Nuclear Power

Overview

- Introduction to nuclear power
- Nuclear reactions
- Nuclear power plant
- Is nuclear energy safe?
  - Chernobyl and Three Mile Island
  - Physiological effects of ionizing radiation
  - Radiation sources and dose comparisons
- Nuclear Waste
- The Future of Nuclear Power

Introduction to nuclear power

- Uranium was discovered in 1789 by Martin Klaproth, a German chemist, and named after the planet Uranus.
- The science of atomic radiation, atomic change and nuclear fission was developed from 1895 to 1945, much of it in the last six of those years
- Over 1939-45, most development was focused on the atomic bomb
- From 1945 attention was given to harnessing this energy in a controlled fashion for naval propulsion and for making electricity
- Since 1956 the prime focus has been on the technological evolution of reliable nuclear power plants.

Economic Advantages

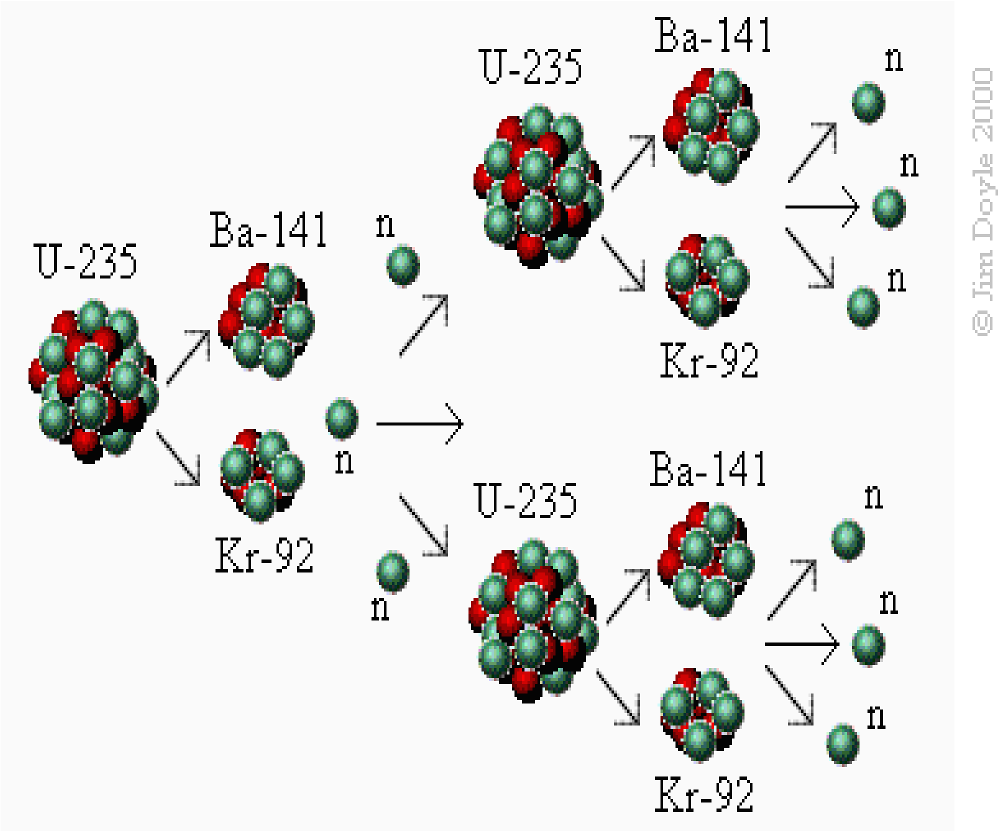
- The energy in one pound of highly enriched Uranium is comparable to that of one million gallons of gasoline.
- One million times as much energy in one pound of Uranium as in one pound of coal.
- Nuclear energy annually prevents 5.1 million tons of sulfur 2.4 million tons of nitrogen oxide 164 metric tons of carbon
- First commercial power plant, England 1956
- 17% of world’s electricity is from nuclear power

Nuclear Reactions

- Nuclear reactions deal with interactions between the nuclei of atoms including of nuclear fission and nuclear fusion
- Both fission and fusion processes deal with matter and energy
- Fission is the process of splitting of a nucleus into two "daughter" nuclei leading to energy being released
- Fusion is the process of two "parent" nuclei fuse into one daughter nucleus leading to energy being released

Fission Reaction

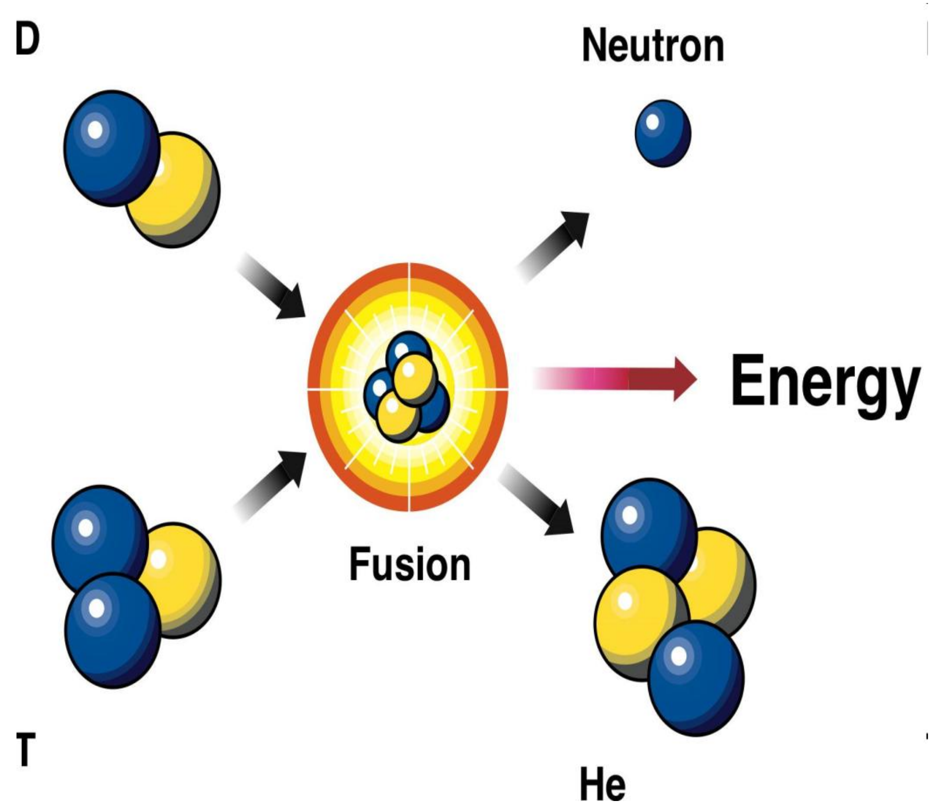
- A classic example of a fission reaction is that of U-235:
- U-235 + 1 Neutron $\longrightarrow$ 2 Neutrons + Kr-92 + Ba-142 + E
- In this example, a stray neutron strikes an atom of U235. It absorbs the neutron and becomes an unstable atom of U-236. It then undergoes fission. These neutrons can strike other U-235 atoms to initiate their fission.



