APES Ch. 13 Notes: Nuclear Power

13.1 Notes

I. Nuclear Power background info
   A. OPEC cut oil production in 1999, causing sharply rising prices of oil
   B. *benefits* of nuclear power
      1) *does not produce Greenhouse gases (GHG)*
      2) *does not deplete fossil fuels*
      3) *it is a renewable resource*
   C. U.S. stats – 31 states have nuclear reactors
   D. Florida statistics

From http://www.eia.doe.gov/cneaf/nuclear/page/at_a_glance/states/statesfl.html :

Florida has five nuclear units located in three power plants: Crystal River unit 3, Turkey Point units 3 & 4, and St. Lucie units 1 &2.

"In 2008, the State of Florida ranked 12th in nuclear capacity and 10th in nuclear generation. Although the energy market of each State is unique, Florida is especially complex. Coal, natural gas, nuclear, and hydropower accounted for nearly 95 percent of the nation's electricity in 2004, but Florida doesn't always follow national trends…

All of the Florida reactors received license extensions from the *U.S. Nuclear Regulatory Commission (NRC),* so nuclear output is not likely to drop significantly for at least a decade. But, in the absence of plans or proposals for construction of new reactors, it seems unlikely that nuclear output will increase substantially either."

Note: MW(e) = Megawatt Electric

From http://www.eia.doe.gov/cneaf/nuclear/page/at_a_glance/states/statesfl.html :

Nuclear Power Plants in Florida - Net Generation and Capacity, 2008

Plant Name	Unit Number	Net Capacity MW	Net Generation Thousand Kwh	Capacity Factor (percent)	Operator/Owner
St. Lucie	1	839	6,673	91	Florida Power & Light Company/Various 1
St. Lucie	2	839	7,087	96	
Total		**1,678**	**13,760**	**94**	--
Turkey Point	3	693	6,140	101	Florida Power & Light Company/Same
Turkey Point	4	693	5,233	86	
Total		**1,386**	**11,373**	**94**	--
Crystal River	3	838	7,000	95	Progress Energy/Various 2

Source: Form EIA-860, "Annual Electric Generator Report," and Form EIA-906, "Power Plant Report."
1. Plant Owners, St. Lucie, Unit 1: Florida Power & Light Company (100%); Unit 2: Florida Power & Light Company (85.1%), Florida Municipal Power Agency (8.8%), and Orland Utilities Commission (6.1%). 2. Crystal River, Unit 3: Progress Energy Florida (91.8%), Seminole Electric Cooperative (1.7%), Orlando Utilities Commission (1.6%), Gainesville Regional Utilities (1.4%), Ocala, Florida (1.3%), Leesburg Electric Department (0.8%), Kissimmee Utility Authority (0.7%), Utilities Commission, New Smyrna Beach (0.6%), Alachua, Florida (0.1%), and Bushnell, Florida (0.1%).

From http://www.eia.doe.gov/cneaf/nuclear/page/at_a_glance/states/statesfl.html :

Florida Nuclear Industry

Electricity Market in Florida, Share of Electricity Output, by Fuel, 2004 to 2007					
Year	**Coal**	**Hydroelectric**	**Natural Gas**	**Nuclear**	**Other**
2007	30	*	45	13	12
2006	29	*	43	14	14
2005	28	*	38	13	20
2004	30	*	35	14	21
Source: EIA Survey 923, "Power Plant Operations Report" and Predecessor Forms. * Less than .05 percent.					

D. U.S. statistics from
http://www.eia.doe.gov/cneaf/nuclear/page/at_a_glance/reactors/nuke1.html
http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html :

1) There are *104 commercial nuclear generating units in the U.S.*
    a) 69 **pressurized water reactors (PWRs)** totaling 65,100 net megawatts
    b) 35 **boiling water reactors (BWRs)** totaling 32,300 net megawatts
2) **NPP** = **nuclear power plant**
3) U.*S. Nuclear Regulatory Commission (NRC)* gives approval for operation

From http://www.icjt.org/an/tech/jesvet/jesvet.htm :

