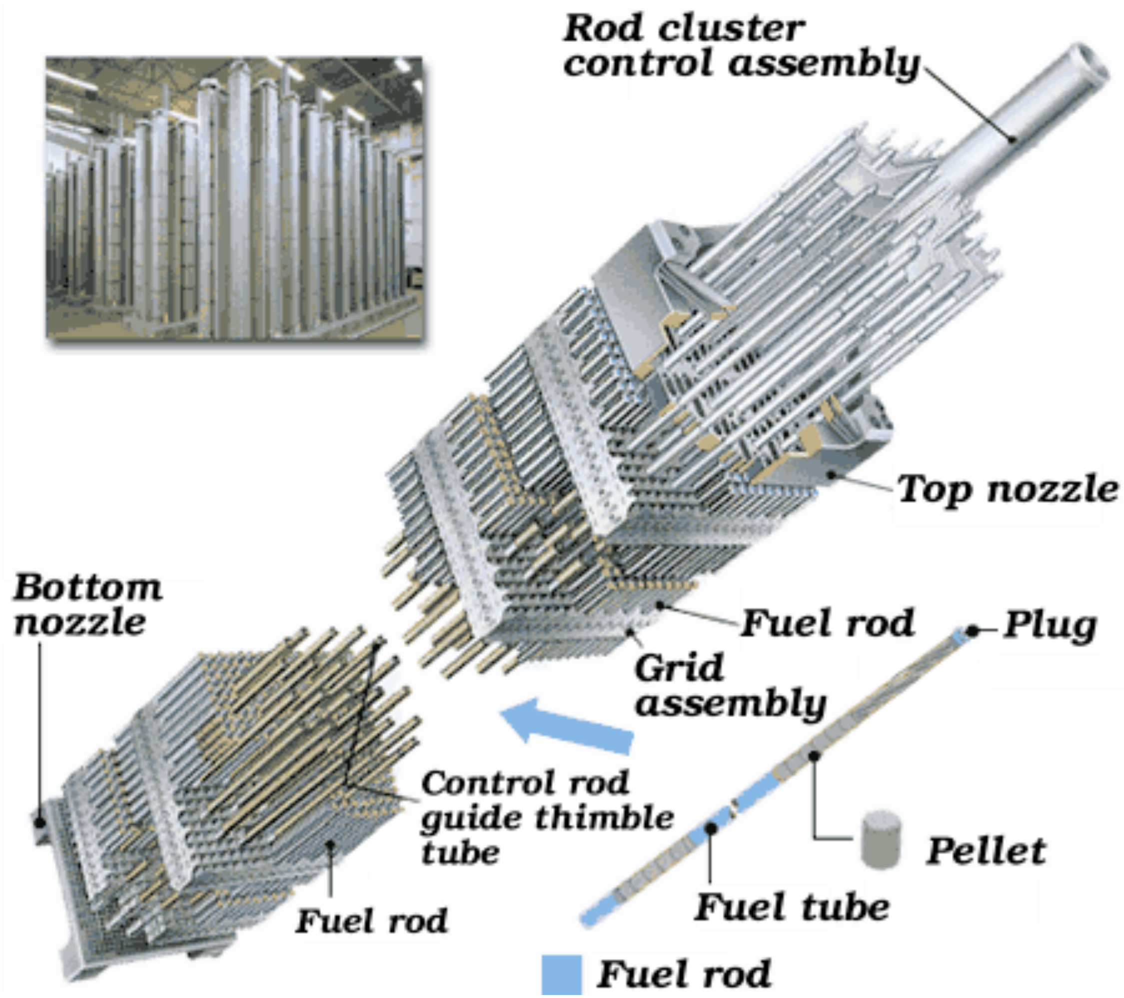




Uranium oxide “TRISO” micro fuel pebble

Image: top, US DOE, Office of Nuclear Energy, Sci. and Tech.
Bottom: ars technica openforum.

