APES Ch. 13 Notes: Nuclear Power

13.1 Notes

I. Nuclear Power background info

A. *benefits* of nuclear power

1) *does not produce Greenhouse gases (GHG)*; "clean burning"
2) *does not deplete fossil fuels*
3) not affected by prices of crude oil, etc.
4) *it is a renewable resource*

B. Global statistics on nuclear power
http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics

> "As of May 2016, 30 countries worldwide are operating 444 nuclear reactors for electricity generation and 63 new nuclear plants are under construction in 15 countries."

C. U.S. statistics on nuclear power

1) 30 states have nuclear reactors
2) *~100 commercial nuclear generating units in the U.S.*
   a) most are **pressurized water reactors (PWRs)**
   b) also **boiling water reactors (BWRs)**
3) latest updates from EIA (U.S. Energy Information Administration): http://www.eia.gov/energyexplained/index.cfm?page=nuclear_use
4) EIA issues and trends: http://www.eia.gov/nuclear/

D. Florida statistics from http://www.eia.gov/nuclear/state/florida/

Florida nuclear power plants, summer capacity and net generation, 2010

Plant name/total reactors	Summer capacity (MW)	Net generation (thousand MWh)	Share of State nuclear net generation (percent)	Owner
St Lucie Unit 1, Unit 2	1,678	12,630	52.8	Florida Power & Light Co. (FPL)
Turkey Point Unit 3, Unit 4	1,386	11,305	47.2	Florida Power & Light Co. (FPL)

E. general terms

1) review basic nuclear chemistry concepts and terms: (SEE ATOM REVIEW NOTES)

proton	isotope	atomic mass	fission
neutron	mass number	half-life	fusion
nucleus	atomic number		

2) **NPP** = *nuclear power plant*
3) *MW(e) = Megawatt electric*
4) U.S. Nuclear Regulatory Commission (NRC) gives approval for operation

13.2 Notes

II. How Nuclear Power Works

A. from mass to energy

1) types of nuclear reactions

a) **fission**—one larger atom is s*plit* into two smaller atoms
- **fission products**—the lighter atoms resulting from the reaction (also called *daughter products*)

b) **fusion**—two smaller atoms are *joined* (fused) to form one larger atom

c) **chain reaction—**a domino effect; a repeating reaction cycle

2) characteristics of nuclear reactions
   a) *mass of products < mass of reactants*
   b) this violates the Conservation Laws
   c) massive energy is released (1 kg is enough to be a full-scale bomb)
   d) $E = mc^2$
   e) **isotopes** are involved: *different forms of the same element, having different numbers of neutrons*
      - example: C-12 and C-14
      - the 12 and 14 are **mass numbers** (protons # + neutron #)

fission reaction

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

neutrons can cause more rxns.--- chain reaction

3) fuel for nuclear power plants
   a) uranium (U) ore is mined and refined, made into *UO_2 (uranium dioxide), also generically called MOX (mined oxide fuel)*
   b) **enrichment**—separating the isotopes (U-238 and U-235)

4) parts of nuclear reactors
   a) *reactor core*, containing tubes called **fuel elements** or **fuel rods**
   b) **control rods,** interspersed between the fuel elements, contain neutron-absorbing material
   c) **moderator**—material that *slows down the neutrons* (such as water); can be referred to as the *coolant*
      - *"light water" = regular H_2O*
      - *"heavy water," D_2O, contains deuterium (H-2)*
   d) *reactor vessel* holds everything

5) types of nuclear reactors
   a) **WATER**
      - **Pressurized Water Reactors (PWR) -** important
      - **Boiling Water Reactors (BWR) -** important
      - *Advanced Boiling Water Reactor (ABWR)*
      - *Advanced Light Water Reactor (ALWR)*
      - *Light Water Cooled Graphite Moderated Reactor (LWGR)*
      - *Pressurized Heavy Water Moderated Reactor (PHWR)*
   b) **LIQUID METAL**
      - *Advanced Liquid Metal Reactor (ALMR)*
      - *Integral Fast Reactor (IFR)*
   c) **GAS**
      - *Modular High Temperature Gas Cooled Reactor (MHTGR)*
      - *Gas Cooled Reactor (GCR)*
      - *Advanced Gas Cooled Reactor (AGR)*

6) nuclear power plant basics
   a) heat generated by the reactor boils water
      - water can be allowed to flow through the reactor
      - double-loop method
         * water is heated to 316 °C (600 °F) but is pressurized (155 atm) so it can't boil
         * superheated water flows through a heat exchanger to boil unpressurized water
   b) water is converted to steam
   c) steam powers turbogenerators
   d) **meltdown**—actual melting of the core materials, causing explosions
   e) **LOCA** – loss of coolant accident

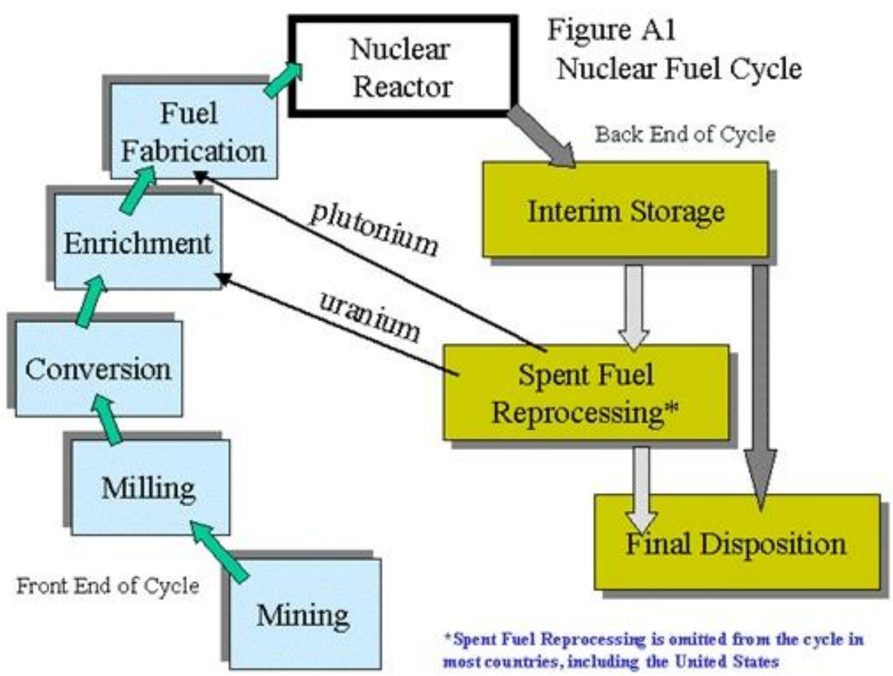
B. comparison of nuclear power with coal power emissions