Basic facts about Nuclear Power Plants in the World

Number of operating NPPs in August 2008	*439*
First NPP	Obninsk, Russia, 1954
Most powerful NPP	Chooz (France) & Ignalina (Lithuania), both 1500 MW
Share of nuclear energy in world energy production	*15%*
Nuclear energy produced in 2005	2.658 TWh
Number of years of operation to January 2008	10,677
Number of countries with operating NPPs	30
Number of NPPs under construction	35
Number of NPPs that started operation in year 2007	3
Number of shut down NPPs	119
Number of decommissioned NPPs	17

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* (SEE ATOM REVIEW NOTES)
      - 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

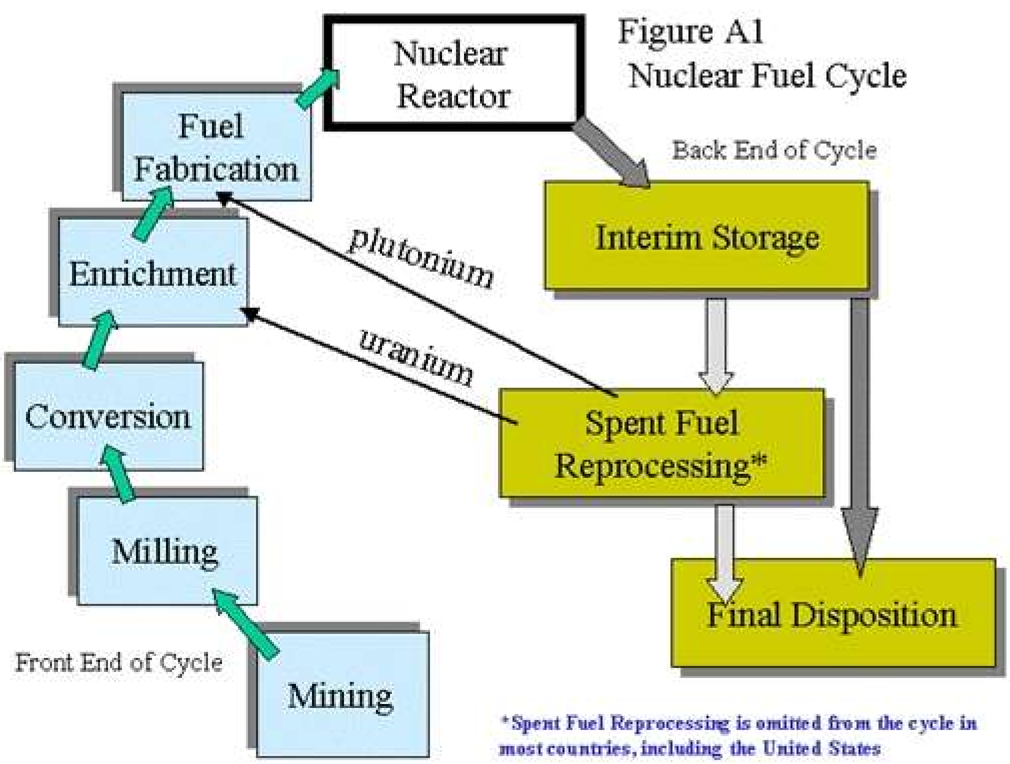
B. comparison of nuclear power with coal power emissions

