Nuclear Reactors

Question:

A nuclear reactor is powered by nuclear fuel rods. After being used for a while, those nuclear fuel rods are

1. Heavier than when they were new
2. Lighter than when they were new
3. The same weight as when they were new

Uranium-235

- Radioactive – fissions and emits neutrons
- Fissionable – breaks when hit by neutrons
- Rare fraction of natural uranium (0.72%)

Uranium-238

- Radioactive – emits helium nuclei, some fissions
- Nonfissionable – absorbs fast neutrons without fission
- Common fraction of natural uranium (99.27%)

Natural Uranium

- Contains mostly ^{238}U, with some ^{235}U
- Fissioning uranium nuclei emit fast neutrons
- ^{238}U absorbs fast neutrons
- Most fission neutrons are absorbed by ^{238}U
- Chain reactions won't work in natural uranium

Thermal Neutrons

- ^{238}U doesn't absorb slow (thermal) neutrons!
- Slowed neutrons bypass ^{238}U
- A ^{235}U chain reaction can occur in natural uranium if the neutrons are slowed by a moderator
- Moderator nuclei
  - Small nuclei that don't absorb neutrons
  - Extract energy and momentum when struck by neutrons
  - Slow neutrons down

Moderators 1

- Hydrogen nuclei (protons)
  - Good mass match with neutron
  - Excellent energy and momentum transfer
  - Slight possibility of absorbing neutron
- Deuterium nuclei (heavy hydrogen isotope)
  - Decent mass match with neutron
  - Good energy and momentum transfer
  - No absorption of neutrons

Moderators 2

- Carbon
  - Adequate mass match with neutron
  - Adequate energy and momentum transfer
  - Little absorption of neutrons
- Choosing a moderator
  - Deuterium is best, but it's rare and reactive (hydrogen)
  - Hydrogen is next best, but its reactive
  - Carbon is acceptable and a convenient solid

Thermal Fission Reactors

- Reactor core contains huge amount of uranium
- Uranium is natural or slightly enriched
- Moderator is interspersed throughout core
- Moderator quickly slows neutrons down
- Nuclear chain reactions occur only among ^{235}U
- Critical mass is controlled by size & shape of core, type of fuel, location and quality of moderator, and positions of neutron-absorbing control rods

Controlling Reactors 1

- Critical mass
  - Below it, fission rate diminish with each generation
  - Above it, fission rate increases with each generation
  - Generation rate of prompt neutrons is very short
  - Controlling prompt-neutron fission is difficult!
- Delayed fission
  - Some fissions produce short-lived radioactive nuclei
  - These radioactive nuclei emit neutrons after a while
  - Delayed neutrons contribute to the chain reactions

Controlling Reactors 2

- There are two different critical masses
  - Prompt critical: prompt neutrons sustain chain reaction
  - Delayed critical: prompt and delayed neutrons required
- Reactors operate
  - Below prompt critical mass
  - Above delayed critical mass
- Control rods govern the fission rate

Using Nuclear Reactors

- Fissions release thermal energy
- Thermal energy is extracted by a coolant
- Coolant is used to power a heat engine
- Heat engine produces power

Nuclear Accidents

- Windscale Pile 1 (Britain)
  - Carbon moderator burned during annealing
- Three Mile Island (US)
  - Cooling pump failed and core overheated (while off)
- Chernobyl Reactor 4 (USSR)
  - Coolant boiled in overmoderated graphite reactor
  - Exceeded prompt critical

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