

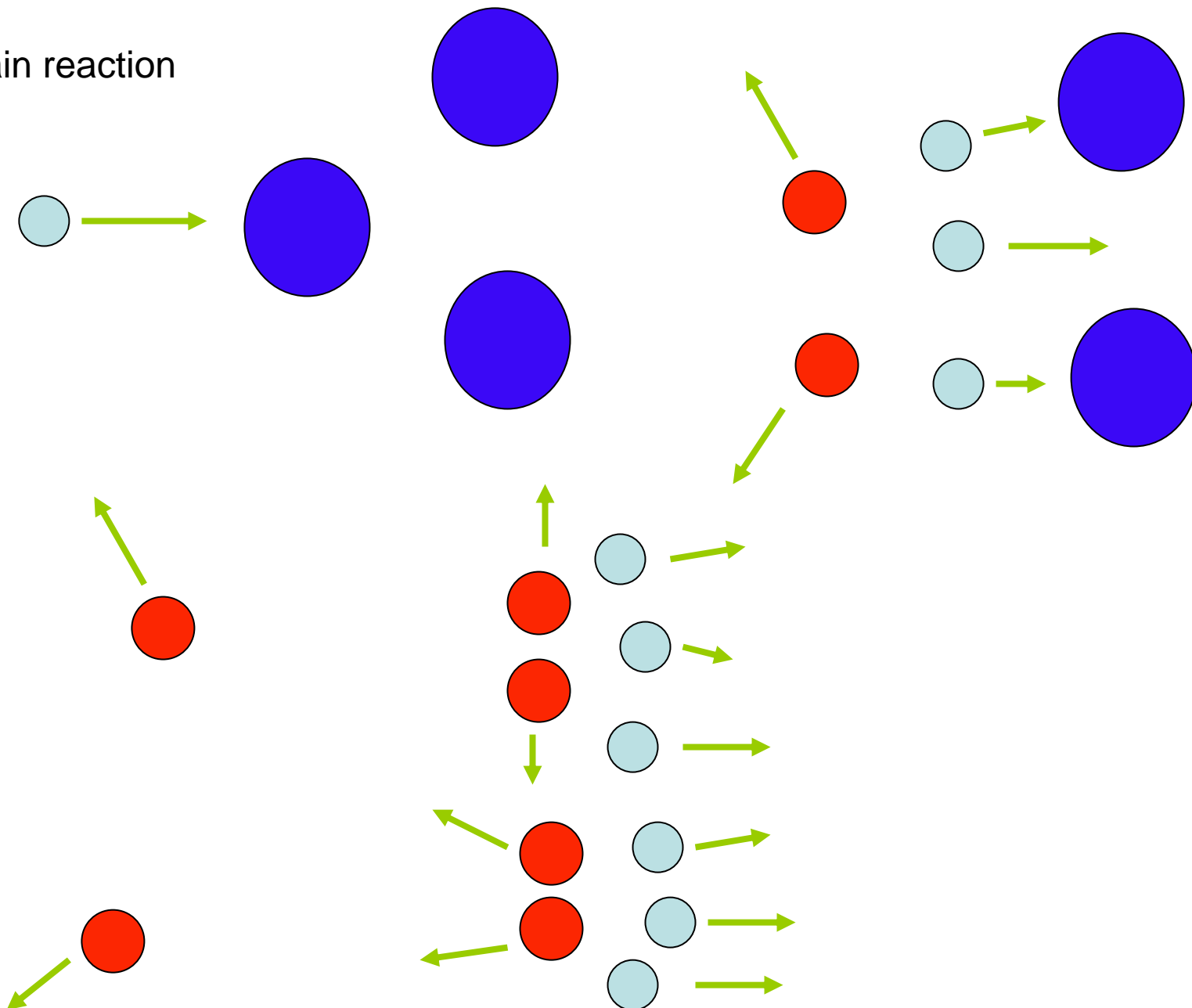
“The world has achieved brilliance without wisdom, power without conscience. Ours is a world of nuclear giants and ethical infants.”