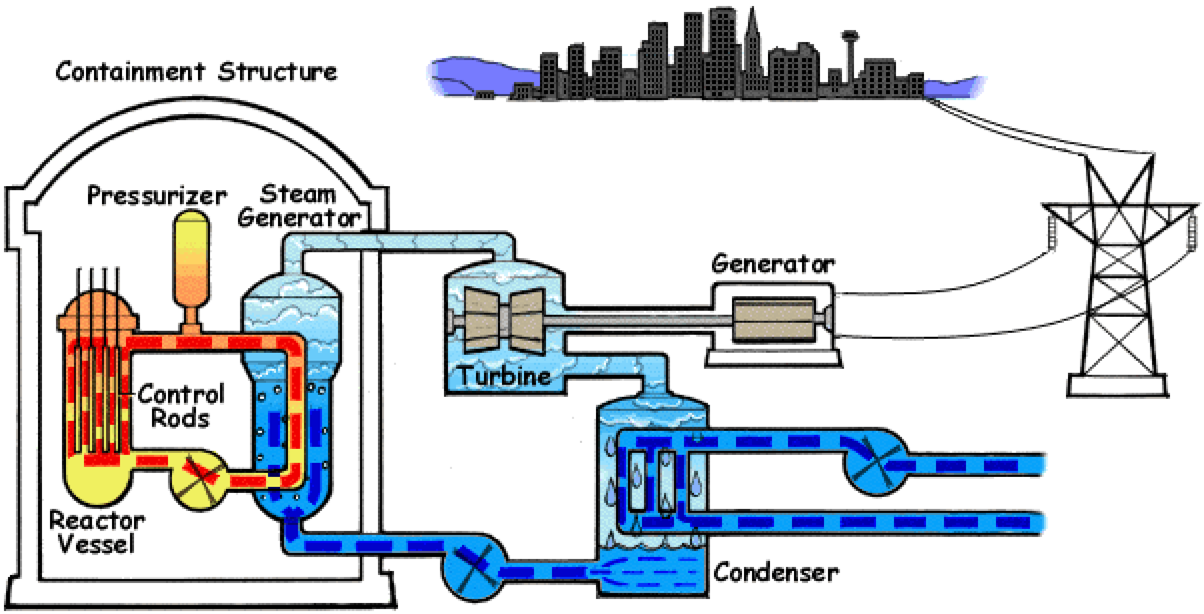
Fusion Reactions

- A classic example of a fusion reaction is that of deuterium (heavy hydrogen) and tritium which is converted to Helium and release energy.

$$p + p \longrightarrow He + n + .42\ MeV$$

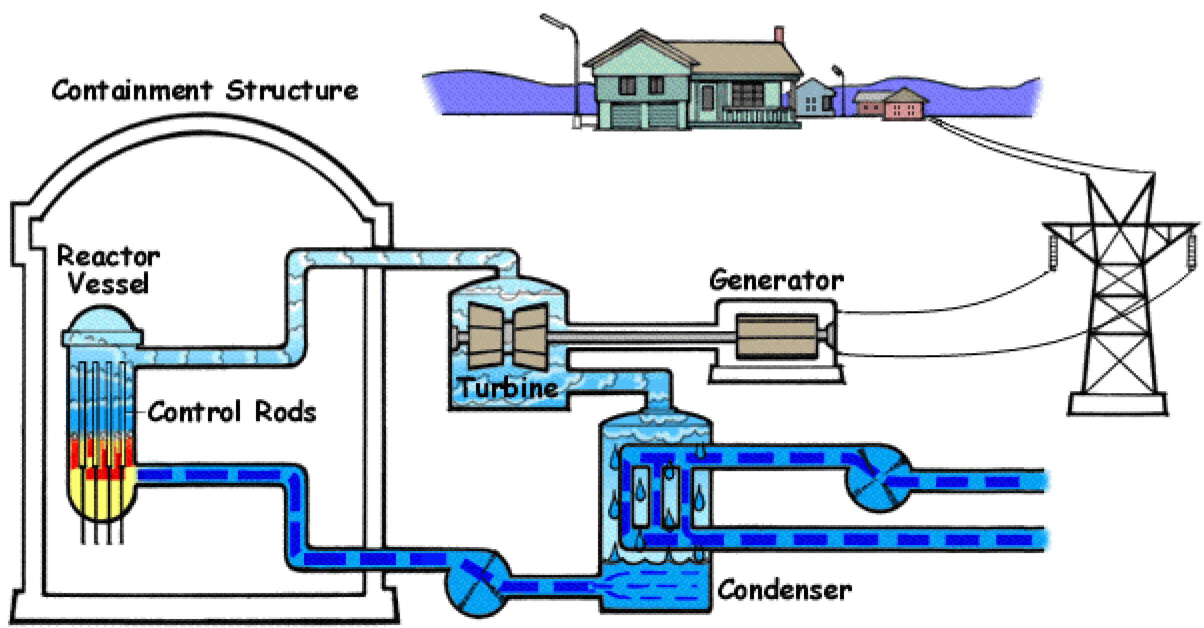


Nuclear Power Plant



The Pressurized Water Reactor (PWR)

Boiling Water Reactor (BWR)



Is Nuclear Energy Safe?

