Nuclear Reactors

Turn off all electronic devices

Observations about Nuclear Reactors

They provide enormous amounts of energy

They consume nuclear fuel

They produce radioactive waste

Their nuclear fuel is sometimes reprocessed

They have safety issues

5 Questions about Nuclear Reactors

1. How can a nuclear reactor use natural uranium?
2. How do thermal fission reactors work?
3. How can a fission chain reaction be controlled?
4. How is energy extracted from a nuclear reactor?
5. What are the safety issues with nuclear reactors?

Question 1

Q: How can a nuclear reactor use natural uranium?

A: Slow the fission neutrons to thermal speeds.

Slow-moving (thermal) neutrons

- can fission the fissionable portion of uranium
- are ignored by the nonfissionable portion of uranium

Slow-moving neutrons can fission natural uranium

A chain reaction is possible in natural uranium

Uranium Isotopes

Uranium-235 (^{235}U - 92 protons, 143 neutrons) is

- radioactive – fissions and emits neutrons
- fissionable – breaks when hit by neutrons
- a rare fraction of natural uranium (0.72%)

Uranium-238 (^{238}U - 92 protons, 146 neutrons) is

- radioactive – emits helium nuclei, some fissions
- nonfissionable – absorbs fast neutrons without fission
- a common fraction of natural uranium (99.27%)

Natural Uranium

Fissioning uranium nuclei emit fast neutrons

- Fast neutrons can fission ^{235}U,
- Fast neutrons are strongly absorbed by ^{238}U.

Natural uranium

- contains mostly ^{238}U, with some ^{235}U
- chain reactions won't work in natural uranium

Thermal (Slow) Neutrons

Slow neutrons affect uranium isotopes differently

- Slow neutrons can still fission ^{235}U
- Slow neutrons don't interact with ^{238}U

A ^{235}U chain reaction can occur in natural uranium if its neutrons are slowed by a moderator

Moderator nuclei

- small nuclei that don't absorb colliding neutrons
- extract energy and momentum from the neutrons
- slow neutrons to thermal speeds

Question 2

Q: How do thermal fission reactors work?

A: Using moderators, they "burn" ordinary uranium.

Reactor core is natural or slightly enriched uranium

Moderator is interspersed throughout core

Moderator slows neutrons to thermal speeds

Nuclear chain reaction occurs only among ^{235}U

Choosing Moderators

Hydrogen nuclei (protons)

- Near-perfect mass match with neutrons
- Outstanding energy and momentum transfer
- Slight possibility of absorbing neutrons

Deuterium nuclei (heavy hydrogen isotope)

- Excellent mass match with neutrons
- Excellent energy and momentum transfer
- No absorption of neutrons

More about Moderators

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 (used as heavy water)
- Hydrogen is next best (used as ordinary water)
- Carbon is acceptable and a convenient solid

Question 3

Q: How can a fission chain reaction be controlled?

A: Use feedback to operate right at critical mass.

Critical mass is governed by

- size and structure of reactor core
- type of nuclear fuel (extent of ^{235}U enrichment)
- location and quality of moderator
- positions of neutron-absorbing control rods
- accumulation of fission fragment nuclei

Controlling Chain Reactions (Part 1)

Critical mass governs chain reaction rate

- 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 neutrons make reaction controllable

- Some fissions produce short-lived radioactive nuclei
- These radioactive nuclei emit neutrons after a while
- Delayed neutrons contribute to the chain reactions

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Controlling Chain Reactions (Part 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 can adjust above or below criticality

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Question 4

Q: How is energy extracted from a nuclear reactor?

A: It becomes heat and operates heat engines.

A nuclear reactor releases thermal power

- Fissions release thermal energy into the reactor core
- Thermal energy is extracted by a coolant
- Coolant is used to power a heat engine (e.g., steam)
- Heat engine is used to generate electrical power

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Question 5

Q: What are the safety issues with nuclear reactors?

A: Preventing the release of radioactive nuclei.

Fission reactors produce

- radioactive nuclei (from fissions)
- plutonium (from neutron capture by ^{238}U)

Containing those nuclei forever is a challenge

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Long Term Safety Issues

Radioactive nuclei are a radiation hazard

- They cannot be made safe, they can only be stored
- They must be sequestered securely for eons

Plutonium is a nuclear proliferation hazard

- It can be used as a nuclear fuel in reactors
- It can also be used in weapons

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Short Term Safety Issues

To avoid catastrophes,

- chain reactions must never get out of control
- reactors and spent fuel must never overheat

Reactors must be designed so that they are

- stable—chain reaction stops if overheating occurs
- redundant—no single failure can cause a disaster
- easy to quench—chain reaction stops immediately

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Nuclear Accidents (Part 1)

Windscale Pile 1 (Britain)

- Carbon moderator burned while being annealed

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 and partially vaporized

Tokia-mura Accident (Japan)

- Critical mass was reached while processing uranium

Nuclear Accidents (Part 2)

Fukushima Daiichi (Japan)

- Earthquake caused reactors to be shut down
- Tsunami disabled cooling pumps
- Cooling water in reactors and spent fuel storage boiled
- Reactor cores and spent fuel overheated and melted
- Explosions damaged containment structures
- Radioactive nuclei leaked into air and water

Summary about Nuclear Reactors

They slow fission neutrons using a moderator

They can use natural or slightly enriched uranium

They control their chain reactions carefully

They produce radioactive waste and plutonium