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

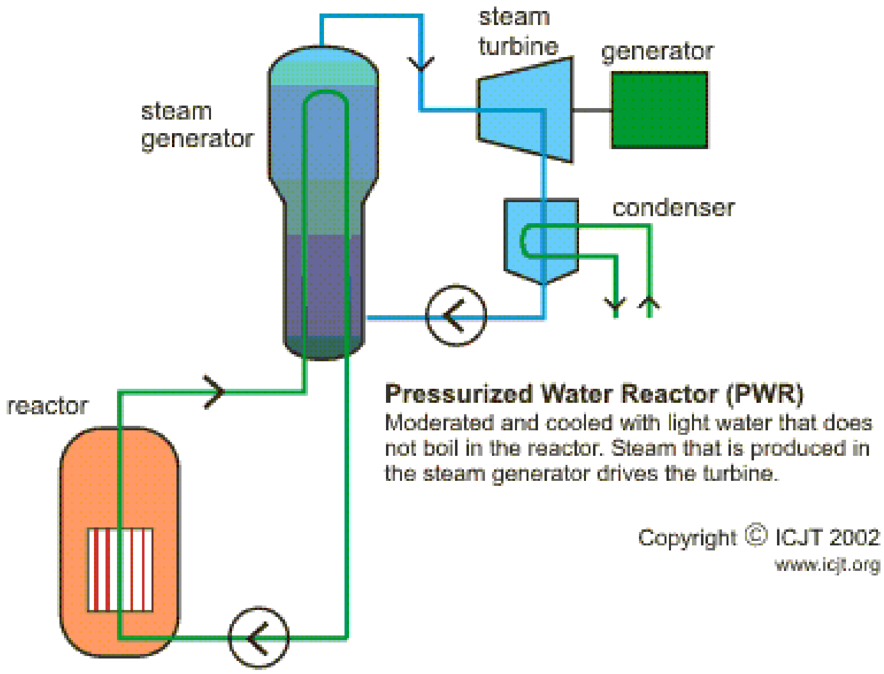
** highly radioactive

NUCLEAR FUEL CYCLE
From http://www.icjt.org/an/tech/jesvet/jesvet.htm :

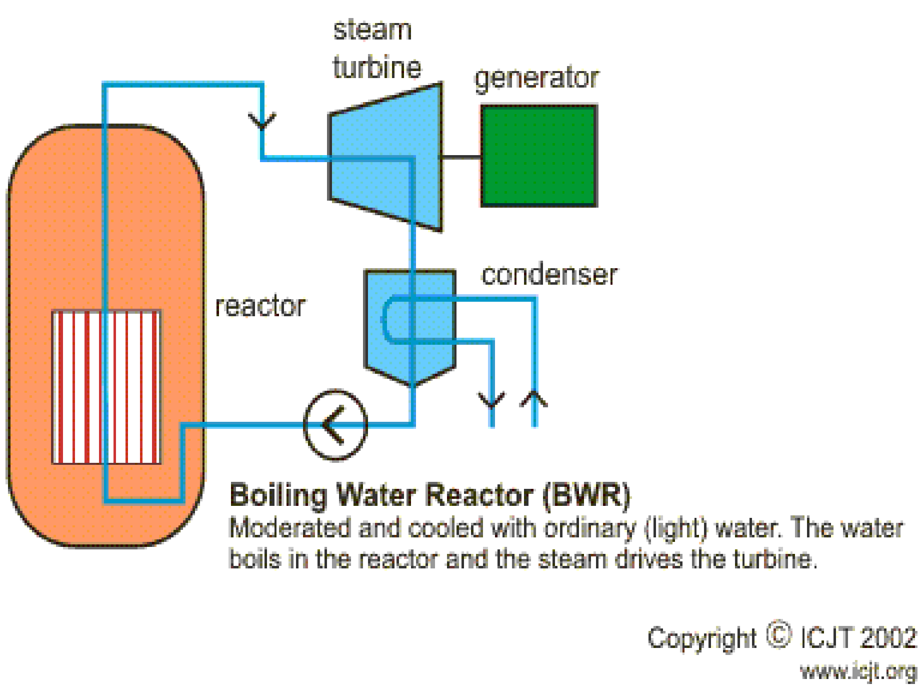


From http://www.icjt.org/an/tech/jesvet/jesvet.htm :

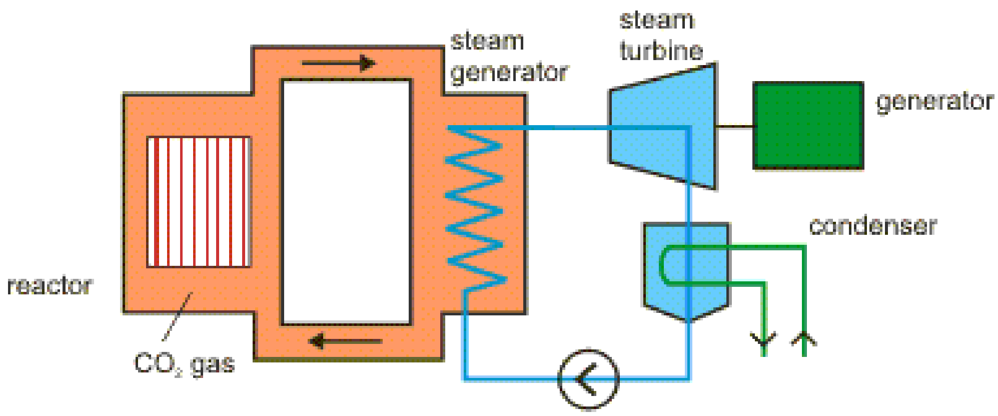
PRESSURIZED WATER REACTOR (PWR) - important