1000 MW plants, 1 year of operation

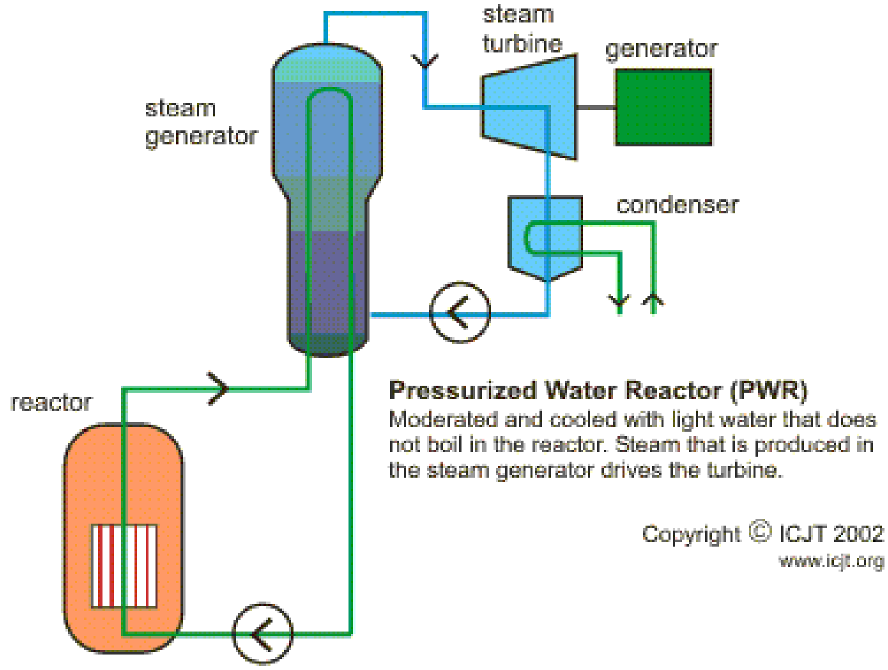
	NUCLEAR (tons)	COAL (tons)
fuel needed	30	3,000,000
CO_2	none	7,000,000
SO_x, NO_x, PM, etc.	none	300,000
radioactive gases	trace	none
solid wastes	250 **	600,000
accidents	widespread	localized

** highly radioactive

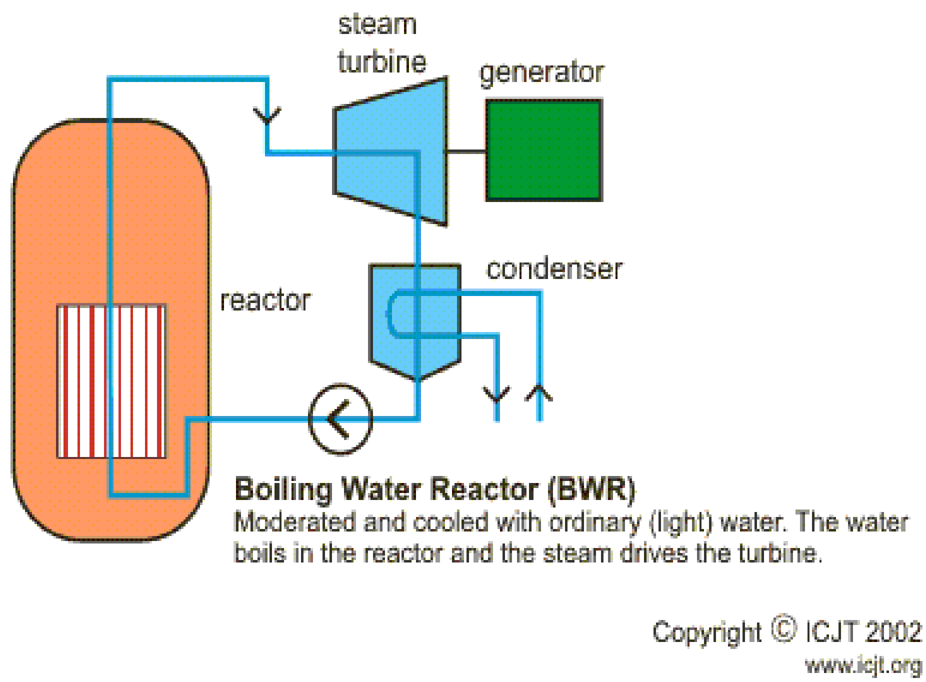
NUCLEAR FUEL CYCLE http://www.icjt.org



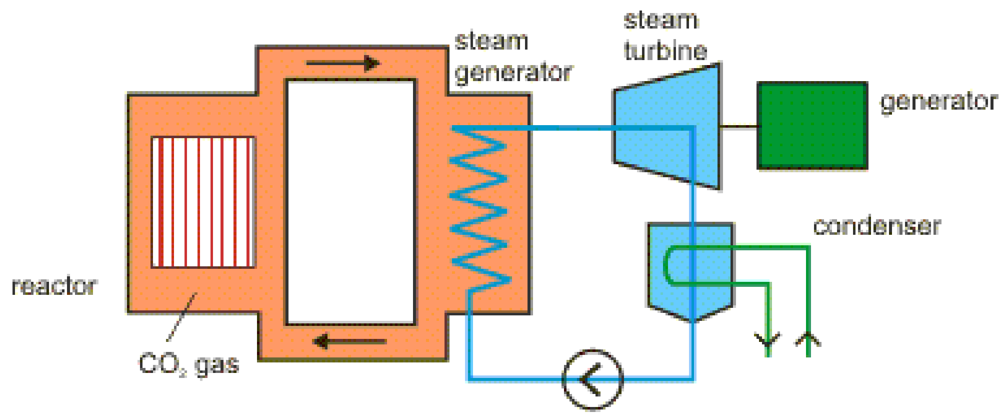
PRESSURIZED WATER REACTOR (PWR) - important