Nuclear fuel pellets must have cladding, be separable

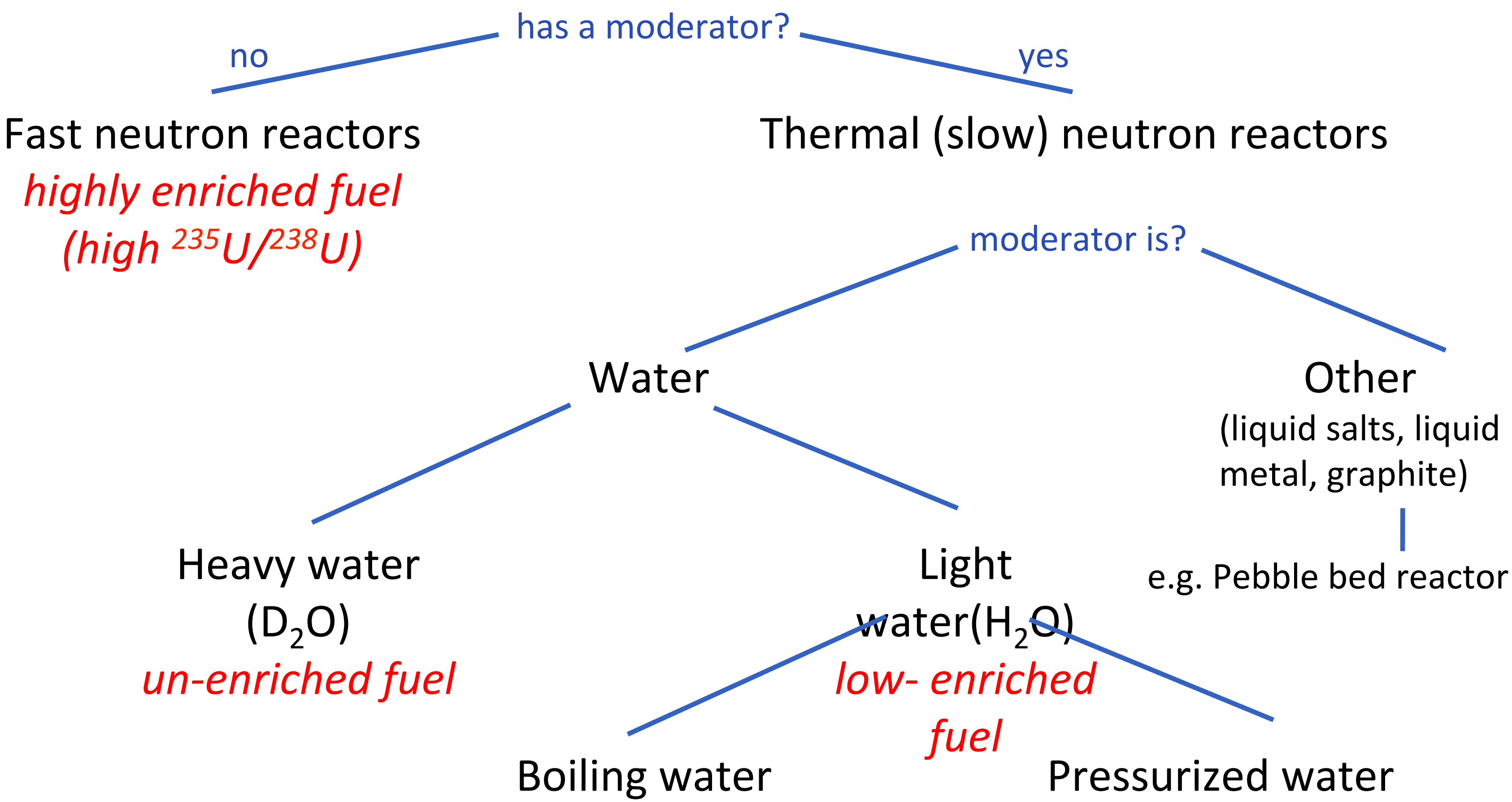


Uranium oxide pellets in fuel rod assembly
(4 m long rods, zirc. clad? for PWR reactor)
Image: Mitsubishi Nuclear Fuel Inc.

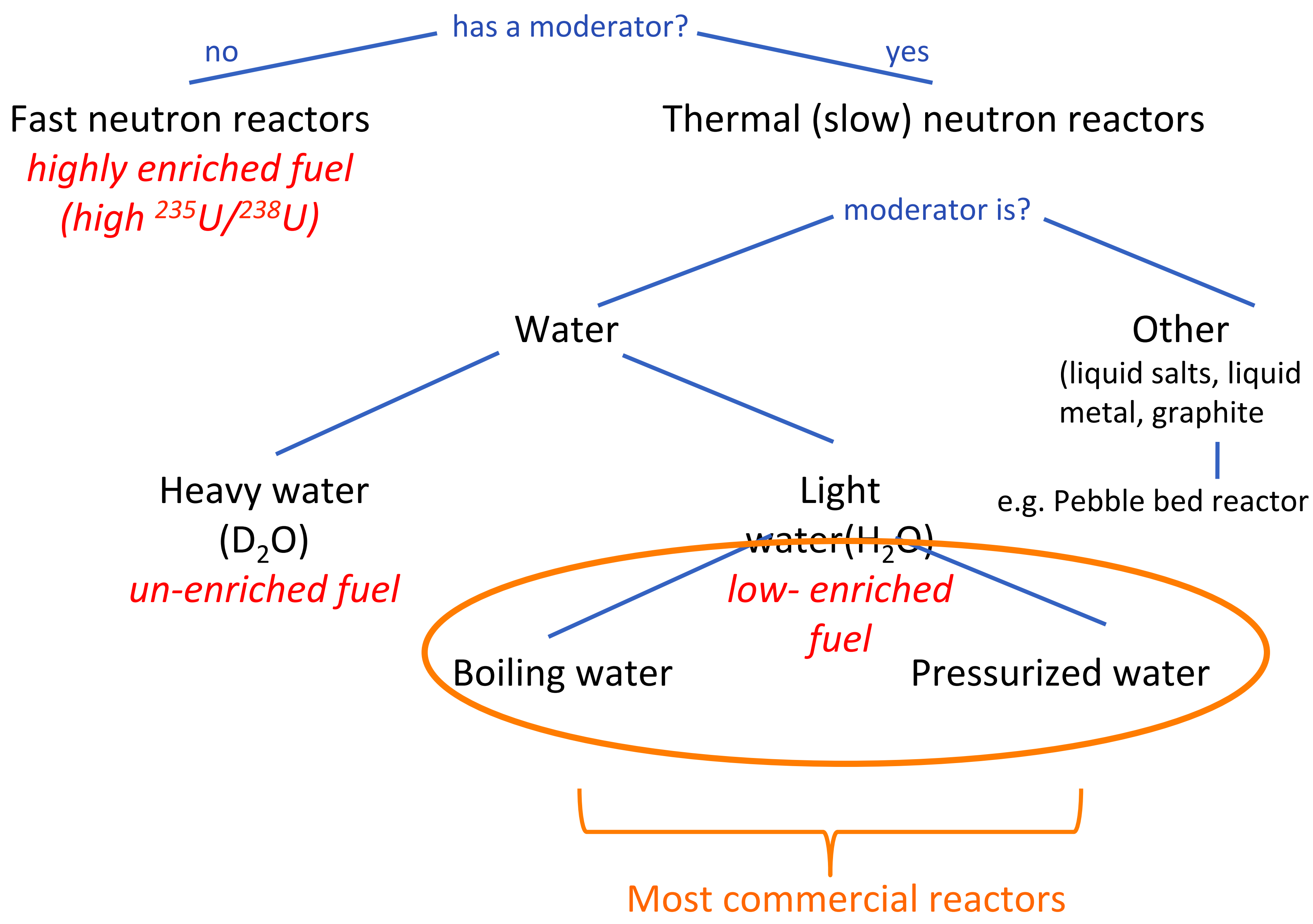
CANDU (CANada Deuterium Uranium) fuel rods, un-enriched uranium oxide pellets in ½ m zirconium tubes.