BOILING WATER REACTOR (BWR) - important

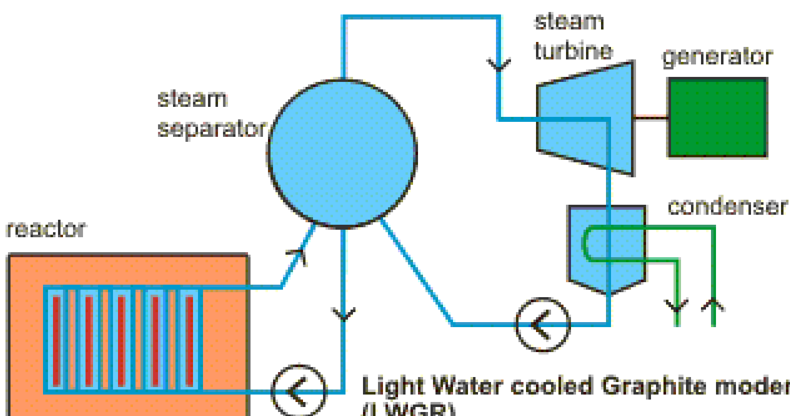


GAS COOLED REACTOR (GCR)



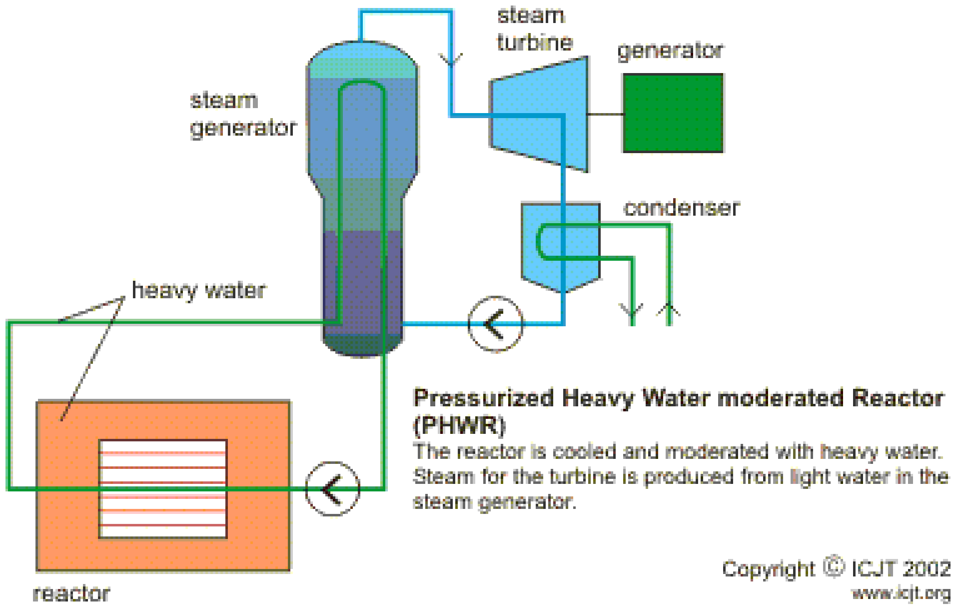
Gas Cooled Reactor, Advanced Gas cooled Reactor (GCR in AGR)
Graphite is used as the moderator and carbon dioxide is used as the coolant. Hot CO2 heats up and boils water into steam that drives the turbine.

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.