BOILING WATER REACTOR (BWR) - important

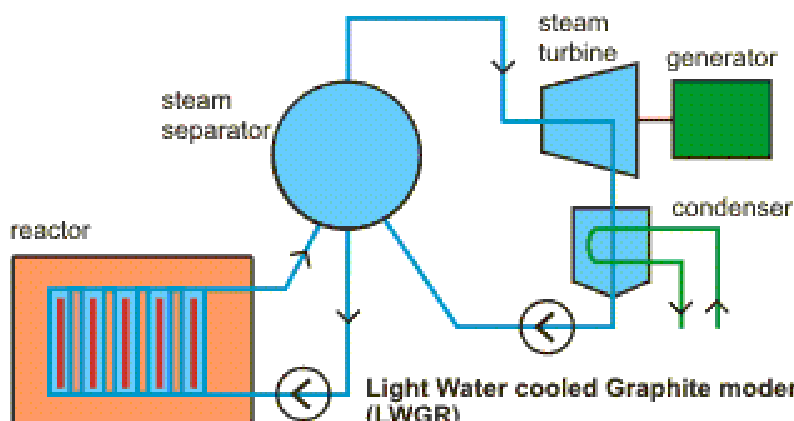


GAS COOLED REACTOR (GCR)



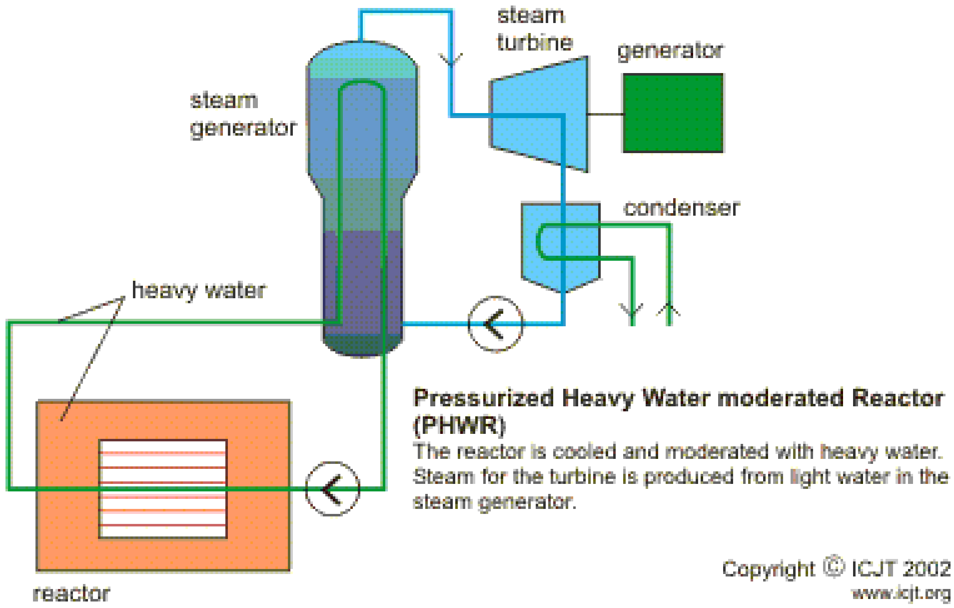
Gas Cooled Reactor, Advanced Gas cooled Reactor (GCR in AGR)
Graphite is used as the moderator and carbon dioxide is used as the coolant. Hot CO2 heats up and boils water into steam that drives the turbine.

LIGHT WATER COOLED GRAPHITE MODERATED REACTOR (LWGR)



Light Water cooled Graphite moderated Reactor (LWGR)
Moderated by graphite and cooled by light water that boils in the reactor. The steam drives the turbine.

PRESSURIZED HEAVY WATER MODERATED REACTOR (PHWR)



Page 13-15… more reactors: **ADVANCED LIGHT WATER REACTOR (ALWR)**

PEBBLE-BED MODULAR REACTOR (PBMR)

LIQUID METAL FAST BREEDER REACTOR (LMFBR)

RADIOACTIVITY SYMBOL

13.3 Notes

III. Hazards and Costs of Nuclear Power

A. radioactive emissions

1) general info from…

www.darvill.clara.net/nucrad/index.htm and www.epa.gov

a) **radioisotopes** (*radioactive isotopes* or *radionuclides*)—unstable isotopes which *spontaneously release particles* (see b)

b) **half life** $(t^{1/2})$ — *the time it takes for half the amount of a radioisotope to decay* (wide range—from a fraction of a second to thousands of years)

c) **radioactive emissions**—possible products of nuclear decay:

i.) **alpha particle =** α

- *made of He nuclei (2 protons, 2 neutrons); positively charged*
- alpha decay example:

$$^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\text{He}$$

ii.) **beta particle = β**

- *made of electrons; negatively charged*
- beta decay example:

$$^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{0}_{-1}\text{e}$$

iii.) **gamma ray = γ**

- *made of electromagnetic (em) radiation, no charge*
- pure energy; wavelengths (λ) of 0.03-0.003 nm!
- gamma decay example:

$$^{3}_{2}\text{He} \rightarrow {}^{3}_{2}\text{He} + \gamma$$

d) emissions are also called *ionizing radiation*

e) many radioactive substances emit α particles and β particles as well as γ rays

f) there is no pure γ source; anything that gives off γ rays will also give off α and/or β

g) **radioactive wastes**—*emissions* from the nuclear reactions as well as *indirect products (elements)*

h) **curie (Ci)—**unit of radioactivity

i) other radiation units (see below):

NUCLEAR UNITS…

Curie:

1 Ci = 3.7×10^{10} decays per second

This is roughly the activity of 1 gram of the ^{226}Ra isotope, a substance studied by the pioneers of radiology, Marie and Pierre Curie. The curie has since been replaced by an SI derived unit, the becquerel (Bq), which equates to one decay per second.