Image: Atomic Energy of Canada

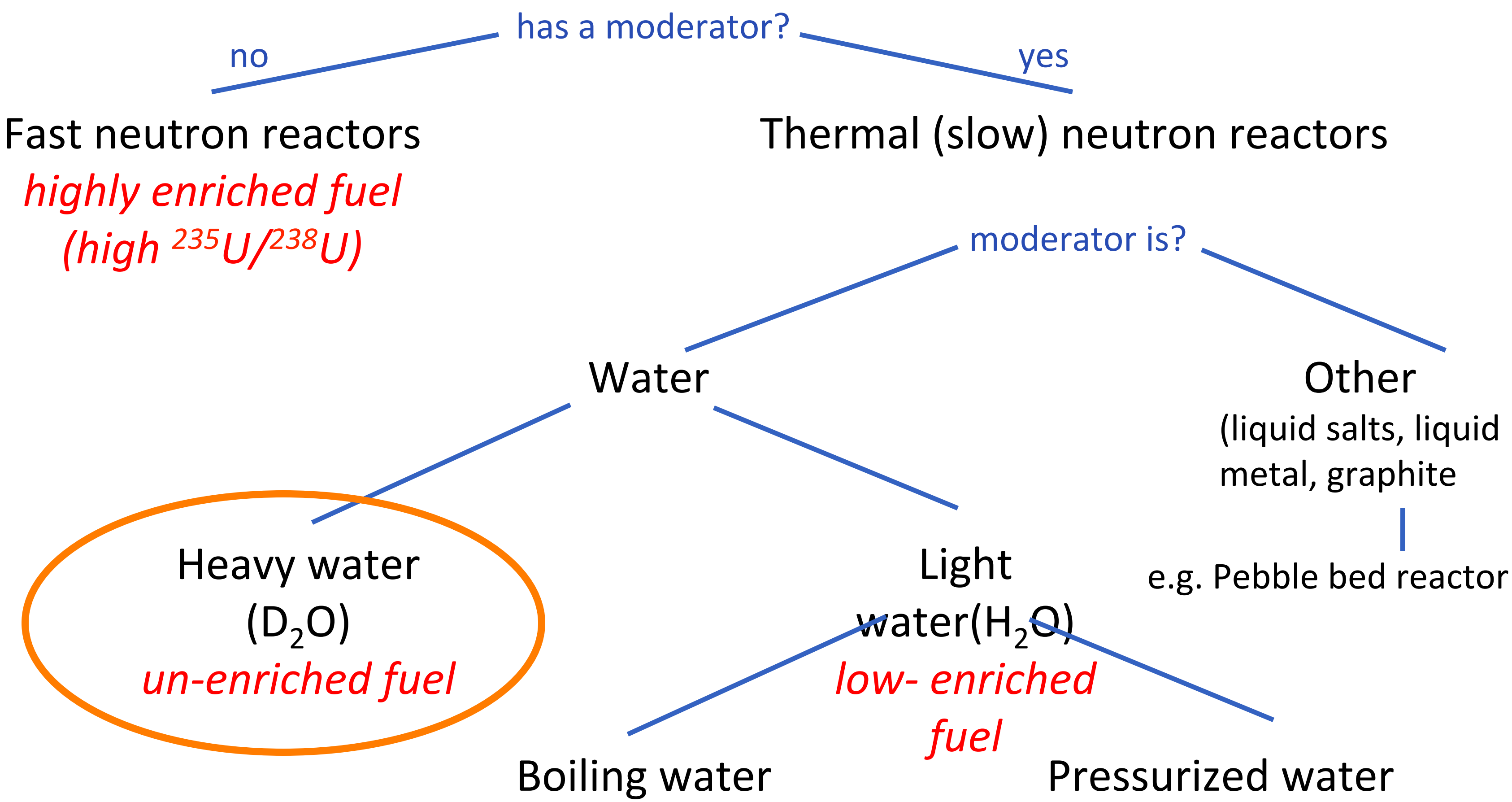
Nuclear power reactor characterization



Nuclear power reactor characterization



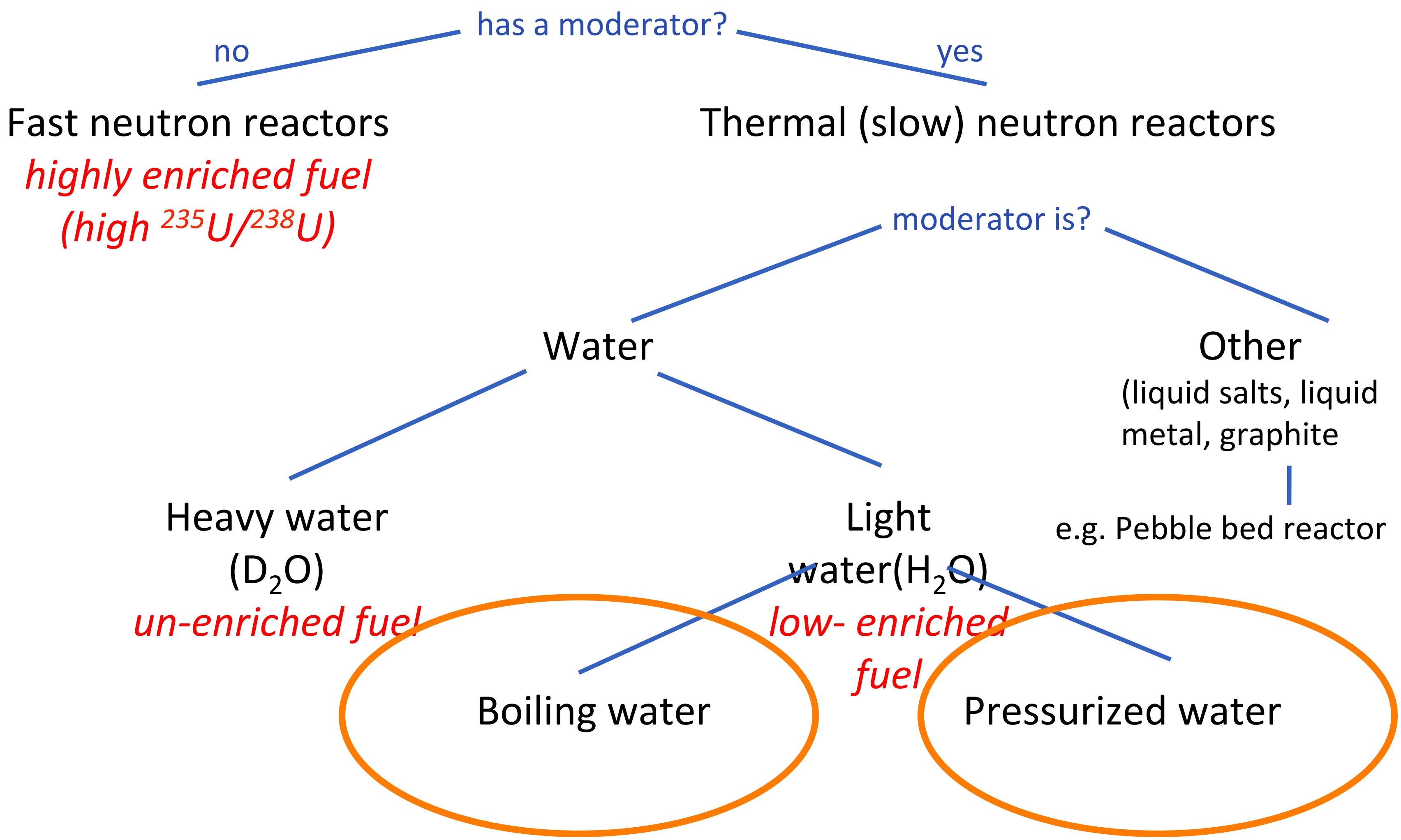
Nuclear power reactor characterization



Heavy water is a great moderator, so critical for nuclear fission without enriched U

