

1. Nuclear reactors

Nuclear reactors

- I. How reactors work
- II. Safety systems
- III. Accidents

I. How reactors work

A. Controlled fission (core)

1. Prevent exponential growth ($2^{t/T(1/2)}$) in ^{235}U (or ^{239}Pu) - enriched to only 3% or 4%
2. Sustain linear growth (no. fissions $\propto t$)
 - a. use **delayed n's** from decays of daughters, etc. - $t \sim 10^{-4}\text{sec}$ - 0.5% of n's
 - b. get $\eta_{\text{prompt}} > 1$ for $t \sim 10^{-8}\text{sec}$, but overall $\eta = 1$ so have longer gen.time (η = ave no. n's per generation: fission, capture, scatter)
3. Absorb some neutrons: **control rods** (C, Be, Pb, ... B, Cd) to keep η at 1 or below - also ^{238}U absorbs n's

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2. Nuclear reactors 2

Nuclear reactors 2

4. Slow down neutrons to *thermal* (Graphite, H_2O , D_2O , ...) - **moderator**
 - a. Graphite - Fermi at U.of Chicago, Hanford, Chernobyl
 - i. Water cooled
 - ii. Gas cooled (exptal)
 - b. H_2O - Light Water
 - i. Boiling Water Reactor - half US commercial - Plymouth
 - ii. Pressurized Water Reactor - TMI, Rowe, subs
 - c. D_2O - heavy water reactor - CANDU - more efficient
5. Keep U density below criticality: Fuel rods with 3-4% enriched U (1 yr operating)

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3. Reactor core

Reactor core

Top View

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NCR diagram from <http://lib44.bryant.edu/ncr/ncr.html>

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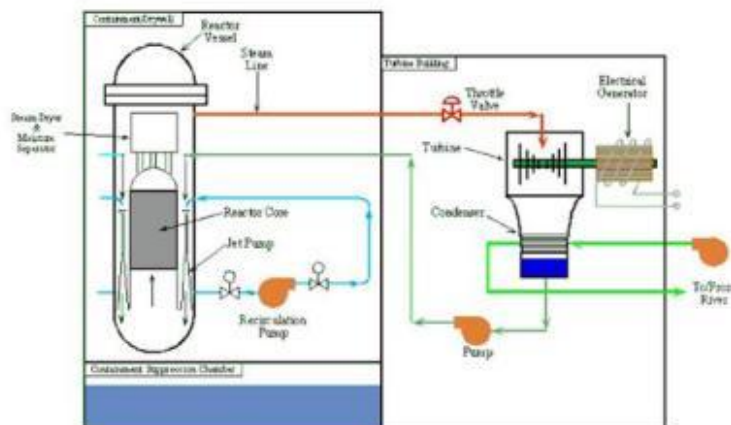
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4. Boiling Water Reactor

Boiling Water Reactor

- One water loop - moderator
- <http://www.nrc.gov/reading-rm/basic-ref/students/animated-bwr.html>



Source: <http://www.nrc.gov/reading-rm/basic-ref/students/animated-bwr.html>

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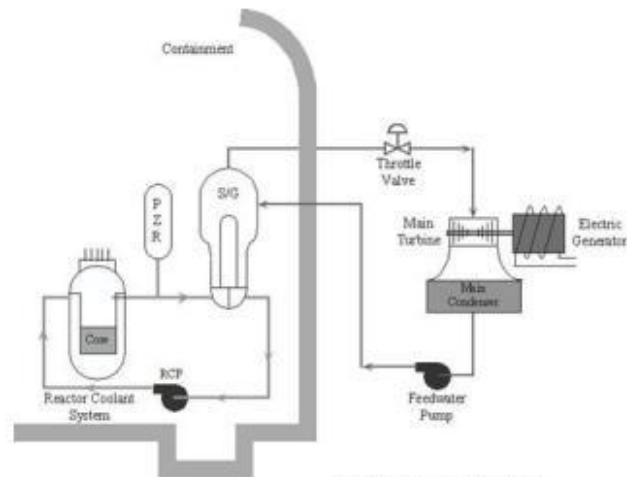
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5. Pressurized Water Reactor