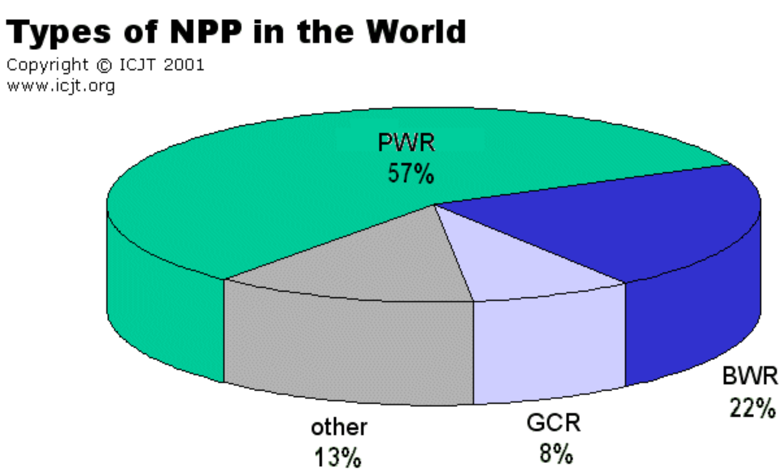
PRESSURIZED HEAVY WATER MODERATED REACTOR (PHWR)



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 from…

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

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

b) **half life** ($t^{½}$) — *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:

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

ii.) **beta particle = β**

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

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

iii.) **gamma ray = γ**

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

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

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:

$1 \text{ Ci} = 3.7\times10^{10}$ 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.

$1 \text{ Ci} = 3.7\times10^{10} \text{ Bq}$ and $1 \text{ Bq} = 2.70\times10^{-11} \text{ Ci}$

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 http://www.epa.gov/radiation/radionuclides/index.html :

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 :

Isotope Half Life			
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	**7.0004×10^8 years**	Pu-241	14.4 years
U-236	2.34×10^7 years	Pu-242	375,000.0 years
U-237	6.75 days	Pu-243	4.95 hours
U-238	**4.47×10^9 years**	Pu-244	8.0×10^7 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*
   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
   (from http://earthwatch.unep.net/radioactivewaste/military.php)
   a) radioactive waste from 80 scrapped nuclear submarines near northern Russia is leaking into the sea
   b) more waste will be generated by dismantling old weapons, including 50 tons of plutonium in the U.S.
   c) the global plutonium stockpile is estimated at 1,100 tons and growing
   d) technical problems with finding safe storage and disposal sites
   e) financial problems covering the costs of security, decommissioning, decontamination and clean-up
   f) 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) *geologic repository*—packaged waste stored in underground tunnels deep below the surface
   d) The facility was originally scheduled to begin receiving wastes in 2010. Pending budget cuts and other issues, the projection is for 2020.

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

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
   - des*ign 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 months
   - increased *thyroid cancer* (from I-131)
   - 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) *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*