Important to development of bomb, hence sabotage of heavy-water facility in occupied Norway, 1943

Nuclear power reactor characterization



Pressurized-water reactor turbine water separate from fuel

3 separate water loops (reactor, turbine, and cooling water)

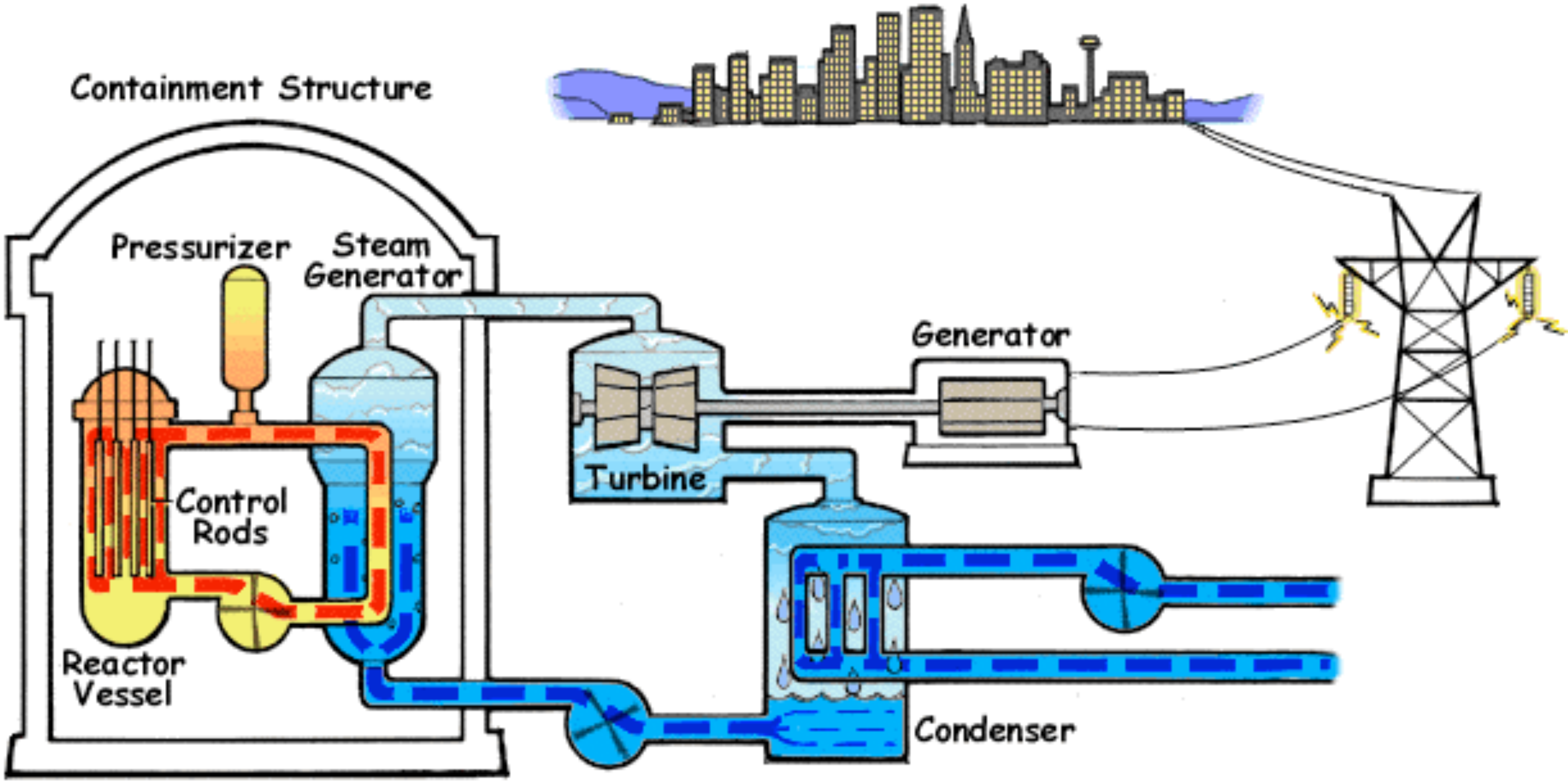
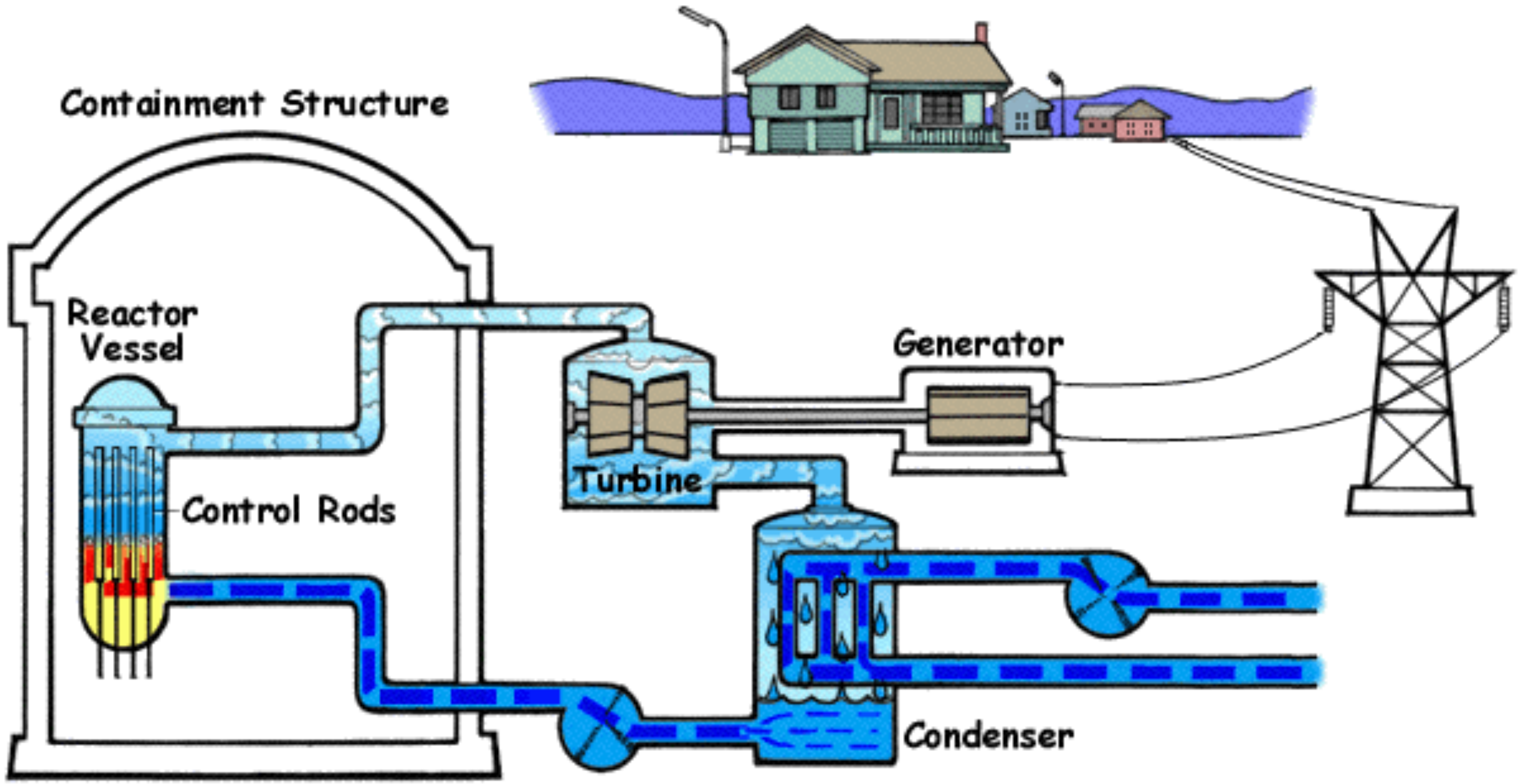