Pressurized Water Reactor

- 2 water loop system - most radiation in containment vessel
- See <http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html>



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Source: <http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html>

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6. Nuclear reactors 3

Nuclear reactors 3

B. Heat transfer:

Fission Energy \rightarrow Heat (mostly KE of daughters in fuel rods)
 \rightarrow Steam (from coolant directly or pressurized water coolant to water)
 \rightarrow Mechanical Energy \rightarrow Electrical Energy + Waste (heat, spent fuel, radionuclides)

1. Coolant to prevent core overheating, melting, igniting H_2O , D_2O , liquid Na, He gas
2. Coolant or heat exchanger to remove heat energy
3. Steam production
4. Hot water needs to be cooled down to recirculate

C. Electrical generators

conventional steam driven turbines - low efficiency

104 nuclear power plants in the United States (69 PWRs and 35 BWRs), which generate about 20% of electrical use.

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7. Safety systems

Safety systems

II. Safety requirements - containment and emergency

SCRAM system

A. Containment vessel to withstand high pressure, heat and contain radionuclides and contaminated materials

1. TMI worked
2. Chernobyl failed

B. Emergency shutdown system

1. Control rods drop
2. More coolant pours in
3. Core is sealed off
4. TMI and Chernobyl failed partially

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8. Accidents

Accidents

III. Accidents

A. Overheating due to

1. loss of coolant
2. uncontrolled reactions due to
 - a. failure of the moderators
 - b. collapse of structures
 - i. due to structural damage from radiation
 - ii. due to meltdown

B. failure of emergency system to respond with extra coolant, shut off valves

C. "Breach of containment" vessels

1. from structural weakening
2. from pressure buildup
3. from explosions

D. Release of contaminated material through failing shutoff valves, fractured pipes

1. to air
2. to site
3. into ground
4. into water table

E. Release of contaminants via fallout

F. Notification of affected areas and evacuation

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9. Historical accidents - TMI

Historical accidents - TMI

- AEC Report on fuel rod damage in Fermi reactor '66. A well handled accident. Irregularities in temperature and control rod position were noticed and acted upon when radioactivity in gases above core was seen to be quite high. Containment was not breached and "scram" procedure for shutdown proceeded successfully. Two fuel rods were damaged (why?).
- Dec. 72 Environmental considerations ruled paramount to financial commitment to build a new plant.
- Dec. 77 TMI accident - a FNU

What happened to the Three Mile Island (TMI) reactor (see: M.J.Lanouette (Bull.Am.Sci. June '79) and R.Nolfen, "Nuclear Choices")

1. Reactor had been shut down for maintenance and testing a few days before Mar28'79. Two valves for auxiliary feedwater had been left shut and not reopened when reactor was restarted that morning.
2. When restarted feedwater pump failed to work in feeding steam turbine, leaving primary coolant going through an insufficient heat sink and keeping too hot while auxiliary feedwater failed to come on.
3. Coolant gets superheated and pressure builds up in both turbine and core setting off scram system (about 5 seconds after startup).
4. High pressure coolant is vented out into containment vessel and out-valve sticks, leaving core uncovered, to heat up.
5. Released coolant builds up on the floor and is pumped out to auxiliary tanks, which are overflowing. Contaminated water vents through ventilators to outside.
6. Emergency Core Cooling System (ECCS) turns on but operators interpret the increasing water level in containment structure as sign that there is too much coolant in core.
7. Operators turn down ECCS and turn off many alarm systems, not knowing they had Loss Of Coolant Accident (LOCA), while they ponder for ~2 hours. The core is uncovered, unbeknownst to the operators.
8. Remaining coolant reacts with Zirconium fuel cladding to produce H bubble. H bubble and water vapor have sufficient pressure to block entry of extra coolant.
9. At 3 hours radioactivity in containment vessel causes alarms leading to emergency notice.
10. By 5 hours NRC and some operators realize core is uncovered.
11. By 7 hours reactor is under control but overflowing water tanks continue to release radioactivity into enviroins.
12. A meltdown had occurred in the process.

