Lec #24: Nuclear Power. II.

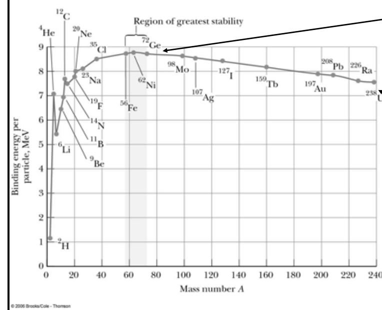
LAST TIME: Introduction (Chaps 13-15)

- Nuclear Power Today
- Fundamentals of Nuclear Physics

TODAY: Fission & Reactors

- Fundamentals of Nuclear Physics;
- Reactor Technology;
- Prospects for Nuclear Power

NEXT: 1) Fusion Power?
2) Introduction to Renewables



Intermediate nuclei is about 8.2 MeV per nucleon.

Tighter binding: Less mass/ nucleon

Heavy nuclei is about 7.2 MeV per nucleon

Looser binding: More mass/ nucleon

Decrease in mass per nucleon appears as released energy in the fission event

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U^* \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n $$

More mass *per* nucleon → **Less mass *per* nucleon** + E

Nuclear Fission (cont.)

B. Fission Example

n + ^{235}U --> ^{236}U

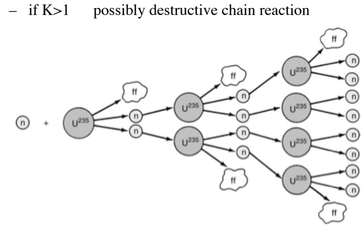
^{236}U --> A* + B* + 3n

A* and B* have too many neutrons to be stable; long series of beta decays to eventually become stable

- energy released as *kinetic energy* of products
- neutron initiates reaction, and reaction produces neutrons
- for Uranium, only slow neutrons will cause fission, but neutrons produced by fission move very fast
- need "moderator" to slow them down
- if 1 or more of these neutrons stimulates another fission, a chain reaction can result

Nuclear Fission (cont.)

- K = average # of fission inducing neutrons per fission
  - water is a moderator: it slows down neutrons
  - depends on material, moderators, shape and size of "pile", temperature, etc.
  - if K<1 reaction dies out
  - if K=1 continuous power production
  - if K>1 possibly destructive chain reaction



Nuclear Fission (cont.)

C. Enrichment of Fissile Material

- Natural isotope ratio: ^{238}U/^{235}U ~ 142
  - 99.3% ^{238}U [changes very slowly
  - 0.7% ^{235}U over time]
- with water as moderator, need 3 or 4% ^{235}U
- with heavy water, we can use natural mix
- for bombs, need 90% or more ^{235}U (or Plutonium)
- how do we change the isotope ratio?
  - Diffusion (ORNL)
  - Centrifuge (LBL)
  - Laser (LANL)
  - Breeder reactor (Hanford, SRS)
  - Fuel reprocessing

^{238}U --> ^{235}U Enrichment in reactor

$$ {}^{238}U + n \rightarrow {}^{239}U + \gamma $$

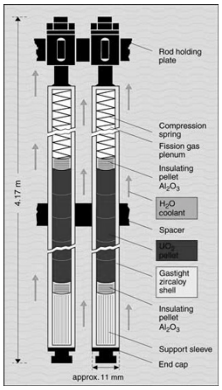
$$ {}^{239}U \rightarrow {}^{239}Np + \beta^- + \bar{\upsilon} \quad (T_{1/2} = 23.5 \text{ min.}) $$

$$ {}^{239}Np \rightarrow {}^{239}Pu + \beta^- + \bar{\upsilon} \quad (T_{1/2} = 2.35 \text{ days}) $$

$$ {}^{239}Pu \rightarrow {}^{235}U + \alpha \quad (T_{1/2} = 2.44 \times 10^4 \text{ years}) $$

NUCLEAR POWER UNITS BY REACTOR TYPE, WORLDWIDE

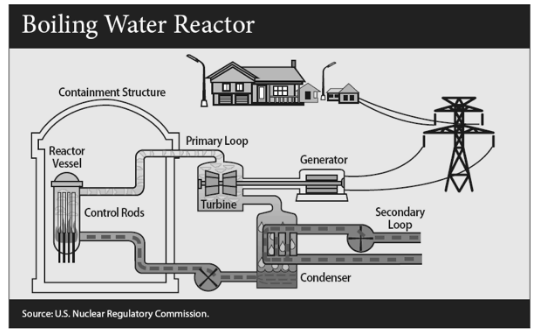
Reactor Type	Units	Net MWe (in operation)	Under Construction
Pressurized light-water reactors (PWR)	243	214,234	43
Boiling light-water reactors (BWR)	91	74,941	8
Gas-cooled reactors, all types	36	12,239	0
Heavy-water reactors, all types	33	18,645	16
Graphite-moderated light-water reactors (LGR)	15	14,785	1
Liquid-metal-cooled fast breeder reactors (LMFBR)	3	928	4