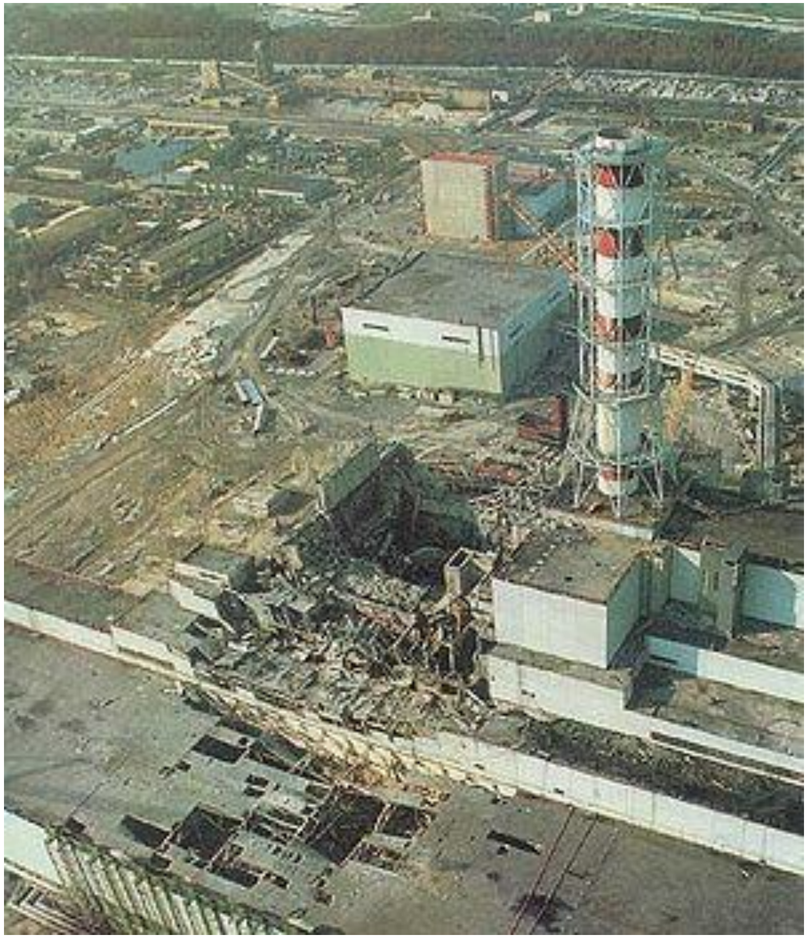
Chernobyl Accident- April 26, 1986

- World's worst nuclear power plant accident
- Chernobyl in Ukraine on Pripyat River
- Population 12,500; 120,000 in 30 km radius
- 4 reactors (2 built in 1970's, 2 in 1980's)
- Combination of design and operator error during electrical power safety check resulted in cascade of events leading to core breach of Reactor 4 with subsequent chemical (not nuclear) explosion

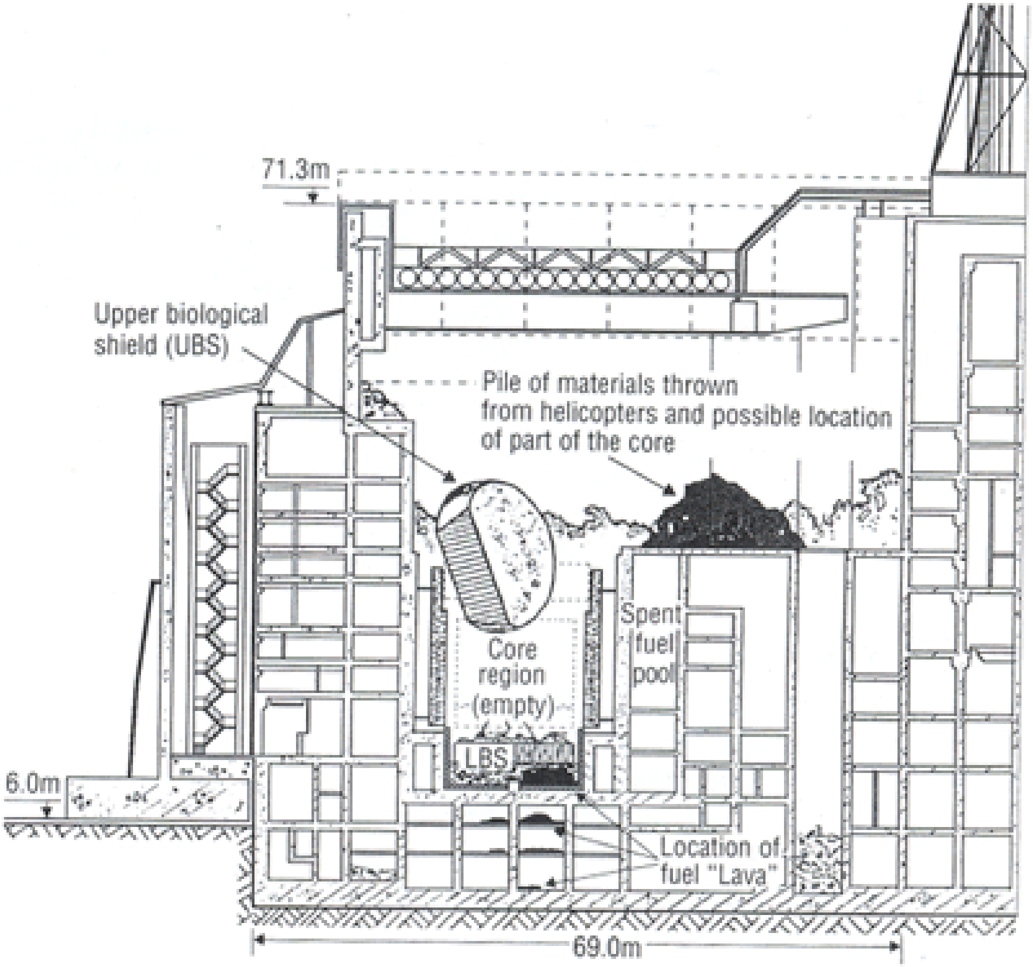
Chemistry in Context, Chapter 7

http://www.world-nuclear.org/info/chernobyl/inf07.htm

Chernobyl- Reactor 4 Site



http://www.greenfacts.org/en/chernobyl/ /UN Chernobyl Forum(2006)
http://en.wikipedia.org/wiki/Chernobyl_disaster



Boron, dolomite, sand, clay, and lead were dropped by helicopter to contain fire and release of radioactive particles.

http://www.world-nuclear.org/info/chernobyl/inf07.htm

Chernobyl Accident

• Flow of coolant water interrupted, insufficient # control rods, core breach

• Graphite used to slow neutrons in reactor caught fire. Water sprayed on graphite, resulting in hydrogen gas formation- chemical combustion reaction and explosion