1 Ci = 3.7×10^{10} Bq and 1 Bq = 2.70×10^{-11} Ci

Roentgen Equivalent Man (rem)— a unit of equivalent dose relating the absorbed dose in human tissue to the effective biological damage of the radiation)

Sv = **sievert** = SI derived unit of dose equivalent, attempting to reflect the biological effects of radiation; J of energy / kg of tissue **1 sievert = 100 rem**

Gray (Gy) = the SI unit of absorbed dose and physical effects; same unit equivalent as Sv

1 gray = 100 rad

Rad = unit of radiation dose, *meaning* "**r**adiation **a**bsorbed **d**ose". It is superseded in the SI system by the gray; the U.S. is the only country that still uses the rad.

2) biological effects of radioactive emissions

a) *stochastic effects*—a long-term, low-level (*chronic*) exposure to radiation
   - stochastic = likelihood that something will happen
   - increased exposure makes the effects more likely to occur but do not influence the type or severity

- types
  - increased incidence of *cancer* by ionizing radiation
  - *mutations* (changes in the DNA structure)

b) *nonstochastic effects*—acute exposure; short-term, high-level exposure

- becoming more severe as the exposure increases
- types
  - *burns*
  - *radiation sickness*
    - symptoms: nausea, weakness, hair loss, skin burns or diminished organ function

Exposure (rem) *	Health Effect	Time to Onset
	radiation burns; more severe as exposure increases	variable
5-10	changes in blood chemistry	variable
50	nausea	hours
55	Fatigue	hours
70	vomiting	hours
75	hair loss	2-3 weeks
90	diarrhea	weeks
100	hemorrhage	weeks
400	death from fatal doses	within 2 months
1,000	destruction of intestinal lining	1-2 weeks
	internal bleeding	1-2 weeks
	death	1-2 weeks
2,000	damage to central nervous system	minutes
	loss of consciousness	minutes
	death	hours to days

3) sources of radiation: cosmic radiation, *natural elements in the crust, X-rays, radon in homes, fallout from testing* (see Table 13-1)
4) *government guidelines = 1.7 mSv/yr exposure, except for X-rays*

B. radioactive wastes ("radwaste")

1) **reprocessing**—recovery and recycling of isotope products of nuclear reactions to be used as fuel again (not done in U.S.)
2) types of radioactive waste

a) *low-level waste*

- *mixed (hazardous and radioactive) waste*
- *waste from commercial or government* (e.g., Department of Energy) *activities*

- *waste exempted or deferred from regulation by the Nuclear Regulatory Commission*
- *waste containing natural radioactivity*
- certain types of *cleanup or decommissioning waste*
- *can take 100-500 years to become safe*

b) *high-level waste*

- *byproduct of producing nuclear materials for defense uses*
- stored in forms such as *sludge, liquid, or pellets which must be solidified* before disposal
- produced when spent nuclear fuel is reprocessed by dissolving it strong chemicals to recover unfissioned uranium and plutonium
  (currently, the U.S. does not reprocess nuclear fuel)
- *generally contains highly radioactive elements, such as cesium, strontium, technetium, and neptunium.*
- *takes thousands of years to become safe*

From https://www.epa.gov/radiation

Commonly Encountered Radionuclides				
Name	Atomic Number	Radiation Type		
		Alpha	Beta	Gamma
Am-241	95	•		•
Cs-137	55		•	•
Co-60	27		•	•
I-129 &-131	53		•	•
Pu (plutonium) - important	94	•	•	•
Ra	88	•		•
Rn	86	•		
Sr-90	38		•	
(Technetium) Tc-99	43		•	•
Tritium (H-3)	1		•	
Thorium (Th)	90	•		•
U - important	92	•		•

from www.chemicalelements.com

<u>Isotope Half Life</u>

U-230	20.8 days	Pu-236	2.87 years
U-231	4.2 days	Pu-237	45.2 days
U-232	70.0 years	Pu-238	87.7 years
U-233	159,000.0 years	**Pu-239**	**24,100.0 years**
U-234	247,000.0 years	Pu-240	6560.0 years
U-235	**7.0004 x 10^8 years**	Pu-241	14.4 years
U-236	2.34 x 10^7 years	Pu-242	375,000.0 years
U-237	6.75 days	Pu-243	4.95 hours
U-238	**4.47 x 10^9 years**	Pu-244	8.0 x 10^7 years
U-239	23.5 minutes	Pu-245	10.5 hours
U-240	14.1 hours	Pu-246	10.85 days

3) disposal

   a) short-term – hold the materials on site

   b) long-term

   - *non-corrosive containers sealed in glass blocks*
   - *buried deep underground in a stable area*
   - *enclosed in concrete and dumped in ocean*

4) military radioactive wastes

   a) radioactive waste is leaking from Russian nuclear submarines

   b) more waste will be generated by dismantling old weapons

   c) technical problems with finding safe storage and disposal sites

   d) financial problems covering the costs of security, decommissioning, decontamination and clean-up

   e) cleaning up the environmental damage just from the U.S. nuclear weapons program was estimated to cost up to $375 billion and to take 75 years (US Department of Energy, 1995).