Image:Wikimedia commons

Boiling-water reactor turbine water touches fuel

2 separate water loops (reactor + turbine, cooling water)

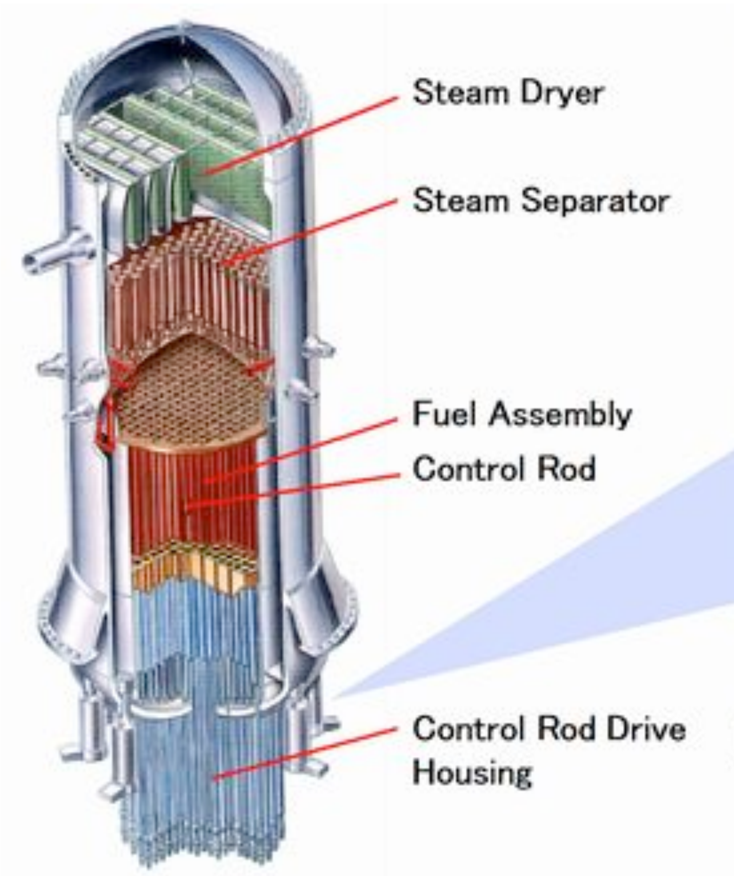


Note that steam in turbine is somewhat radioactive – ^{16}O in water is converted to radioactive ^{17}N in reactor

Image: Wikimedia commons

Boiling-water reactor turbine water touches fuel

Simple to build, a bit uncomfortable as a concept



Basically a BWR is a big hot pot

Images: L. source unknown, R. dreamtime.com

Who uses boiling-water reactors?