  • $2H_2O(l) + C(graphite) \rightarrow 2\ H_2(g) + CO_2(g)$
  • $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

• Large amount of radioactive fission products dispersed into atmosphere for 10 days (about 100X greater than Hiroshima/Nagasaki)

• 150,000 people in 60 km radius permanently evacuated

• Toll: several workers immediately, about 30 firefighters/emergency workers from acute radiation exposure, and a smaller # from subacute effects (overall, about 60 deaths)

• About 250 million people exposed to radiation levels which may reduce lifespan, including about 200,000 in the clean-up crew ("liquidators") who buried the waste and built a concrete "sarcophagus" around Reactor 4

Chemistry in Context, Chapter 7
http://www.world-nuclear.org/info/chernobyl/inf07.htm

Chernobyl Accident

- Initial radiation released primarily I-131 (half life= 8 days), later Cs-137 (half life= 30 years)
- Children particularly susceptible to I-131. Thyroid takes up I^- to produce the hormone thyroxine (T4, growth/metabolism).
    - I-131 decays be beta emission with accompanying gamma ray
    - If ingested, can cause thyroid cancer
    - About 4000 cases of thyroid cancer in exposed children (2000), nine related deaths in this group
- Preliminary evidence (2006) suggests increased risk of leukemia and possibly other cancers in “liquidator” group and others with higher exposure in the first year- “Among some 600,000 workers exposed in the first year, the possible increase in cancer deaths due to this radiation exposure might be up to a few percent.”

Chemistry in Context, Chapter 7
http://www.world-nuclear.org/info/chernobyl/inf07.htm

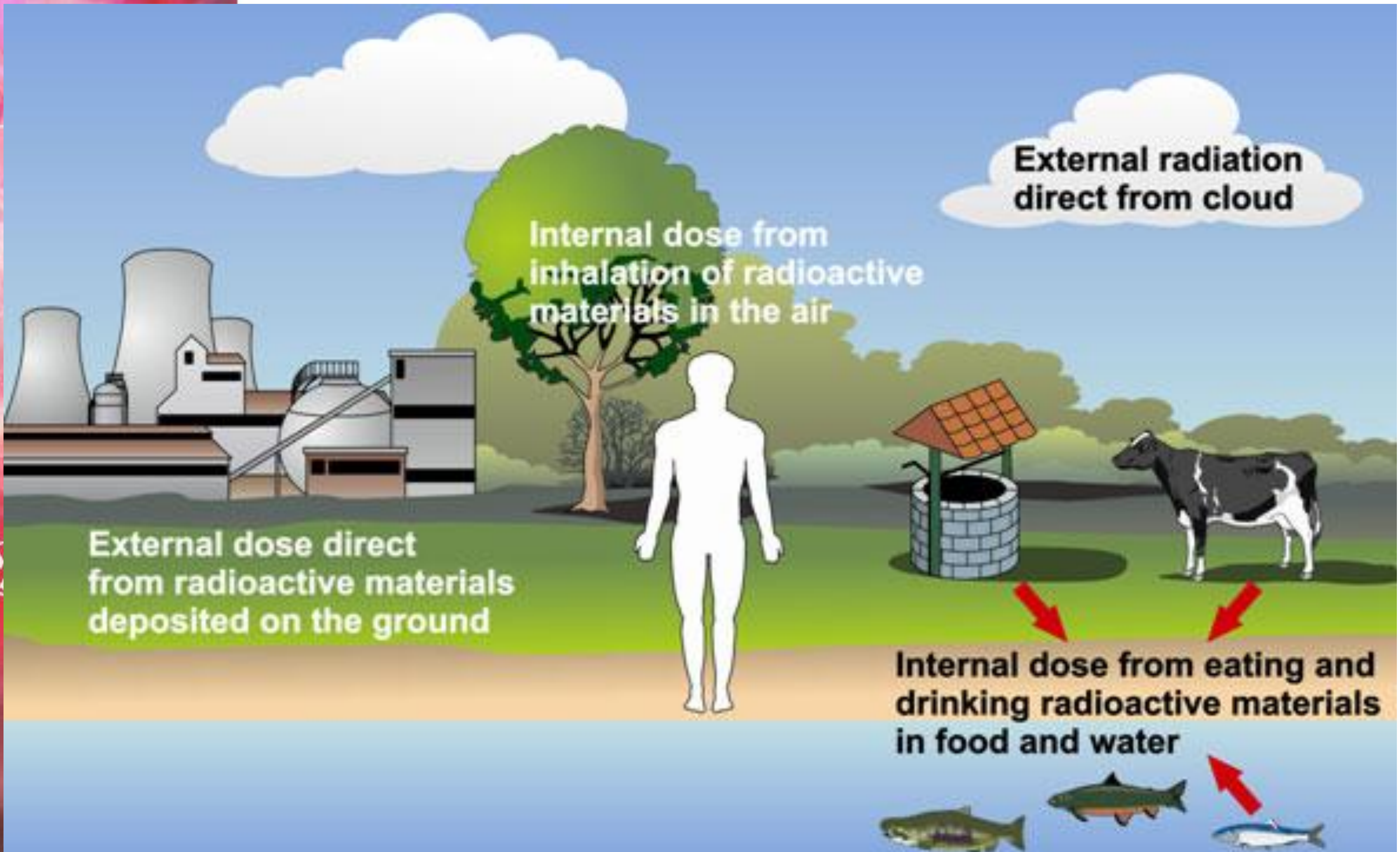
Chernobyl Accident

- Otherwise, UN report (2000)- "there is no scientific evidence of any significant radiation-related health effects to most people exposed"
- No evidence of increase in birth defects, abnormal pregnancies, or reduced fertility
- Secondary effects- fatalism, mental health problems, smoking, alcohol abuse, general poor health and nutrition
- Surrounding farmland (1000 square miles) not farmable due to high Cs-137 (exception, one small area in Belarus)
- High levels of Cs-137 found down wind in reindeer meat in Scandinavia
- Contamination effects on plants/animals within 30 km
- Contamination of nearby water bodies and fish