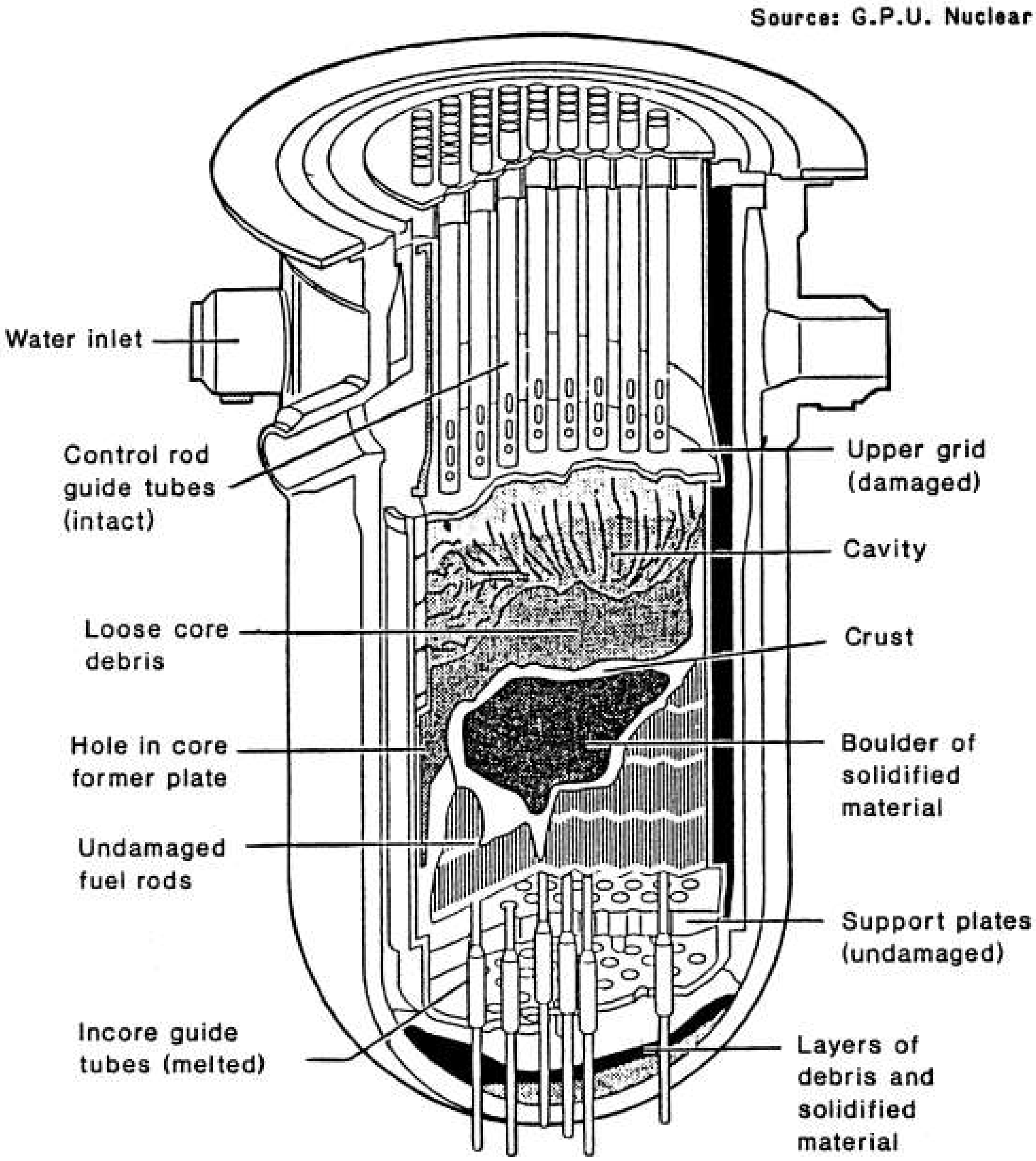
c) effects
   - lack of public trust
   - very low exposure to 2,000,000 people in the area
   - *stricter standards of design, inspection, backup equipment, and human experience/ skill, troubleshooting*
   - reactor shut down permanently

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)