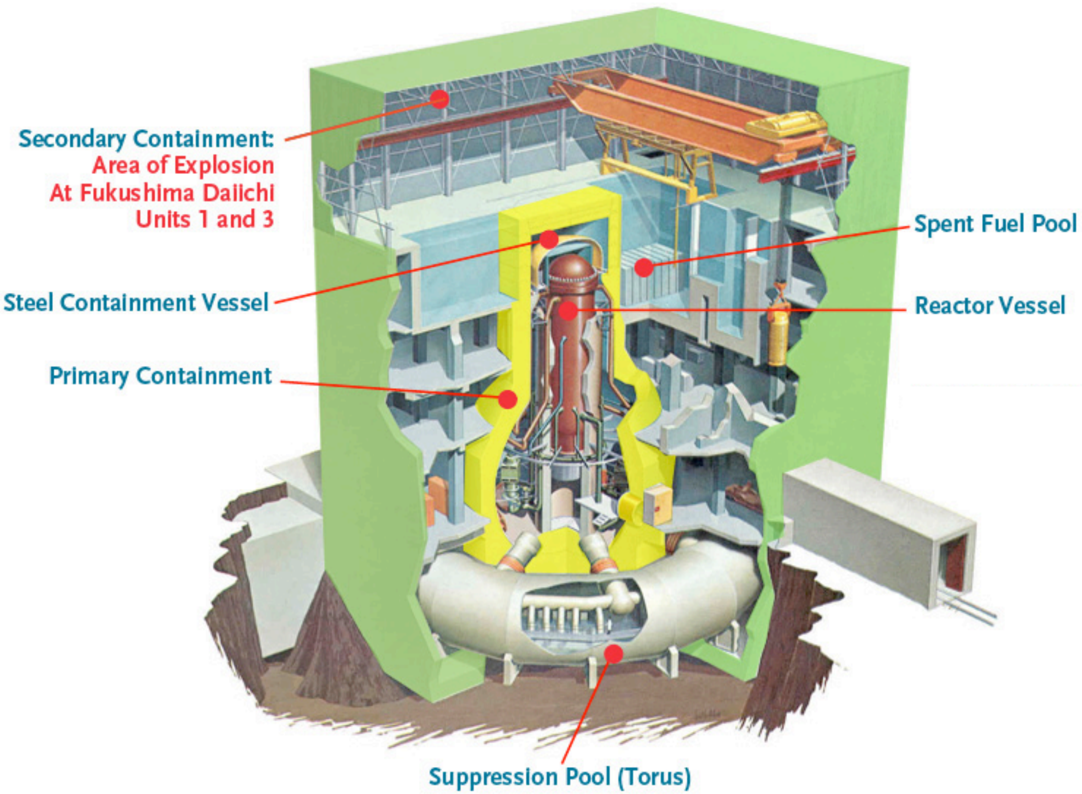
Dresden power station
(Exelon)
1970 GE Mark I BWR

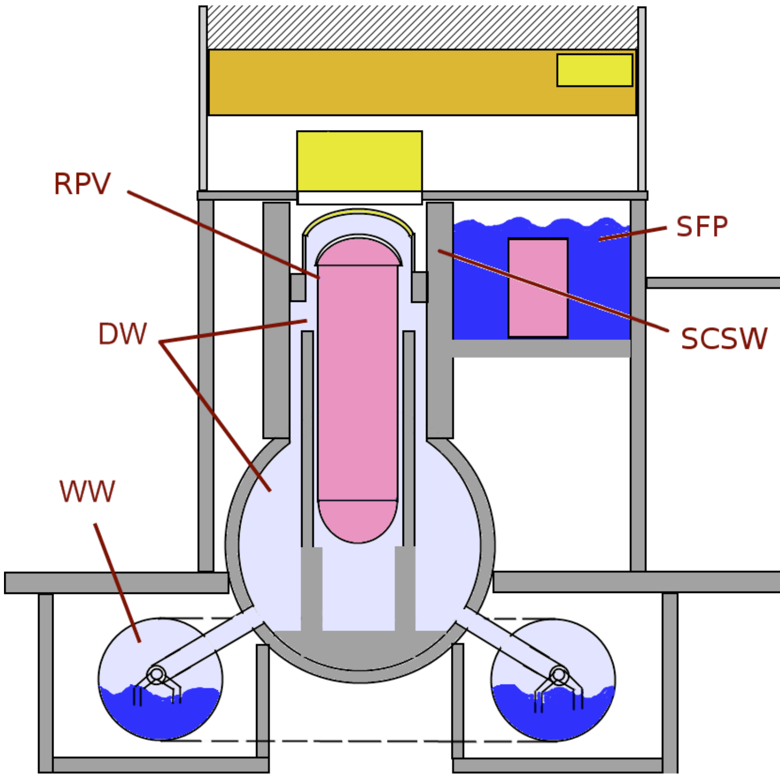
Fukushima power station
(Tokyo Elect. Power)
Units 1, 2, 6
1971 GE Mark I BWRs

Images: Top, Nuclear Power Industry news. Bottom, Reuters

Boiling-water reactor turbine water touches fuel

Worse if you don't build it very well: the GE Mark I reactor





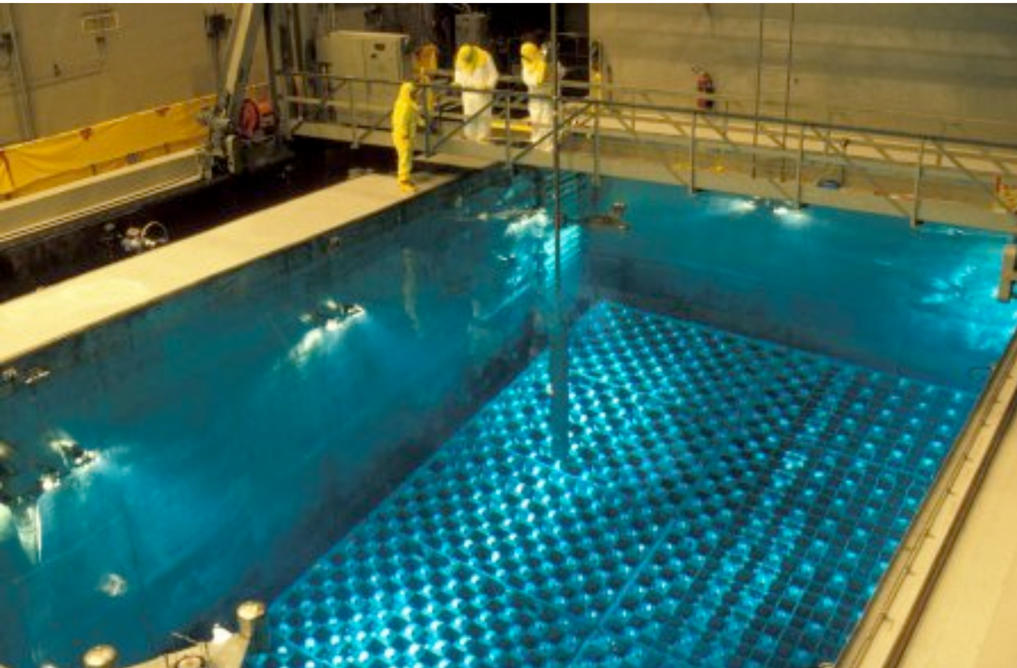
Torus is for …..
managing overpressure events