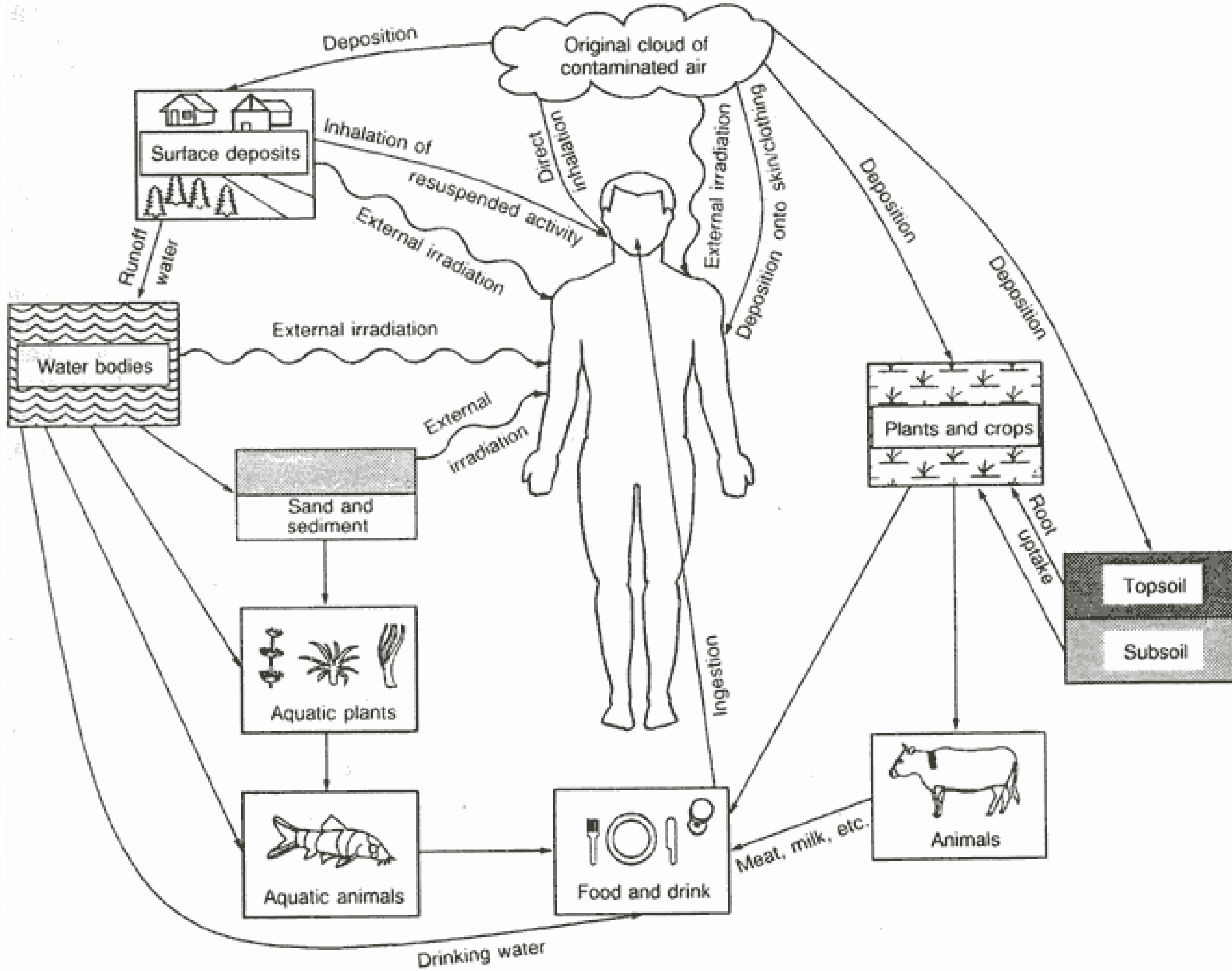
http://www.world-nuclear.org/info/chernobyl/inf07.htm

http://www.greenfacts.org/en/chernobyl/

Pathways Of Exposure To Man From Release of Radioactive Materials



http://www.greenfacts.org/en/chernobyl/, Chernobyl Forum(2006)



Main environmental pathways of human radiation exposure

[Source : IAEA technical report ISBN 92-0-129191-4 Vienna 1991]

http://www.world-nuclear.org/info/chernobyl/inf07.htm

Nuclear Energy- US Experience

Three Mile Island- March 28, 1979

• Near Harrisburg, Pennsylvania
• Most serious US nuclear plant incident
• Valve malfunction and lost coolant with partial meltdown
• Some radioactive gas released, **no** fatalities
• No significant increase in cancer deaths in exposed population
• Damage largely contained
• China Syndrome released 12 days before
• Construction of new nuclear plants ↓↓ shortly after
• Resulted in broad changes in the nuclear power industry and NRC regarding emergency response, operator training, engineering/design criteria, radiation protection, and oversight to enhance safety

Chemistry in Context, Chapter 7
http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

http://en.wikipedia.org/wiki/Three_Mile_Island_accident

Safety of Nuclear Plants

- Steel-reinforced concrete and a dome-shaped containment buildings surround all US reactors (inner wall several feet thick and outer wall at least 15 inches thick)
- Designed to withstand hurricanes, earthquakes, high winds
- Reactors have detectors to quickly shut down in event of tremor (about 20% are in regions with seismic activity like Pacific Rim)
- In considering safety, must address…
    - Faults in plant design
    - Human error
    - Risks associated with terrorism/political instability

Effects of Ionizing Radiation

- Ionizing radiation has sufficient energy to knock bound elections out of an atom or molecule
- Includes alpha/beta particles and gamma/x-rays
- Can form highly reactive free radicals with unpaired electrons
  - For example, $H_2O \rightarrow [H_2O\cdot] + e^-$
- Rapidly dividing cells in the human body are particularly susceptible to damage by free radicals
  - Radiation can be used to treat certain cancers and Graves disease of the thyroid
  - However, ionizing radiation can also damage healthy cells
  - Biological damage determined by radiation dose, type of radiation, rate of delivery, and type of tissue

Radiation Units

Activity- disintegration rate of radioactive substance

- Becquerel- SI unit (Bq) = 1 disintegration per second (dps)
- Curie (Ci) = 3.7×10^{10} Bq = # dps from 1g Ra