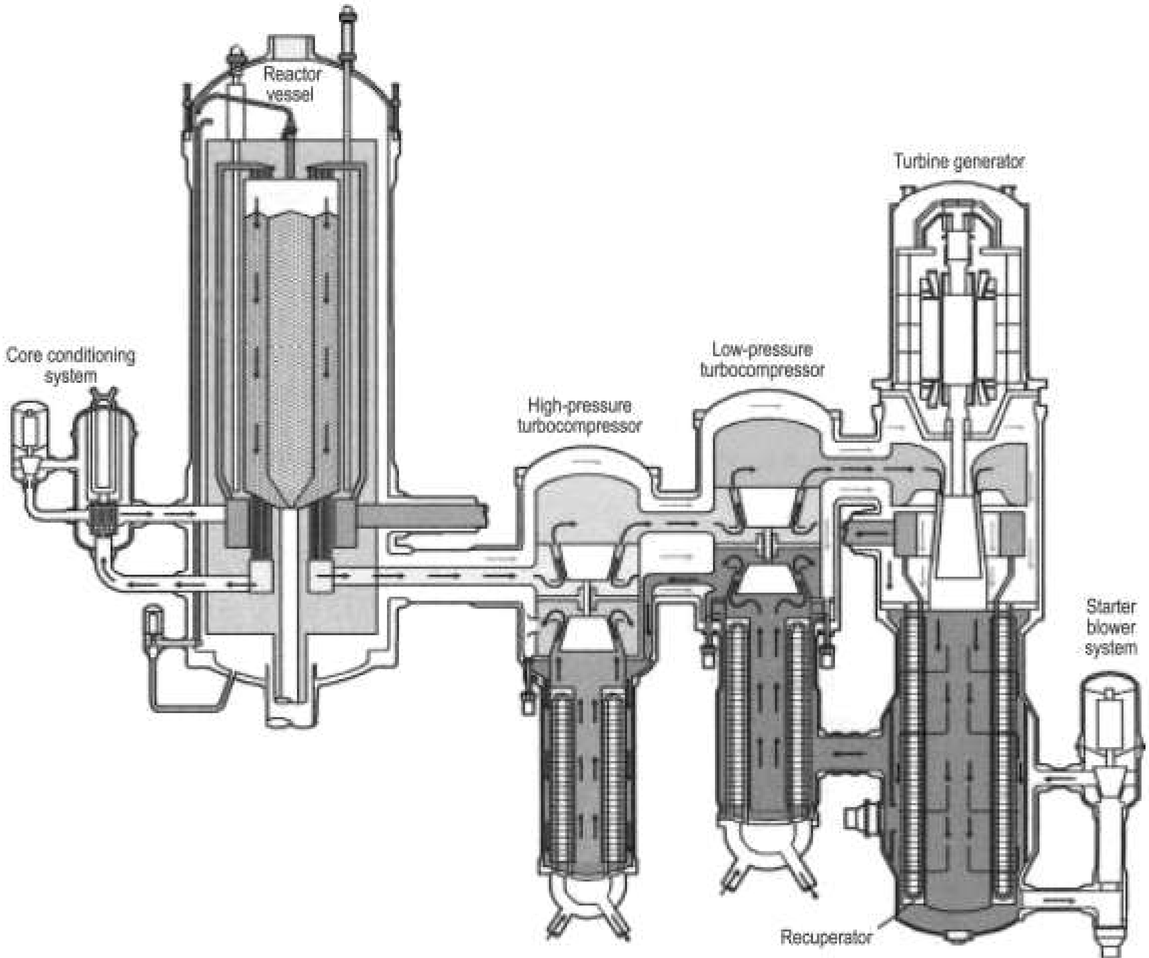
d) Generation IV – **PBMR (pebble-bed modular reactor)**

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)

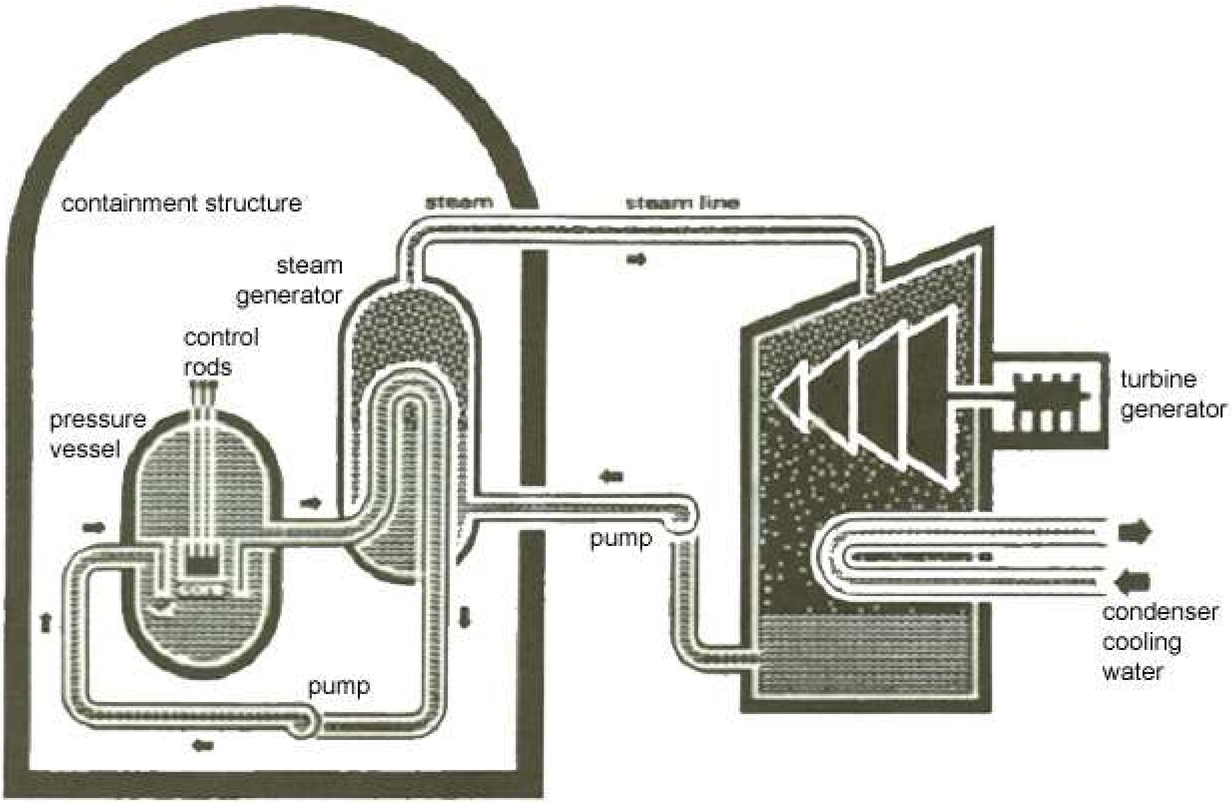
E. Economic problems with nuclear power
  1) power plants lasting an average of only 17 years
    a) **embrittlement**— the reactor parts themselves become brittle
    b) **corrosion**—chemically eaten away; causes cracks in the pipes
  2) **decommissioning** *(closing down)* a power plant is costly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