- Omar Bradley (US general)

“The discovery of nuclear reactions need not bring about the destruction of mankind any more than the discovery of matches”

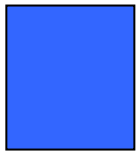
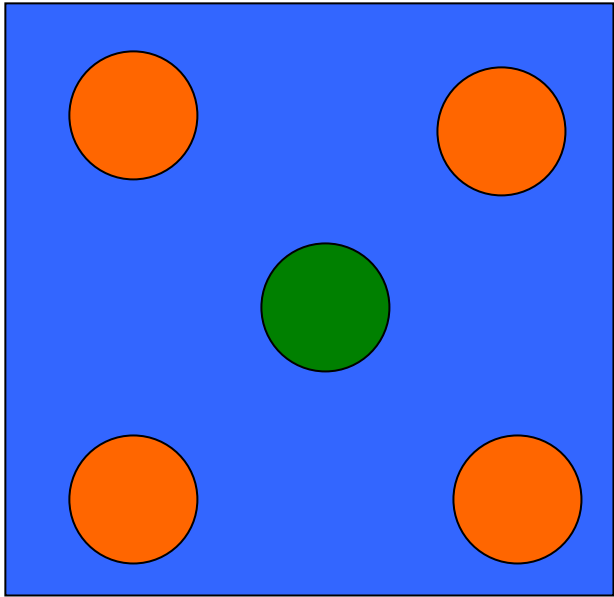
- Albert Einstein

Chain reaction

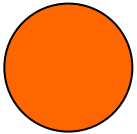


Key facts:

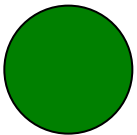
1. Only fissile materials readily fission ($^{235}_{92}\text{U}$ and $^{239}_{94}\text{Pu}$)
2. Uranium found on Earth is 99.3% $^{238}_{92}\text{U}$ and 0.7% $^{235}_{92}\text{U}$
3. $^{238}_{92}\text{U}$ absorbs neutrons and does not readily fission
4. On average 2.6 neutrons are emitted when $^{235}_{92}\text{U}$ fissions and they are very energetic (*fast*).
5. For controlled reaction, want (on average) fission neutrons to cause *exactly one* more fission to occur
6. Low energy (*slow*) neutrons are more likely to cause fission than fast neutrons
7. Some neutrons are emitted upon radioactive decay of fission products (*delayed neutrons*)



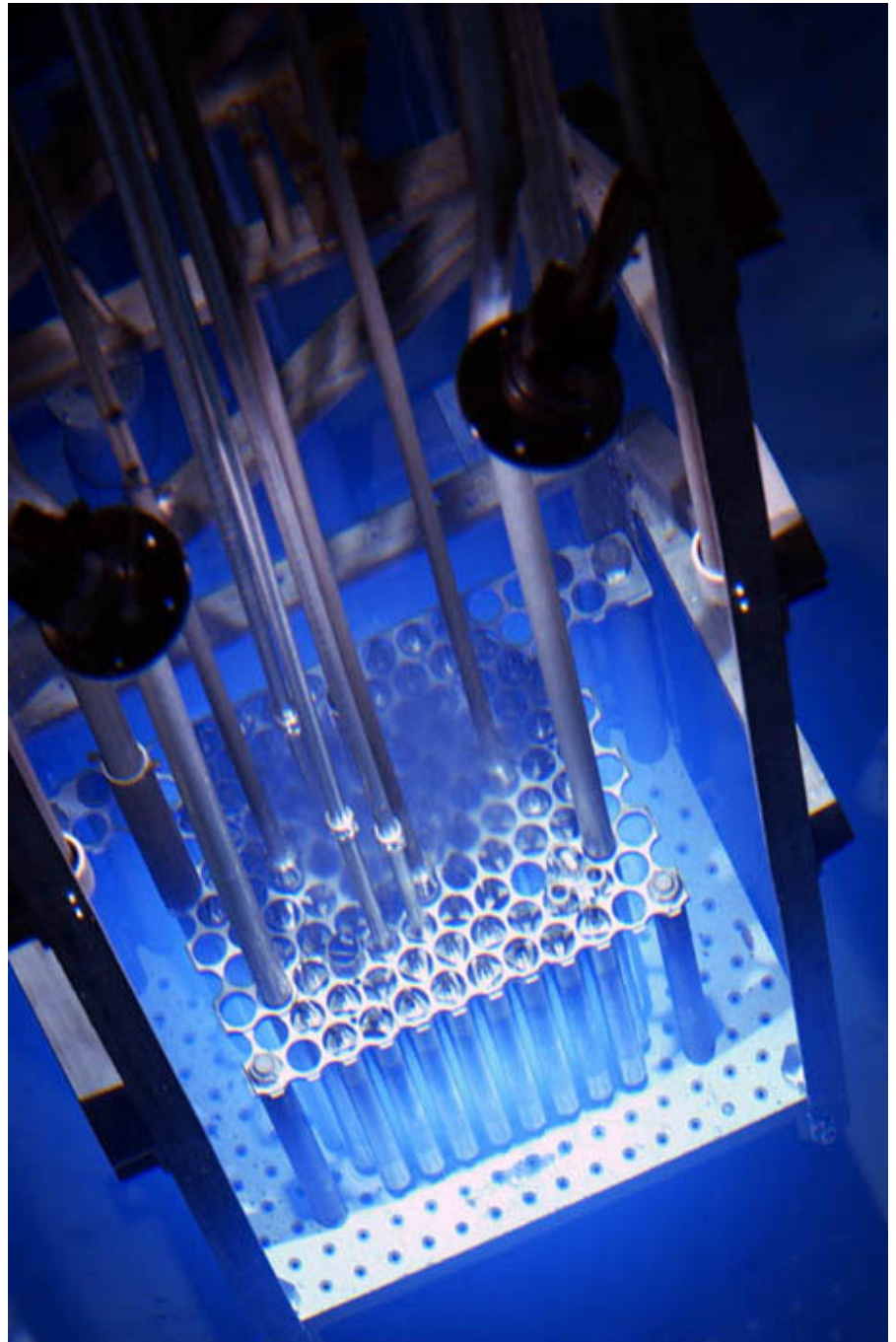
D₂O or graphite (C)
(moderator)