Absorbed dose- energy imparted by radiation onto an absorbing material

- Gray- SI unit (Gy) = 1 joule per kilogram
- 1 Gy = 100 rads

Dose Equivalent (DE)- dose in terms of biological effect

- DE = Absorbed dose X Quality factor (Q)
- Q = 1 for beta particles and gamma/x-rays
- Q = 10 for alpha particles
- Sievert- SI unit (Sv)
- 1 Sv = 100 rems

http://www.mcgill.ca/ehs/radiation/basics/units/

Physiological Effects of Acute Radiation Exposure

No observable effect (< .25 Gy)- .25 Gy is nearly 70 times average annual radiation exposure!
White blood cell count drops (.25 to 1 Gy)
Mild radiation sickness (1 to 2 Gy absorbed dose)
- Nausea and vomiting within 24 to 48 hours
- Headache
- Fatigue
- Weakness

Moderate radiation sickness (2 to 3.5 Gy)
- Nausea and vomiting within 12 to 24 hours
- Fever
- Hair loss
- Vomiting blood, bloody stool
- Poor wound healing
- Any of the mild radiation sickness symptoms
- Can be fatal to sensitive individuals

Chemistry in Context, Chapter 7
http://www.mayoclinic.com/health/radiation-sickness/DS00432/DSECTION=symptoms

Severe radiation sickness (3.5 to 5.5 Gy)

- Nausea and vomiting less than 1 hour after exposure
- Diarrhea
- High fever
- Any symptoms of a lower dose exposure
- About 50% fatality

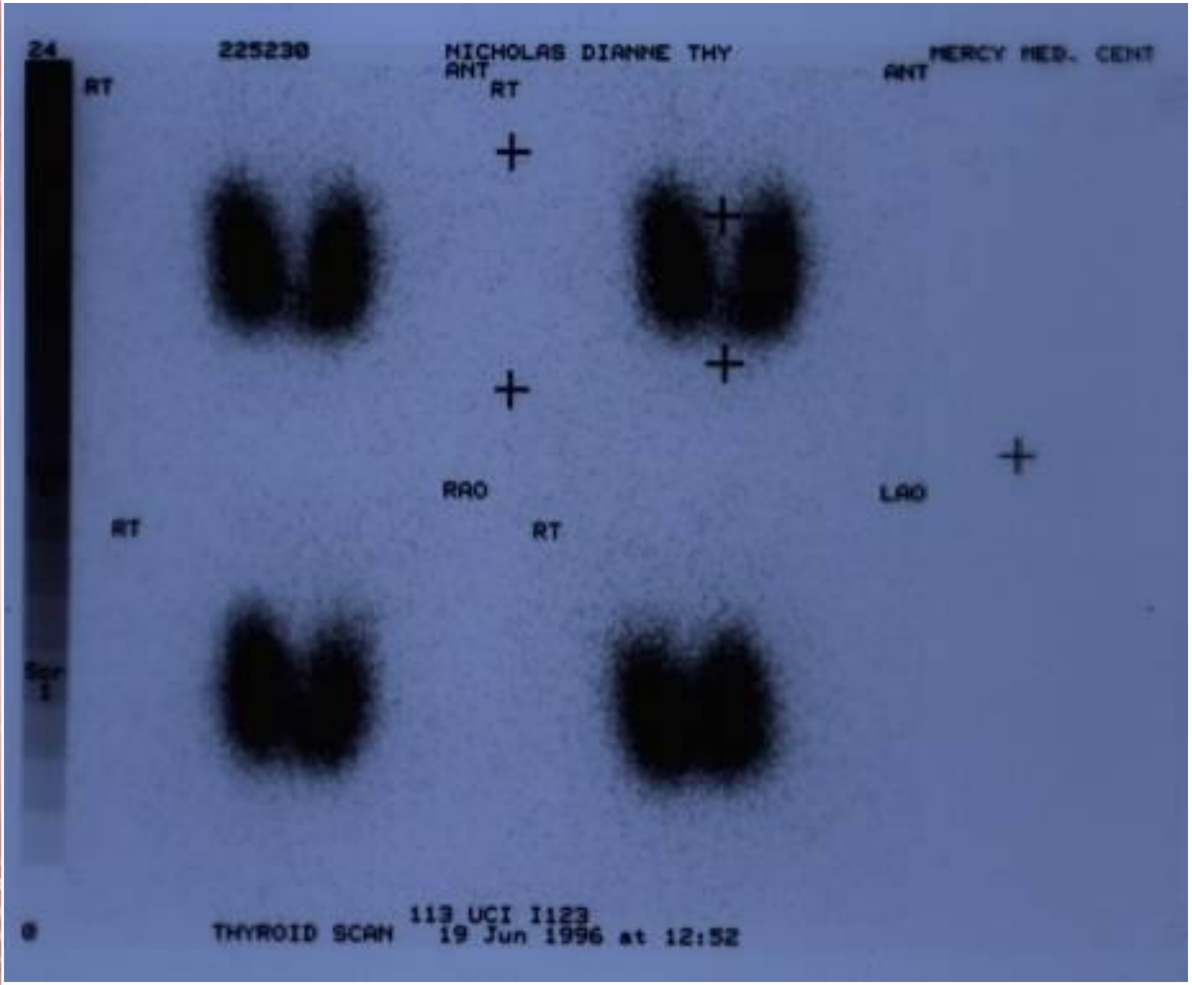
Very severe radiation sickness (5.5 to 8 Gy)

- Nausea and vomiting less than 30 minutes after exposure
- Dizziness
- Disorientation
- Low blood pressure
- Any symptoms of a lower dose exposure
- > 50% fatality