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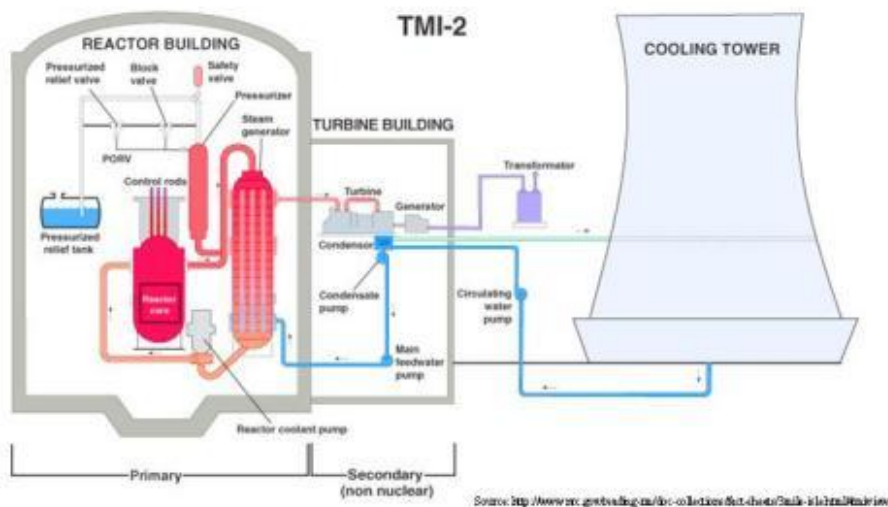
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10. TMI diagram

TMI diagram



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11. Chernobyl

Chernobyl



Source: <http://www.usc.com.au>

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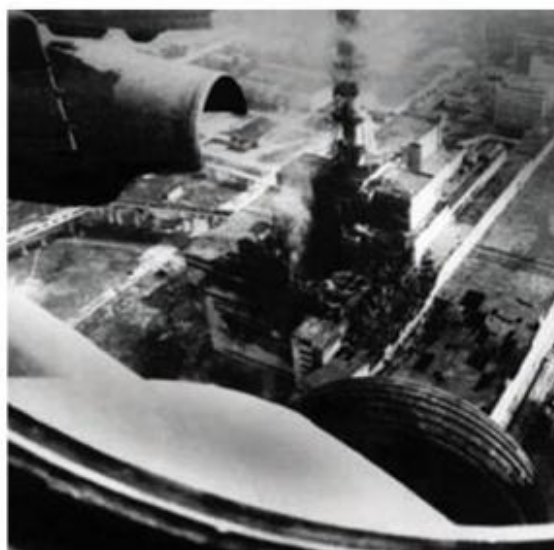
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12. Reactor on fire

Reactor on fire



Source: <http://www.chernobyl.info/index.php>

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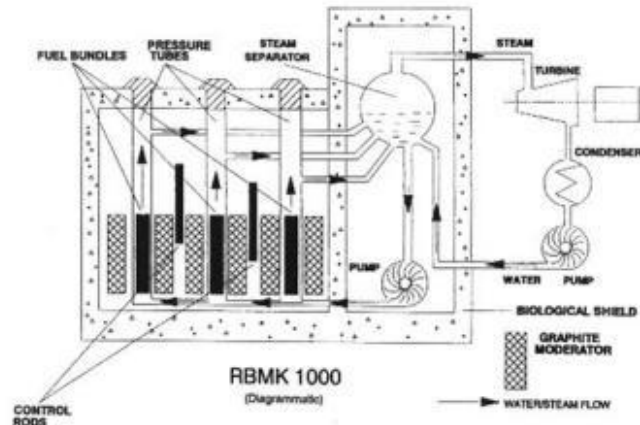
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13. Chernobyl reactor

Chernobyl reactor



Source: <http://www.dumchyl.edu/index.php>

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14. Chernobyl

Chernobyl

The Chernobyl disaster. RBMK reactor has graphite moderator and H₂O coolant (+ n absorber):