5) high-level nuclear waste disposal – *Yucca Mountain*
   http://www.yuccamountain.org/

   a) located in a remote desert on federally protected land within the secure boundaries of the Nevada Test Site in Nye County, Nevada

   b) ~ 100 miles NW of Las Vegas

   c) supposed to be a *geologic repository*—packaged waste stored in underground tunnels deep below the surface

   d) project is presently stalled

> "Federal funding for DOE's repository program is currently nonexistent; as of January 2016, no federal appropriations have been authorized to support NRC licensing and/or DOE site investigations at Yucca Mountain. It's worth noting, however, to date the U.S. Department of Energy (DOE) has spent at estimated $8 billion studying the site and constructing the exploratory tunnel beneath Yucca Mountain. Moreover, to actually construct and operate a repository at Yucca Mountain, DOE's own estimate suggests the cost could reach $97 billion. …Today the Yucca Mountain site has been abandoned and nothing exists but a boarded up exploratory tunnel; there are no waste disposal tunnels, receiving and handling facilities, and the waste containers and transportation casks have yet to be developed. Moreover, there is no railroad to the site, and the cost to build a railroad through Nevada could exceed $3 billion. Today, the only thing that actually exists at Yucca Mountain is single 5 mile exploratory tunnel."

C. potential for accidents

1) *Chernobyl* (former USSR; Ukraine, 4/26/86)

NatGeo photos of Chernobyl plant:
http://ngm.nationalgeographic.com/2006/04/inside-chernobyl/ludwig-photography

World Nuclear Association:
http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx

   a) summary

   - power plant located 80 miles north of Kiev; had 4 reactors
   - safety systems were disabled while running tests on a nearby generator
   - reactor overheated, chain reaction went out of control, steam built up and blew the steel and concrete top off the reactor

b) causes

- *known design weaknesses* going unchecked
- design *flaw in the reactor* – unstable at low power: heats up too quickly
- *procedural violations*: cooling system was disabled; 6-8 control rods were in place instead of at least 30
- *breakdown in communication* between the test team and the reactor team

c) effects

- 29 died within the first three months
- increased *thyroid cancer* (from I-131), and Cs-137
- increased other types of *cancer*
- increased cases of *anxiety*, *depression, PTSD*
- estimated 140,000-475,000 cancer deaths worldwide
- last reactors of the power plant shut down in 2000
- lack of public trust

2) Fukushima (3/11/11)
http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx

a) summary

- Japan
- produced 1/10 the radiation of Chernobyl
- released I-131 (8-day half-life) and Cs-137 (30-yr half-life)

b) causes

- occurred after earthquake and tsunami
- tsumani broke reactor's connection to the power grid
- reactors overheated – meltdown of all three

c) effects

- close monitoring of 3700 plant workers
- seawater monitoring
- airborne radiation spread
- hindered access to site and equipment – storm damage

3) *Three Mile Island 2* (TMI-2) http://www.threemileisland.org/
(near Middletown/Harrisburg, Pennsylvania, 3/28/79)

a) summary

- steam generator shut down due to lack of feedwater
- valve opened to let out excess steam but did not close
- equipment did not show that the valve was still open
- partial meltdown of the core