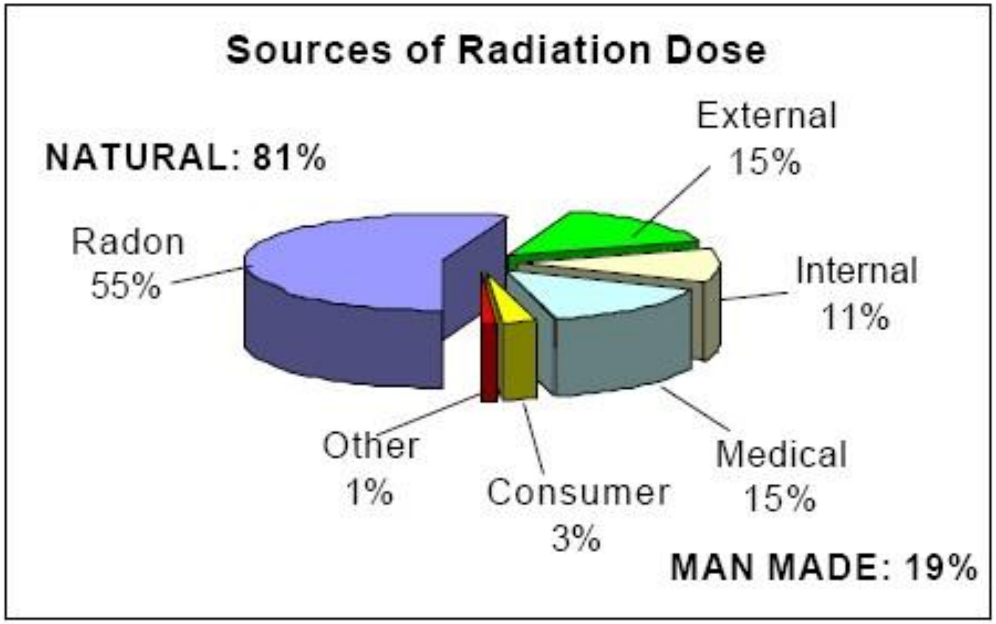
Longer term or chronic radiation effects include genetic mutations, tumors/cancer, birth defects, cataracts, etc.

Chemistry in Context, Chapter 7
http://www.mayoclinic.com/health/radiation-sickness/DS00432/DSECTION=symptoms

Thyroid Scan- Graves Disease

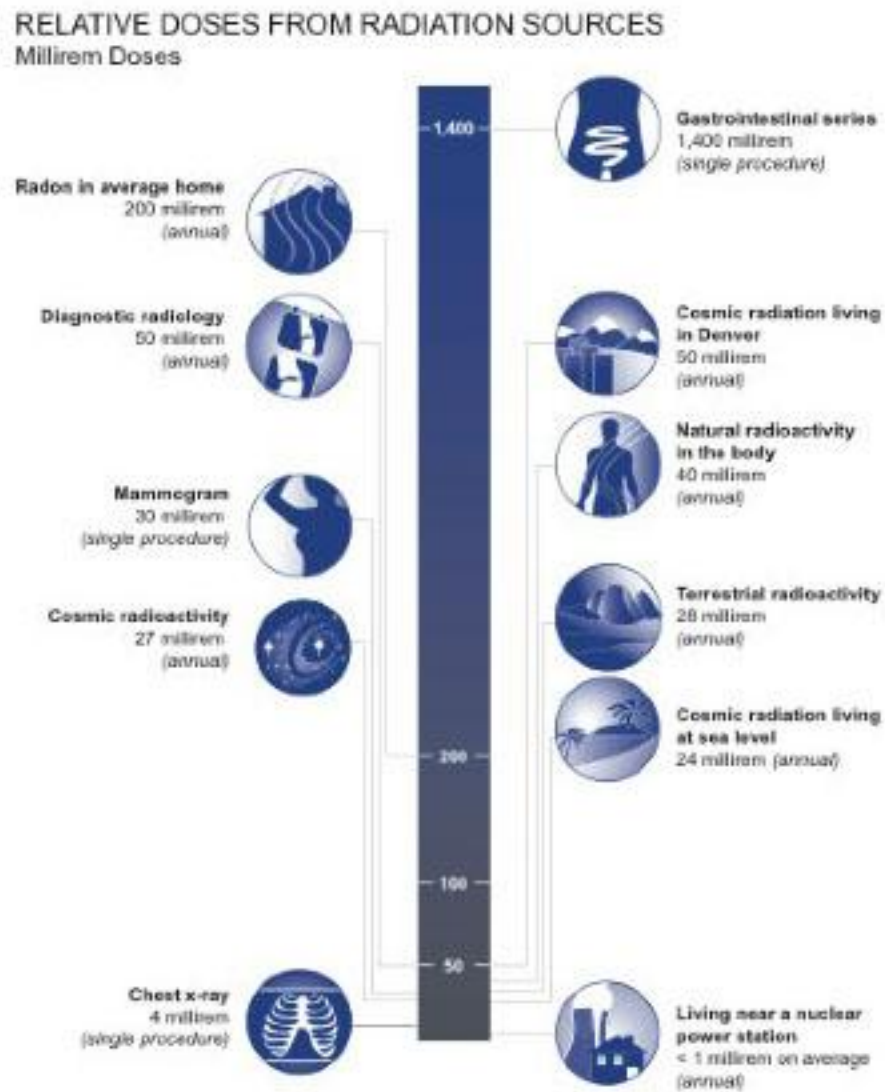


http://home.rica.net/deecee/images/scan.jpg



- **Natural sources (81%)** include radon (55%), external (cosmic, terrestrial), and internal (K-40, C-14, etc.)
- **Man-made sources (19%)** include medical (diagnostic x-rays- 11%, nuclear medicine- 4%), consumer products, and other (fallout, power plants, air travel, occupational, etc.)

http://www.doh.wa.gov/ehp/rp/factsheets/factsheets-htm/fs10bkvsman.htm
NCRP Report No. 93
www.epa.gov/rpdweb00/docs/402-f-06-061.pdf



www.epa.gov/rpdweb00/docs/402-k-07-006.pdf

Radiation Dose Comparisons

Source	Dose (mrem)
Chest X-ray	10
5-hour plane flight	3
Live within 50 miles of coal-fired power plant for 1 year	.03
Live within 50 miles of a nuclear plant for 1 year	.009
US Average Annual Whole Body Radiation Dose	360

Chemistry in Context, Chapter 7
http://www.who.int/ionizing_radiation/env/cosmic/en/index1.html

Effect of Smoking on Radiation Dose

- Average annual whole body radiation dose is about 360 mrem
- If you smoke, add about 280 mrem (source does not specify # packs per day smoked)
- Tobacco contains Pb-210, which decays to Po-210.
- Pb-210 deposits in bones.
- Po-210 in liver, spleen, and kidneys

http://www.doh.wa.gov/ehp/rp/factsheets/factsheets-htm/fs10bkvsman.htm

http://web.princeton.edu/sites/ehs/osradtraining/backgroundradiation/background.htm

Long Term Effects of LOW Radiation Doses

- Long term effects of low doses of radiation still unknown
- Two radiation dose-response models
  - Linear non-threshold
    - More conservative model used by EPA and other federal agencies
    - Radiation harmful at all doses, even low ones
  - Threshold
    - Assumes cellular repair at low doses
    - Assumes low doses are safe