13.4 Notes

IV. More Advanced Reactors

A. **breeder reactors (**liquid metal fast breeder reactors)
  1) a *U-235 fission rxn*. (reaction)
  2) *uses U-238 to absorb extra neutrons; becomes Pu-239*
  3) *almost all naturally occurring U is U-238*; this makes good use of it since it is nonfissionable

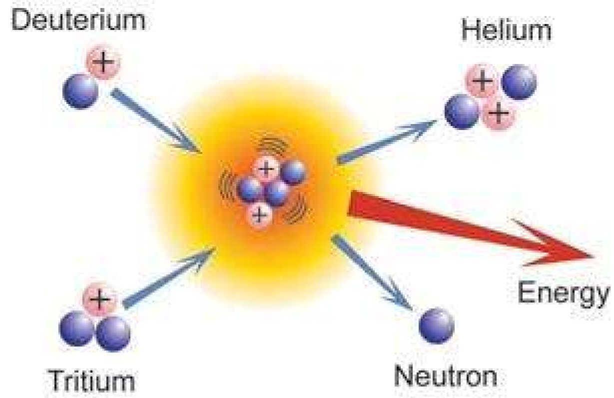
4) meltdowns would be very serious since Pu-239 has a long half-life
5) France and Japan—only countries with commercial breeder reactors
1 g Pu = 1 ton oil that would be burned to produce power
6) U.S. has small, military breeders



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 expected in 2016
   g) more hot fusion options…

From http://pesn.com/2009/10/28/9501583_Focus-Fusion-1_success/ :

"After seven years of theoretical work and raising money, five months of design, five months of construction and assembly, and a week of testing, Lawrenceville Plasma Physics (LPP) now has a functioning dense plasma focus, Focus-Fusion-1.

This isn't a demonstration of scientific feasibility, but now we have a tool to do the job", said Eric Lerner, President and founder of LPP. LPP is currently researching and developing the dense plasma focus (DPF) for hydrogen-boron nuclear fusion. Focus Fusion is projected to be a safe, clean, easy, reliable energy solution that could provide electricity at a few tenths of a cent per kilowatt-hour -- a far more feasible and profoundly less expensive approach to hot fusion, in contrast to what the international project (ITER) in France is pursuing. The end product is projected to be a 5 to 20 MW power plant the size of a gas station, which would cost between $200,000 and $300,000 to build. One person could operate two dozen such stations remotely.

Bruno Coppi, Professor of Physics Senior Fusion Researcher at MIT, said: 'Even if this approach does not succeed in producing fusion energy, the research will produce valuable technology in the near term.'"

6) *cold fusion* process occur in a unique solid structure without significant energy being applied
    a) concept first publicized in 1989
    b) products would be mainly helium with very few neutrons and occasional tritium
    c) could theoretically run at room temp.
    d) cold fusion dismissed by many scientists as "pseudoscience"
    e) 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