GE Mark I Boiling-water reactor

Images: General Electric (annotation by others)

Spent nuclear fuel storage **fuel pools are default strategy**

No long-term national strategy for disposal, all currently on-site



While we ponder the best long-term solution we're doing the worst possible practice…

Energy Northwest spent fuel pool

Image: Nuclear Fuel Reprocessing Coalition

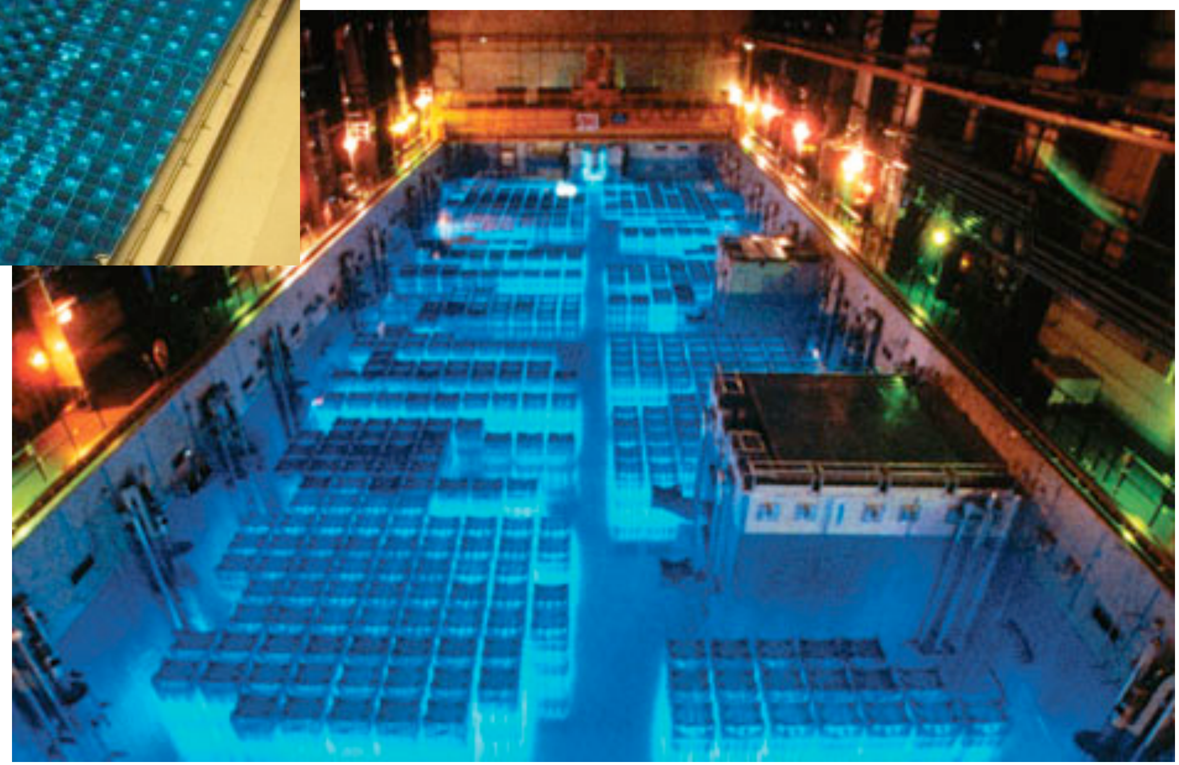


Image: source unknown

- ~63,000 tons spent fuel in 2009
- 78% in spent fuel pools
- 22% in dry casks
- total increases by ~2200 t/yr

Data: Congressional Research Service, via U.S. Nuclear Regulatory Commission

Spent nuclear fuel still very radioactive

Use only small fraction of ^{238}U, 2/3 of ^{235}U, fission products still "hotter"