1. Apr. 25, 1986 operators prepare to test reactor ECCS components by lowering power and turning off ECCS. Power goes from 3200 MW down to 30 MW.
2. ¹³⁵Xe builds up. This isotope normally absorbs neutrons to transmute into other species, but with such low levels of neutrons being produced now, ¹³⁵Xe "poisons" the reactor.
3. Instead of waiting for the 9 hour half-life, operators remove control rods to restart reactor. Continuing test, they turn on water pumps.
4. 20 minutes into restoring power, coolant pumping is reduced, causing danger signals.
5. To continue test, operators vent steam from turbine to lower load on reactor. Lower water level in core causes steam and LOCA.
6. Lower water level increases fission rate and reactor runs away (500 times maximum in 5 seconds).
7. Rapid production of steam blows off concrete lid.
8. Uncovered fuel rods react with water to produce H₂.
9. H₂ ignites and graphite burns carrying core material aloft.
10. Reactions continue and meltdown occurs.
11. All gaseous material escapes and 3% of solids. Contamination through fallout is continental.
12. Tens to hundreds of thousands extra cancer deaths. (Still inconclusive 20 year later.)
13. Cleanup and containment continue, with continuing structural damage.

Recent articles: NY Times on NY area immigrants from Chernobyl area - 4-fold increase in thyroid cancer in NYC attributed to exposed immigrants (~20 year "incubation") <http://www.nytimes.com/2006/04/26/nyregion/26-chenobyl.html>

NY Times on 20 year anniversary 04/26/2006 See op ed also William Sweet

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15. Abandoned village of Prapiyat

Abandoned village of Prapiyat



The deserted city of Prapiyat, Chernobyl nuclear power plant in the background. Ukraine.
0.96.07.01.04 DEC 1995
CHERNOBYL UKRAINE D
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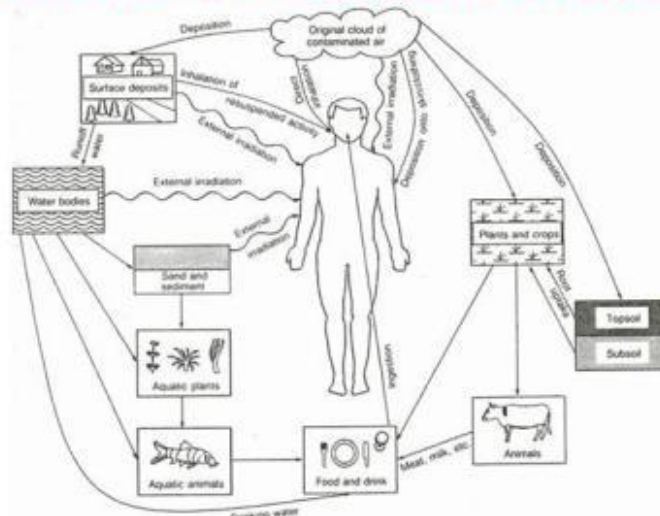
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16. Chernobyl radiation effects

Chernobyl radiation effects



Main environmental pathways of human radiation exposure
[Source: IAEA technical report ISBN 92-0-125191-4 Vienna 1991]

Source: www.iaea.org, Tech. Reports Series No. 363

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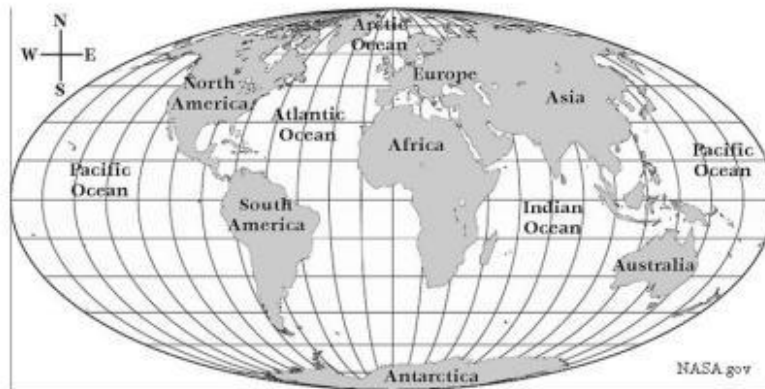
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Lecture 24: Nuclear Reactors: Slide 17

The World



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