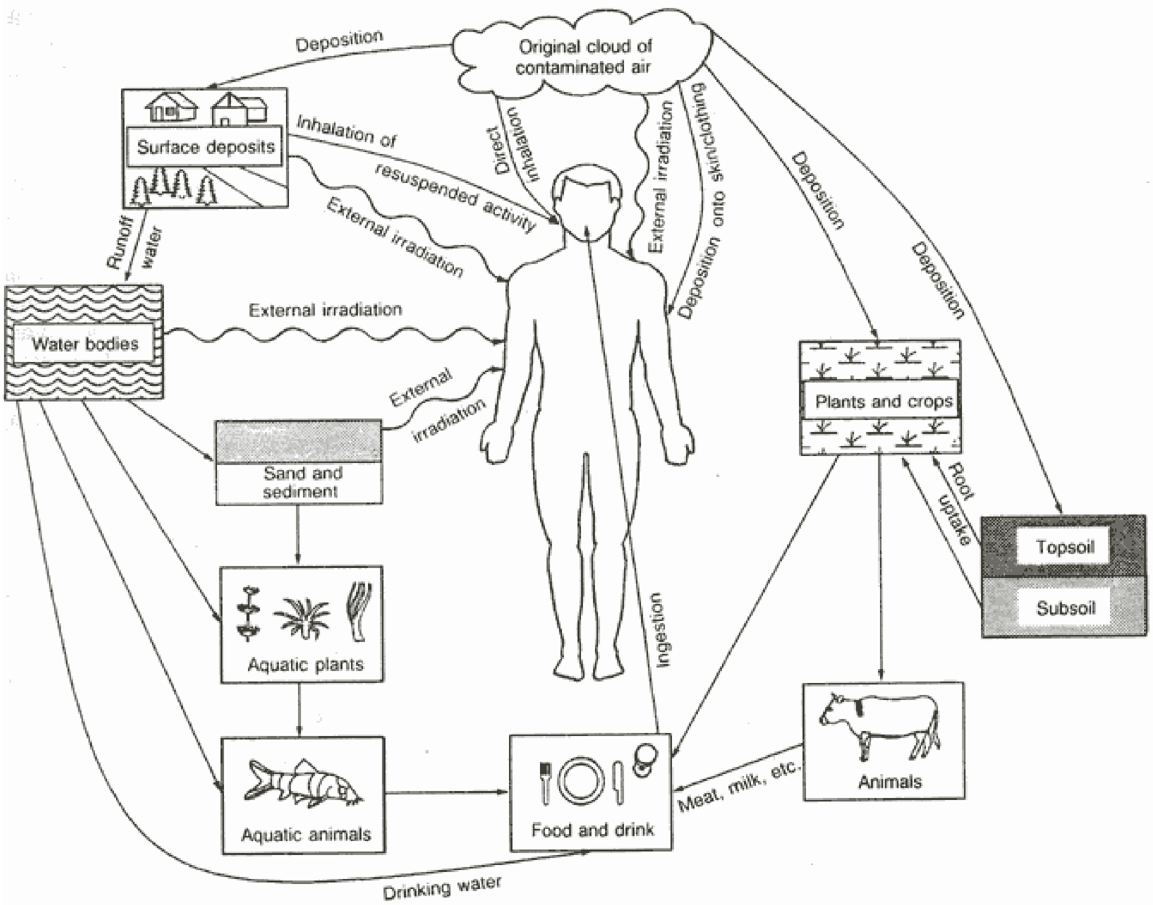
b) causes

- *design problems*
- *equipment malfunctions*
- *miscommunication*

c) effects

- lack of public trust
- very low exposure to 2,000,000 people in the area

- *stricter standards of design, inspection, backup equipment, and human experience/ skill, troubleshooting*
- reactor shut down permanently

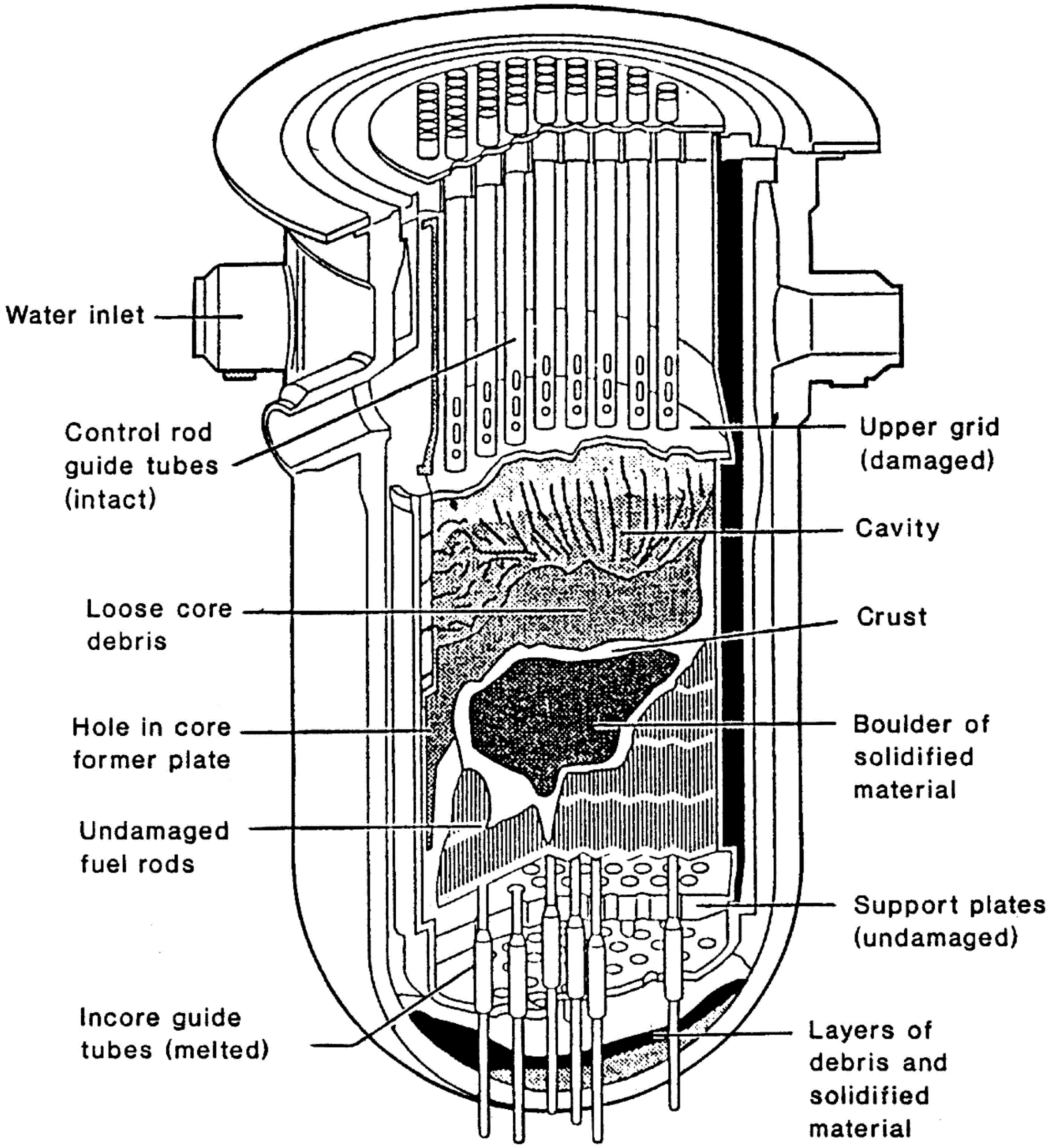


Main environmental pathways of human radiation exposure
[Source : IAEA technical report ISBN 92-0-129191-4 Vienna 1991]

D. Safety and nuclear power
   1) **active safety**—human-controlled actions, external power, equipment signals
   2) **passive safety**—design components
   3) new generations of reactors
      a) Generation I – built in the 1950s-60s; most are decommissioned
      b) Generation II – most currently operating reactors
      c) Generation III – smaller, simpler designs; passive safety features
         - Example: **ALWR – advanced light water reactors** prevent a *LOCA (loss of coolant accident)*

ADVANCED LIGHT WATER REACTOR (ALWR)