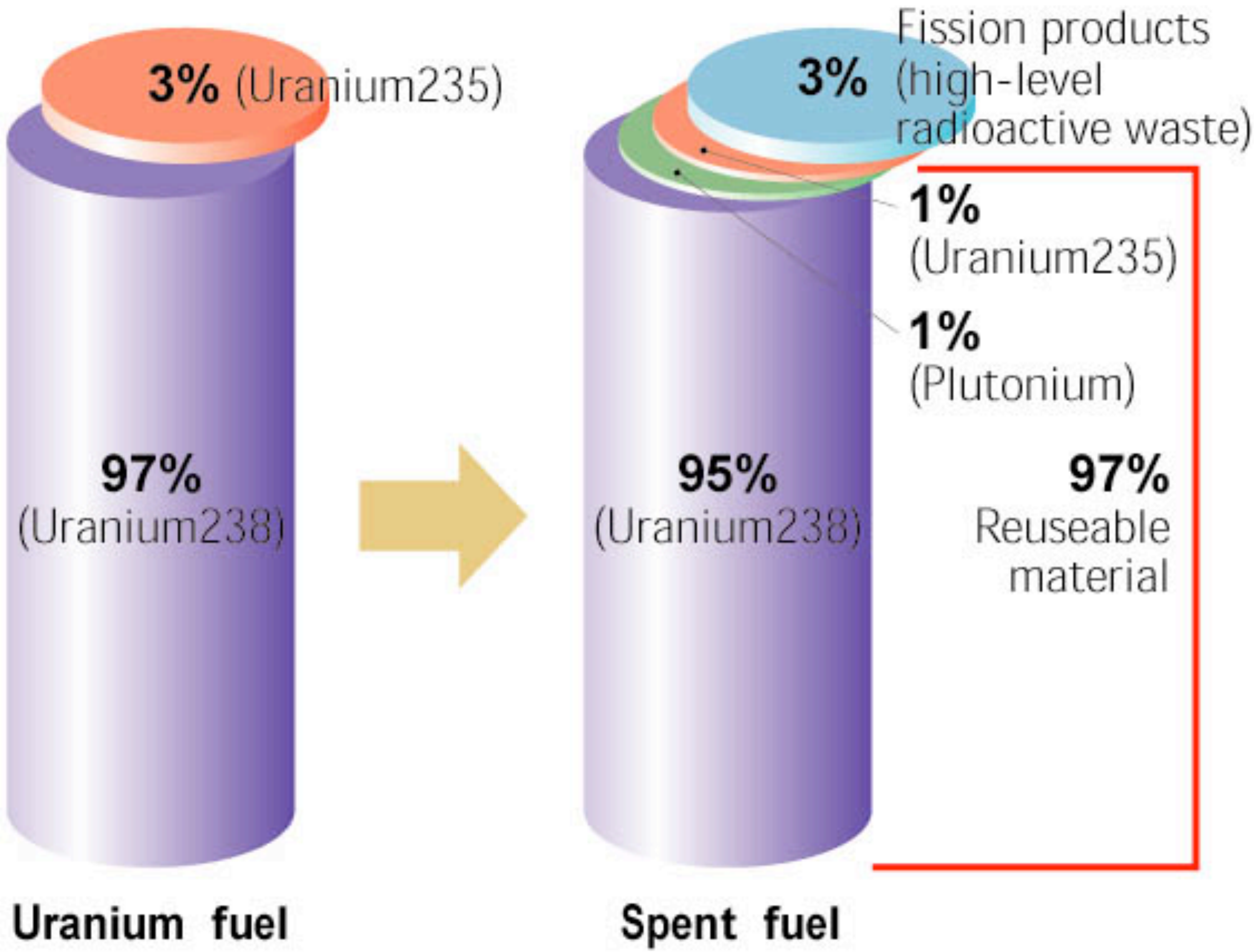


Image: Cool Hand Nuke

Spent nuclear fuel variety of half-lives in fission products

Short = dangerous immediately; long = radioactive for millenia

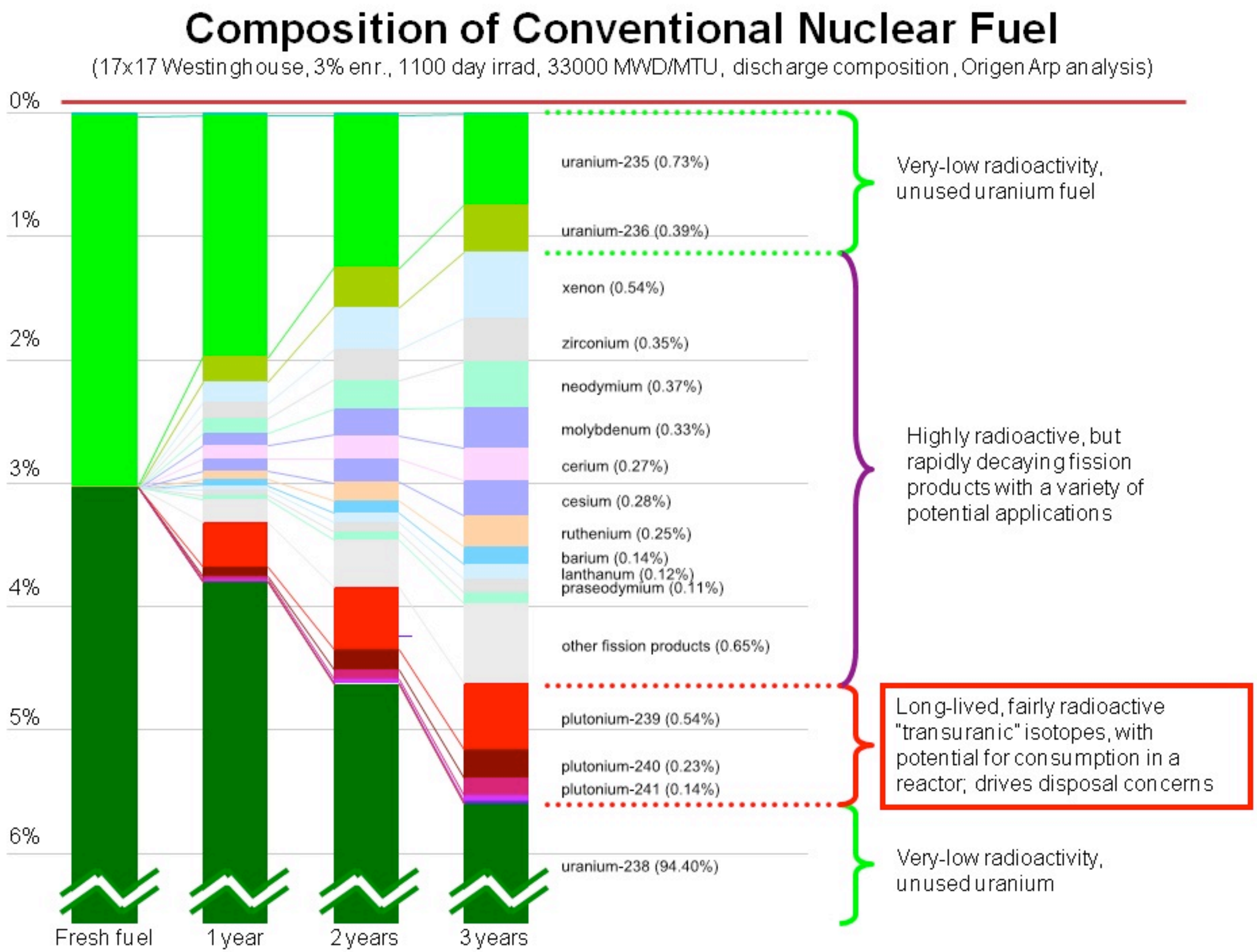


Image: Source unknown

Why waste all that good radioactive stuff? Can be recycled...

Can use **breeder reactors** to **reprocess** spent nuclear fuel:

boost fissionable content until the fuel can once again support a chain reaction in a power reactor. Reprocessed fuel is commonly called **"MOX"** (for "mixed oxide" fuel).

Problems:
the fuel you're left contains dangerous plutonium, which

1) makes reactor meltdowns worse, and
2) can be used to make bombs

U.S. does not currently reprocess fuel, though it is done in France, U.K., Russia, Japan, India.