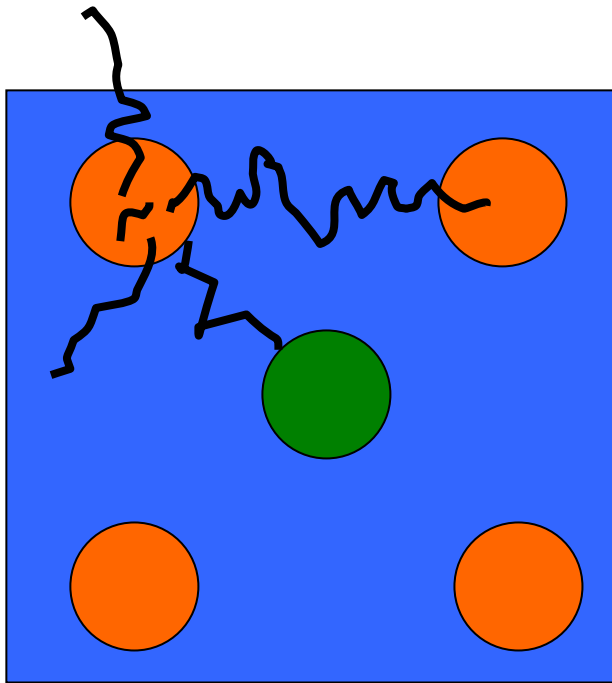


Natural uranium
(fuel rod)



Neutron absorber
(control rod)





Neutron loss mechanisms:

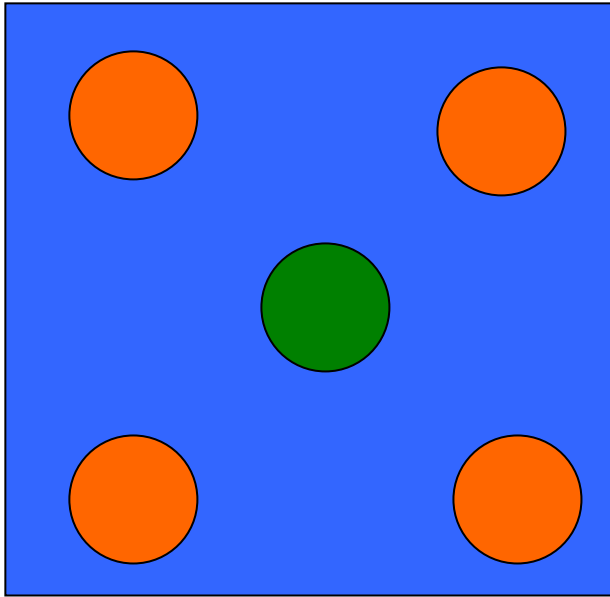
1. Absorbed by $^{238}_{92}\text{U}$
2. Absorbed by control rod
3. Absorbed by moderator
4. Escapes from core