Source: G.P.U. Nuclear



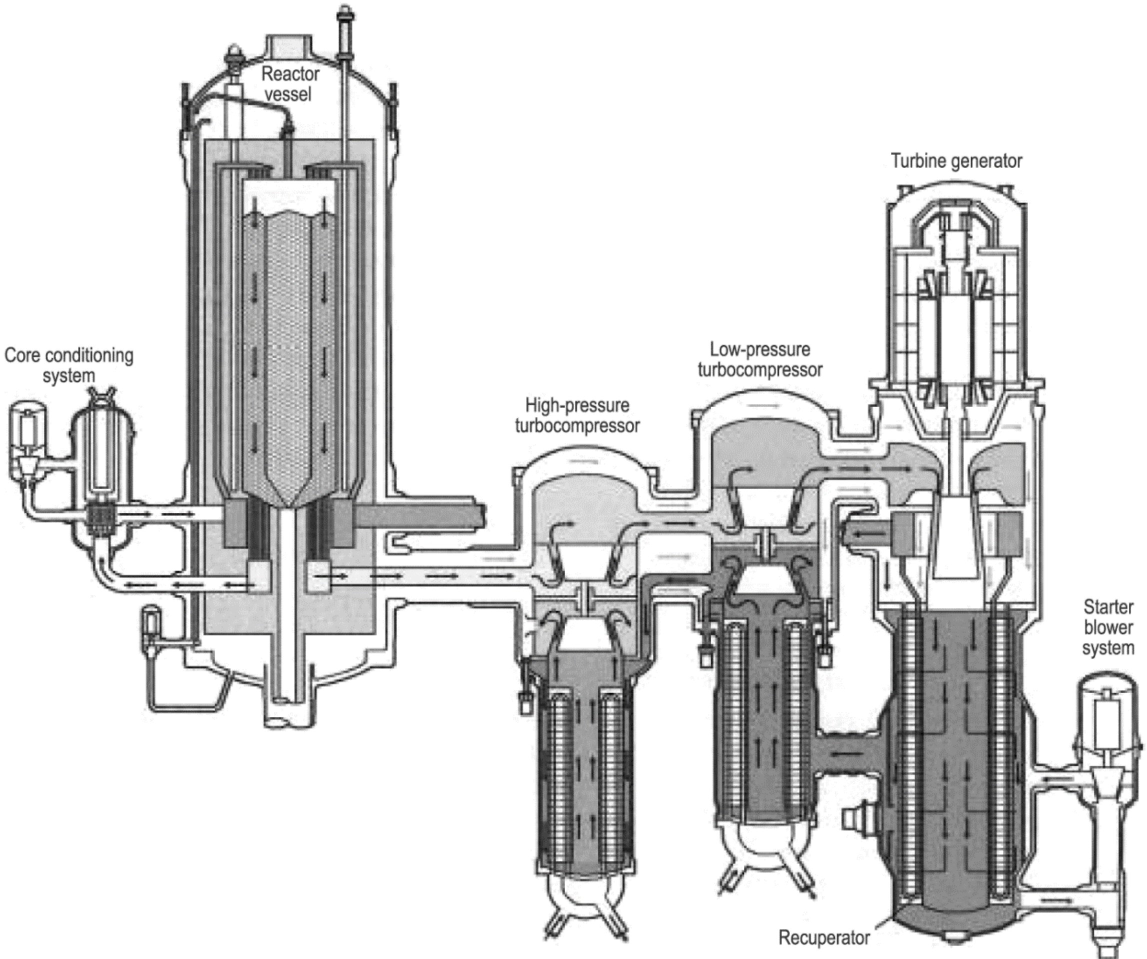
d) Generation IV – **PBMR (pebble-bed modular reactor)**

From http://www.pbmr.com

"The PBMR is a High Temperature Reactor (HTR), with a closed-cycle, gas turbine power conversion system. Although it is not the only HTR currently being developed in the world, the South African project is internationally regarded as the leader in the power generation field. Very high efficiency and attractive economics are possible without compromising the high levels of passive safety expected of advanced nuclear designs.

The PBMR essentially comprises a steel pressure vessel which holds the enriched uranium dioxide fuel encapsulated in graphite spheres. The system is cooled with helium and heat is converted into electricity through a turbine."

PEBBLE-BED MODULAR REACTOR (PBMR)



Source: Weil (2001)

E. Economic problems with nuclear power
  1) power plants lasting an average of only 17 years
    a) **embrittlement**— the reactor parts themselves become brittle
    b) **corrosion**—chemically eaten away; causes cracks in the pipes
  2) **decommissioning** *(closing down)* a power plant is costly (hundreds of millions of dollars)
  3) technical problems

13.4 Notes

IV. More Advanced Reactors

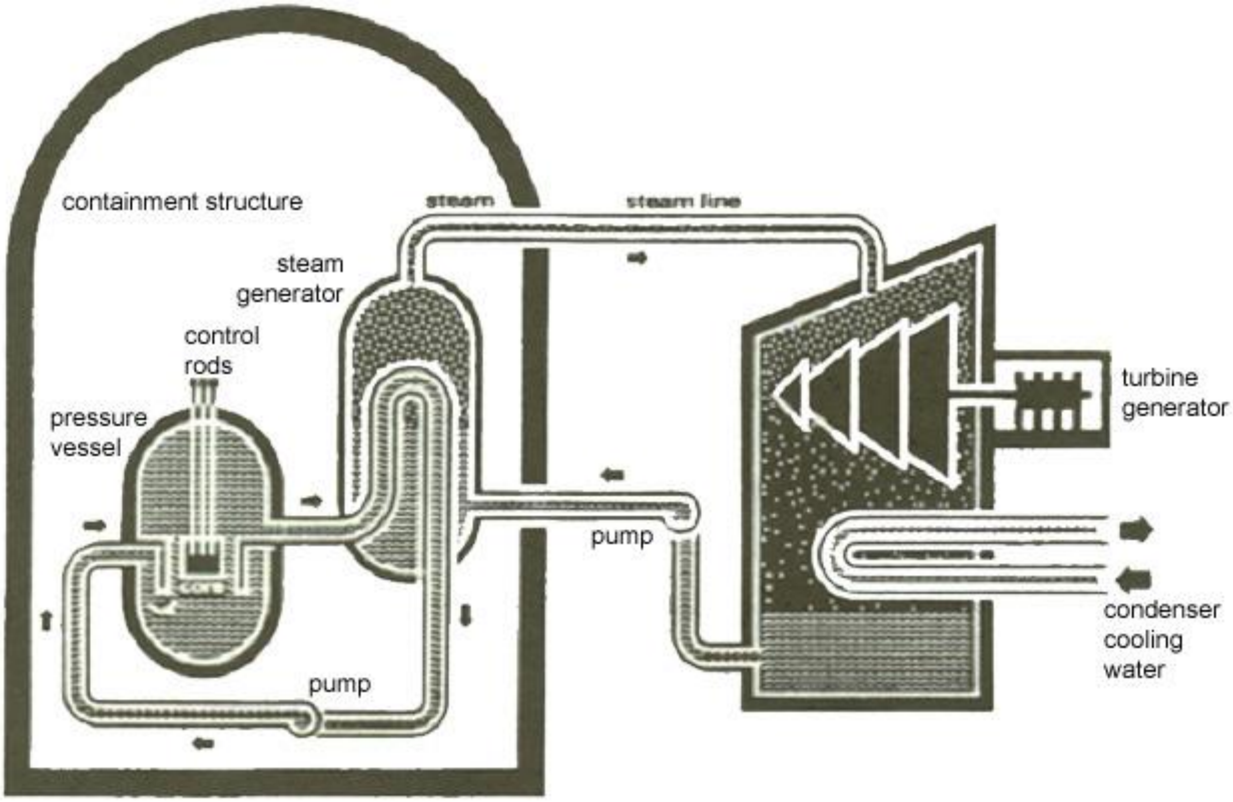
A. **breeder reactors (**liquid metal fast breeder reactors)
  1) *uses U-238 to absorb extra neutrons; becomes Pu-239*