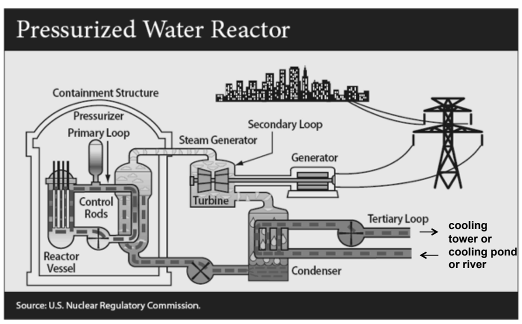


Fuel Assembly

- **Heat it and chemically process to form LEU uranium dioxide (UO_2) powder.**
- **Press this powder into pellets, sinter into ceramic form, load into Zircaloy tubes, and construct into fuel assemblies. The size of a fuel rod = 4 m long and 1 cm dia.**

Of the 104 commercial reactors in the US, 69 are PWRs and 35 are BWRs





Primary water loop: 600°F; the water is under high pressure and it does not boil.
Secondary water loop: 450 to 500°F; the water is under lower pressure and it creates steam.
The steam hits turbine blades with a pressure of about 1,000 pounds per square inch.

Special Concerns

- want to release only heat (hot water a/o steam) to environment
- some gas build up is inevitable; can include radioactive gasses; must be released (hydrogen is worst case scenario)
- radiation damage to "plumbing" in primary loop (or entire turbine for BWR)
- radiation, neutron bombardment of container
- highly radioactive waste left over in spent fuel rods
- can produce more fissile material in reactor (e.g. Plutonium), which can be
  - useful if put back in a reactor or
  - harmful if it can be extracted, b/c it can be bomb-grade

Reactor Operation and Safety

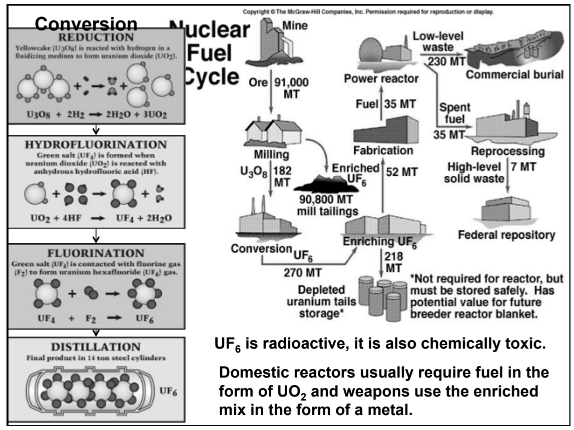
- much less than critical mass; not highly enriched
  - core can NOT explode!
- control rods absorb neutrons, K<1 when they are in
- walls, moderator also absorb neutrons
- thermal energy continually produced w/ K=1
  - temperature will go up unless energy is carried away
  - water very effective, but w/out it, core can melt
  - LOCA very bad --> need backups and failsafes
  - also need confinement vessels
- most reactors are inherently stable
  - if Temp goes up, moderator effectiveness goes down, so K goes down, so reaction slows down
  - there are some designs (breeders, for example) that are not inherently stable, but they are not used in power plants

Nuclear Power: Where We Stand

- Nature stores most of its energy in nuclei
- If we want LARGE quantities of energy w/o disrupting natural balances, nuclear is probably the only way
- Relative to coal, the lack of combustion, lack of greenhouse gas emissions, and small waste stream are very attractive
- The technology for power production is well developed, but getting antiquated. We could do even better now.
- With reprocessing and breeding, nuclear fission can provide large quantities of electrical power for a very long time
- Still, it's very controversial, and there are unresolved issues
- Nuclear power itself is relatively "safe", but what about the byproducts?

Some Unresolved Issues

- Reactor design/capital costs:
  - cheap to operate, but very expensive to build
  - in large part, this is due to very strict environmental impact laws and litigation costs
  - amortization and stranded costs must be addressed
- High-Level Waste Disposal
  - US has been unable to come to grips with this
  - Current methods are unacceptable
  - "Permanent" solutions have problems
    - transportation of waste to storage facility
    - tracking of fissile material (can be used to make bombs)
    - tracking of toxic material (can be used in dirty bombs)



Some Unresolved Issues (cont.)

- Proliferation
  - reactor fuel is only slightly enriched; nowhere near "bomb grade"
  - spent fuel contains plutonium and other fissile material
  - when extracted, it is already enriched
  - but extraction is very difficult and expensive; not likely to be done by terrorists or rogue nations
  - however, the more enriched material there is to keep track of, the more likely some will be "lost"
  - it doesn't take very much to make a bomb
  - we have measures in place to safeguard against this, but it will be more difficult to enforce is nuclear power is expanded

Status and Future of Nuclear Power

- TMI and Chernobyl affected public attitudes severely, but environmental groups are taking a second look.
- High-Level waste disposal problem
  - WIPP
  - Yucca Mountain
- High capital costs (billions to build)
  - Fear and economics
- Relicensing; Restructuring
- New designs; cheaper, smaller, faster, safer
- Proliferation of bomb-grade material a problem
  - N. Korea; Iran
  - terrorism
- Global Warming much more of an issue now
- Expect leveling off for next 10 years then decline