“Turns out” that for natural uranium can only get chain reaction if you have a moderator that absorbs very few neutrons

- D_2O “heavy water”
- very pure graphite

History (Fermi’s first chain reaction, German difficulties)

Canadian reactors (CANDU)



Light water reactors use H_2O as moderator, but to make up for larger amount of neutron absorption need to use *low-enriched uranium (LEU)* as fuel

Typical enrichment for reactors in US is between 3% and 5% $^{235}_{92}\text{U}$

Can't make bomb from LEU itself

Demo from www.kernenergie.net

http://www.kernenergie.net/kernenergie/en/interaktiv/nuclear_reactor.php?navid=6

Timing is critical to control of reactors

Average time for the neutrons from a fission to create another fission is called the *generation time*. Typical generation time for a neutron from a fission to directly induce another fission (*prompt reaction*) in a typical reactor is 1/10,000 of a second.

Imagine average number of fissions produced by one fission is 1.01, not 1.00. Then,

after one generation the power output is (1.01) that before (1% increase)

after two generations the power output is $(1.01)^2$ that before (2% increase)

....

after 10 generations the power output is $(1.01)^{10}$ that before (10% increase)

...

after 100 generations the power output is $(1.01)^{100}$ that before (270% increase)

So in 1/100 of a second the power output has almost tripled! Hard to use mechanical control rods in this short time

Fortunately not all neutrons are prompt neutrons. Recall there are delayed neutrons emitted from radioactive decay of fission products. Typical time for delayed neutrons to induce a fission is related to half life of fission products. The generation time is then lengthened to 1/10 second, as long as you are so close to critical that you need the delayed neutrons to stay at critical.

Worst case scenario is if something happens so that you don't need delayed neutrons to sustain criticality (*prompt critical*) then power runs away faster than you can control. (Still not a bomb, but a big, potentially deadly, mess, *i.e.*, Chernobyl)

Even when chain reaction stops, heat is being produced due to radioactive decay of fission products. This *decay heat* is 6.5% of the reactor power level when the chain reaction ceased. This decays to 1% after 1 hour.

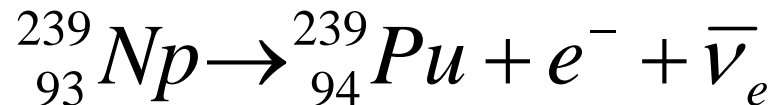
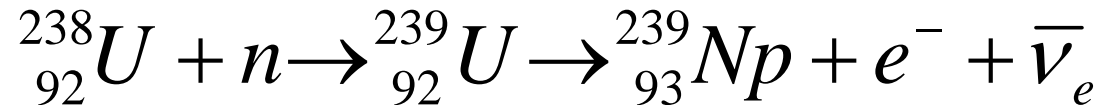
If reactor has lost coolant, decay heat can melt the core. (*E.g.*, Three Mile Island)

Breeder reactors

Current US policy is to discard uranium fuel after burn up of $^{235}_{92}\text{U}$.
That discards $^{239}_{94}\text{Pu}$ that could be used as fuel