example of breeder reactions

$$^{1}_{0}n + ^{238}_{92}U \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

beta decay beta decay

2) *almost all naturally occurring U is U-238*; this makes good use of it since it is nonfissionable
3) meltdowns would be very serious since Pu-239 has a long half-life
4) France and Japan—only countries with commercial breeder reactors
   1 g Pu = 1 ton oil that would be burned to produce power
5) U.S. has small, military breeders



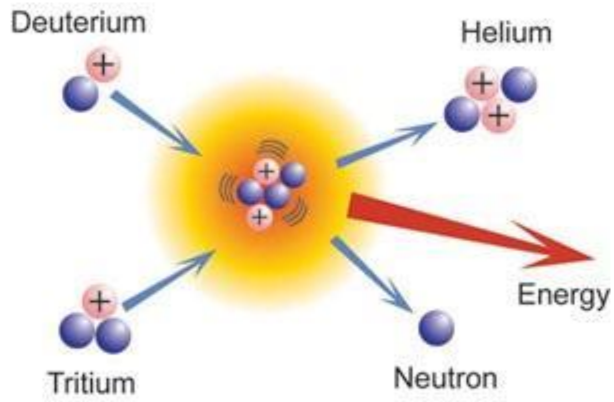
Liquid metal fast breeder reactor (LMFBR)

B. fusion and fusion reactors
   1) general fusion info
      a) **fusion**—the joining of nuclei of two smaller atoms to form one larger atom
      b) stars are nuclear reactors (sun converts H to He)
   2) *hot fusion*—deuterium (H-2) fusion, done in plasma
      ”http://library.thinkquest.org/17940/texts/fusion_dt/fusion_dt.html
      a) reaction results in equal quantities of tritium and neutrons
      b) produces large amount of heat energy
      c) “heavy hydrogen” isotopes *deuterium (D; H-2)* and *tritium (T; H-3)* are used in a **d-t reaction**
         - *T does not occur in nature* and is made in the lab (radioactive)

- *D can be extracted from seawater* – heavy but not radioactive

d) fusion requires 3,000,000 °C as well as high pressure—usually *ignited by a fission reaction*!

HOT FUSION from www.iter.org :



3) problems with fusion
   a) would use too much energy to get started
   b) how to contain the hydrogen at such high temps without the structure itself disintegrating
4) possible techniques
   a) Tokamak design, using a magnetic field
   b) laser fusion, using frozen hydrogen
   c) Z machine, using electricity
5) **ITER: International Thermonuclear Explosion Reactor** www.iter.org
   a) international project involving China, European Union, Switzerland, Japan, Republic of Korea, Russian Federation, U.S.
   b) located in France
   c) hydrogen plasma at 150 million °C – 10x higher than sun's core! (remember that plasma is a hot, electrically charged gas)
   d) Tokamak device that uses magnetic fields to contain and control the hot plasma
   e) will produce 500 MW of fusion power
   f) construction is underway and the first plasma operation is targeted for 2020, with full operation targeted for 2027
   g) more hot fusion options…
   http://pesn.com/2009/10/28/9501583_Focus-Fusion-1_success/

6) *cold fusion*
   a) concept first publicized in 1989
   b) process would occur in a unique solid structure without significant energy being applied
   c) products would be mainly helium with very few neutrons and occasional tritium
   d) could theoretically run at room temperature
   e) cold fusion dismissed by most scientists as "pseudoscience"
   f) LENR (Low Energy Nuclear Reaction), CANR (Chemically Assisted Nuclear Reaction), Condensed Matter Nuclear Science (CMNS)

13.5 Notes

V. The Future of Nuclear Power

A. Opposition, more than ever

1) many countries phasing it out (but China, Japan, S. Korea, India still developing it)
2) fear of accidents
3) distrust of bureaucratic procedures and safety regulations
4) cost: most expensive method of energy generation to produce and maintain
5) short life of equipment
6) nuclear waste disposal issues
7) addressing our needs: nuclear power produces electricity, not fuel like oil used for transportation

B. rebirth and revitalization?

1) use more small ALWR reactors with safety protocols
2) phase out custom-built large reactors
3) put new reactors on the sites of old reactors
4) revisit guidelines for proving sites safe for 100,000 years
5) strong leadership