Nuclear Waste

- Challenges in the storage of spent reactor fuel

- **Waste**
    - Contains radioactive fission products
    - Can be hazardous for thousands of years
        - Half-life of Pu-239 is 24,110 years
    - Fission products, if released, can build up in the body and be fatal

Types of Nuclear Waste

- **High-level radioactive waste (HLW)**
  - Long half-lives of radioisotopes
  - Requires permanent isolation
  - “Mixed waste” because hazardous chemicals & radioactivity
  - National risk because the waste could be extracted and used to make nuclear weapons
  - From nuclear power plants
    - Spent Nuclear Fuel (SNF): radioactive material remaining in fuel rods after it’s used to generate power in nuclear reactor
      - Contains Pu-239

Types of Nuclear Waste

- **Low-level radioactive waste (LLW)**
  - Waste with smaller amounts of radioactive materials
  - No spent nuclear fuel
  - Includes contaminated lab clothing, gloves, and tools (radioactivity levels are low)

- **90% of nuclear waste is LLW not HLW**

Options for Nuclear Waste

- **Almost all nuclear waste is stored where it was generated**
  - sites are not intended for long-term storage

- **Outside the US, countries reprocess their SNF using breeder reactors**
  - Nuclear reactor that can produce more fissionable material than it consumes (recovering Pu-239 from U-235)

Options for Nuclear Waste

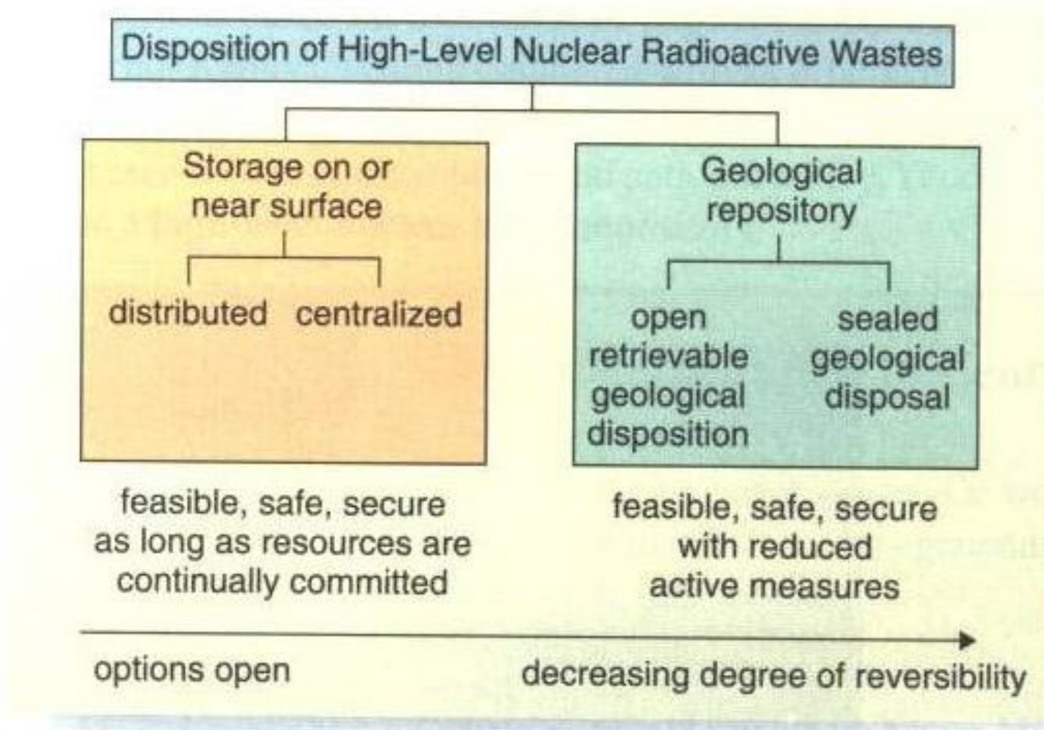


Figure 7.23

Methods of high-level nuclear waste deposition.

- Vitrification: spent fuel elements or mixed waste are encased in ceramic or glass and put in long-term underground repository
- Possible site for repository: Yucca Mountains in NV.

Risks & Benefits of Nuclear Power

Table 7.6 Risks from Coal and Nuclear-Powered Electricity Generators

Hazard Type	Coal	Nuclear
Routine occupational hazards	Coal mining accidents and black lung disease constitute a uniquely high risk.	Risks from sources not involving radioactivity dominate.
Deaths*	2.7	0.3–0.6
Routine population hazards	Air pollution produces a relatively high, though uncertain, risk of respiratory injury.	Low-level radioactive emissions are more benign than the corresponding risks from coal.
Deaths*	1.2–50	0.03
Catastrophic hazards (excluding occupational)	Acute air pollution episodes with hundreds of deaths are not uncommon. Long-term climatic change, induced by CO_2, is conceivable.	Risks of reactor accidents are small compared with other quantified catastrophic risks.
Deaths*	0.5	0.04
General environmental degradation	Strip mining and acid runoff; acid rainfall with possible effect on nitrogen cycle.	Long-term contamination with radioactivity.

*Deaths are the number expected per year for a 1000-megawatt power plant. In all cases, 6000 person-days lost are assumed to equal one death.

Source: Modified from *Perilous Progress: Managing the Hazards of Technology*, by Robert W. Kates, Ed., 1985, Westview Press, Boulder, Colorado.

Risks associated with energy produced by nuclear power are less than from coal-burning plants.

Risks & Benefits of Nuclear Power

Coal-fired electric plants (one 1000 MW plant)	Nuclear plants (one 1000 MW plant)
• releases 4.5 million tons of CO_2	• produces 70 ft^3 of HLW/year
• produces 3.5 million ft^3 of waste ash/year	• no CO_2 released
• releases 300 tons of SO_2 and ~100 tons NO_x/day	• no acidic oxides of sulfur and nitrogen released
• releases Uranium and Thorium from coal	

Future of Nuclear Power

- A new growth phase of nuclear power in near future
  - 2005 Energy Bill: tax incentives for electricity produced by new nuclear plants
  - New reactor designs
  - Expansion in other countries
  - New fuel technology – mixed oxide (MOX)
    - Pu from nuclear warheads and SNF can be made into MOX

- Still a debate if risks of nuclear power outweigh those of global warming, acid rain, and nuclear terrorism.
  - Both our need for energy and the mass of radioactive waste are issues to balance.