Why? Worries about nuclear proliferation

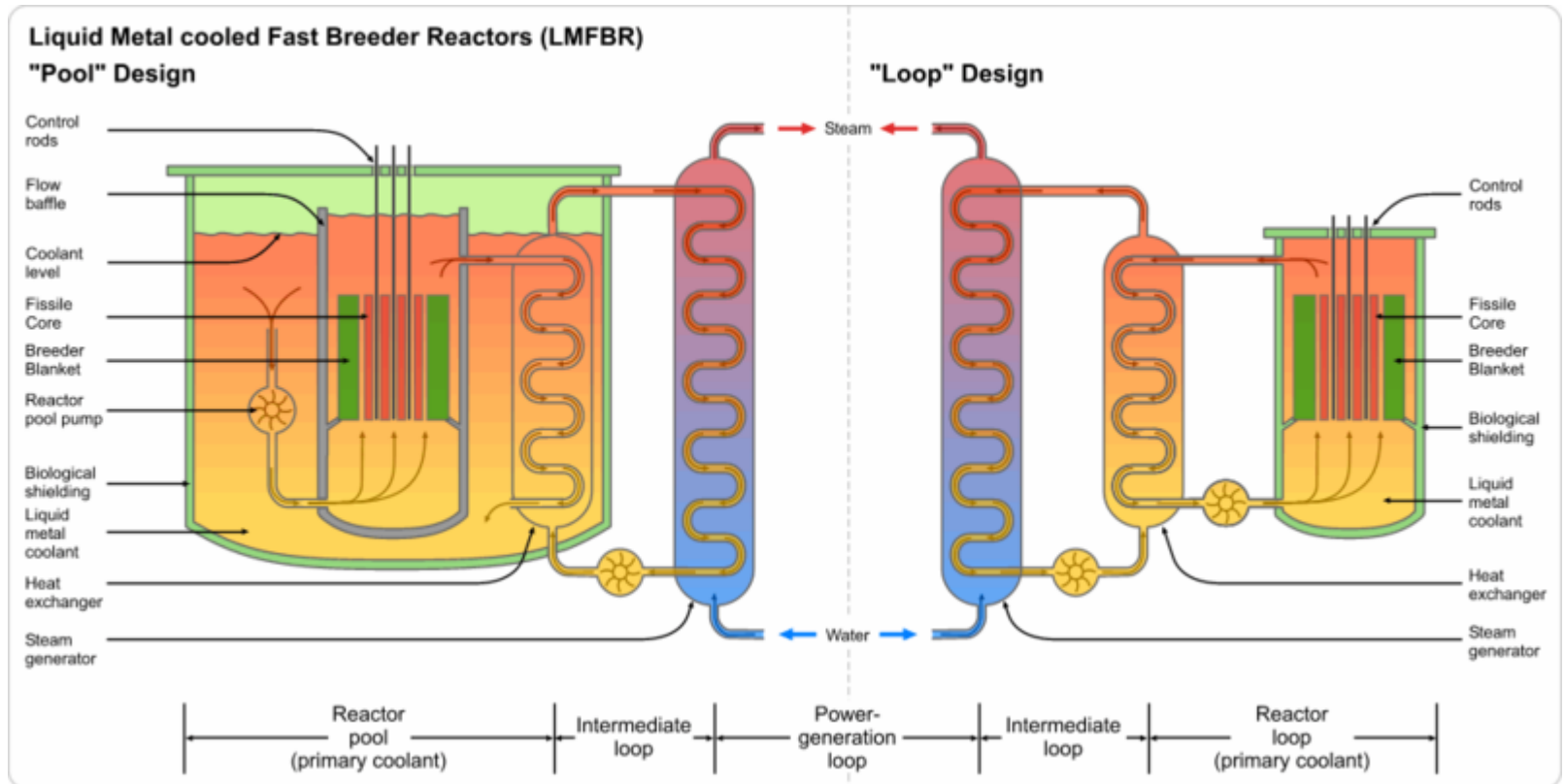
Why not? Under current policy, known reserves of uranium could generate US power for a few decades. Using this discarded fuel would allow nuclear power to generate our electricity for 1000 years.



Breeding absorbs neutrons, so need highly fissile fuel, typically $^{239}_{94}\text{Pu}$

Use any source of $^{238}_{92}\text{U}$ in *blanket*

Can also use $^{232}_{90}\text{Th}$ to create $^{233}_{92}\text{U}$ by neutron capture and beta decay



Plutonium economy

After initial charge, 1 milk-crate sized chunk of natural uranium provides 1 GW of power for a month, indefinitely

Can do reprocessing on-site. Much less waste to dispose of, transport

Strong effort in Japan

Downsides

Not currently economically feasible, but check back when uranium prices go up

A lot of plutonium in the world...

Future?

