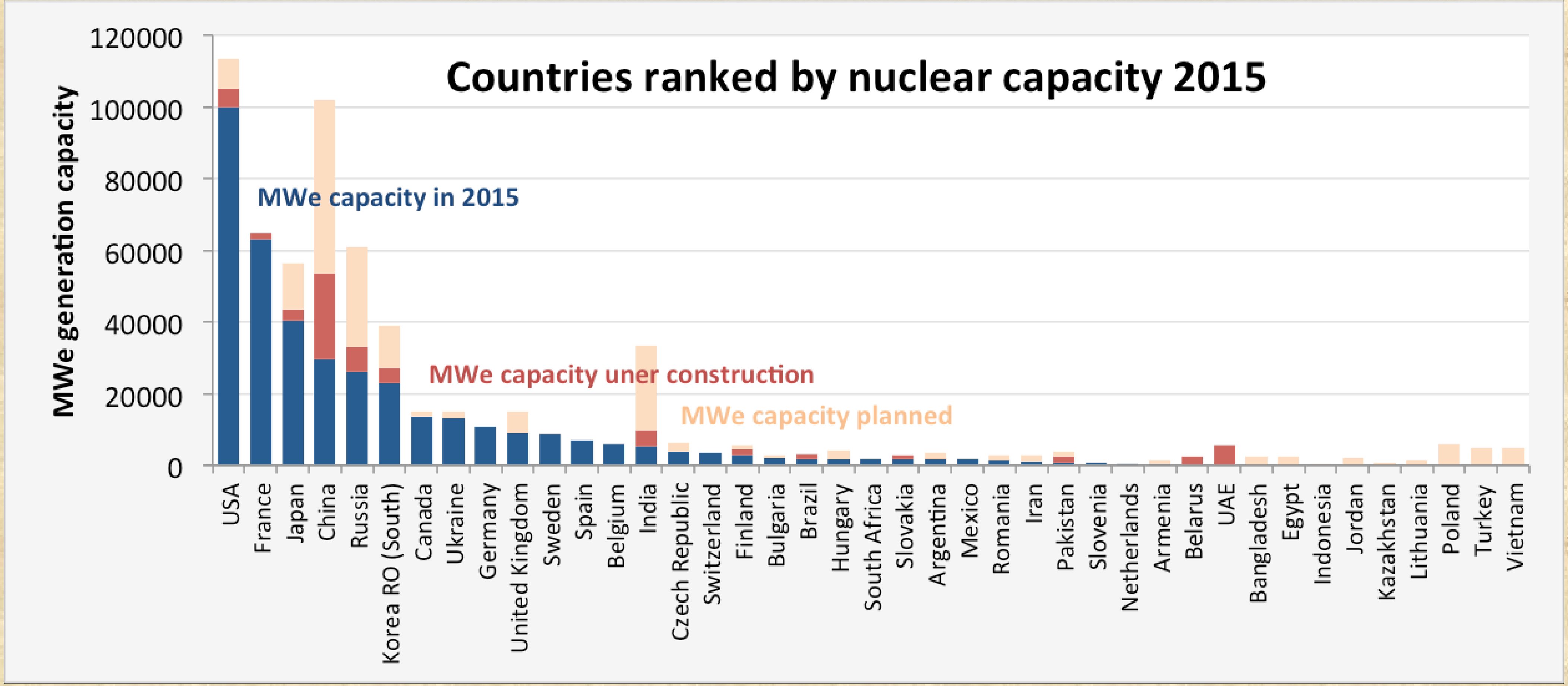
Nuclear-fueled Power Plants

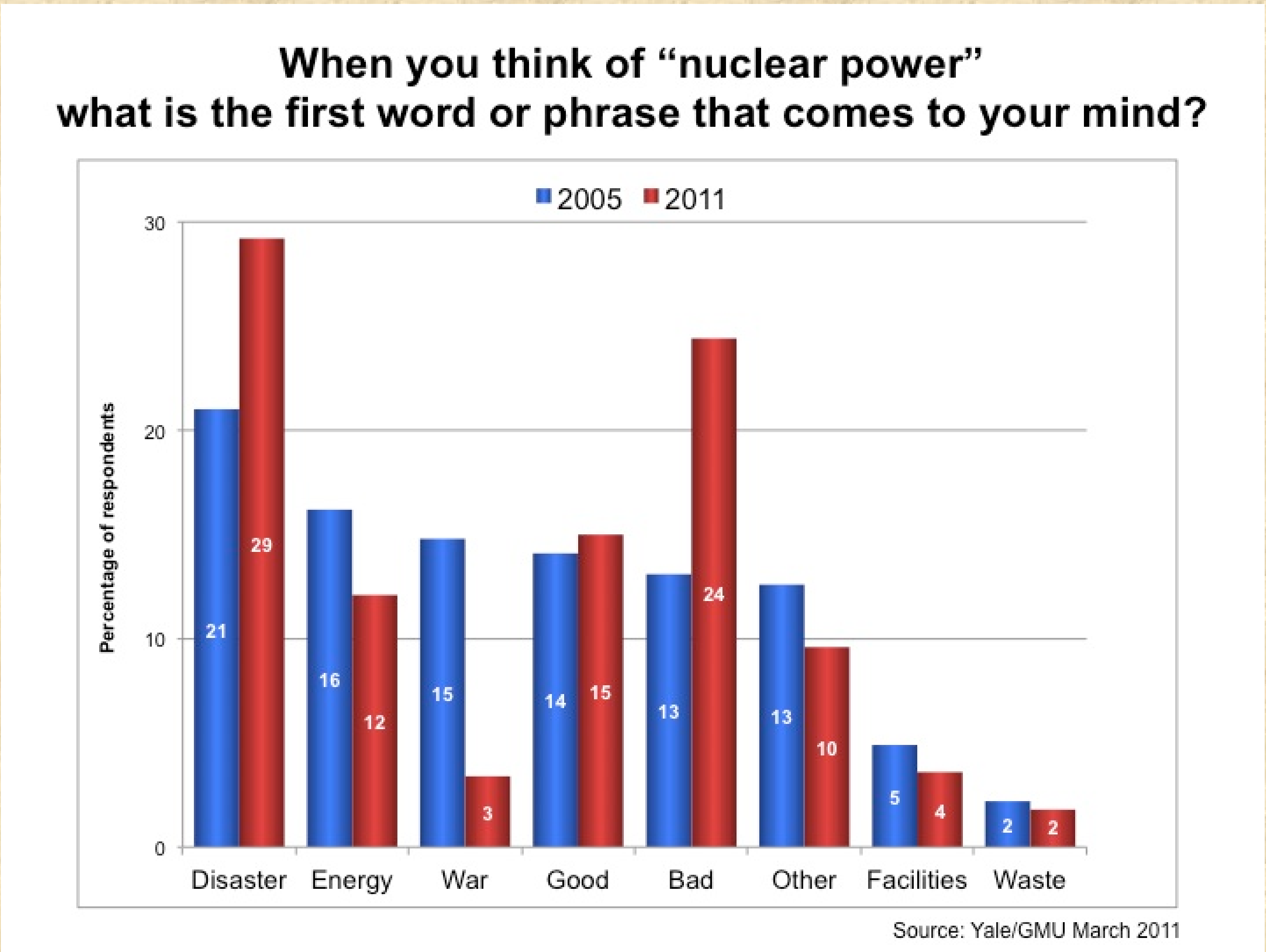


Countries ranked by nuclear capacity 2015
MWe generation capacity
120000
100000
80000
60000
40000
20000
0
MWe capacity in 2015
MWe capacity uner construction
MWe capacity planned
USA
France
Japan
China
Russia
Korea RO (South)
Canada
Ukraine
Germany
United Kingdom
Sweden
Spain
Belgium
India
Czech Republic
Switzerland
Finland
Bulgaria
Brazil
Hungary
South Africa
Slovakia
Argentina
Mexico
Romania
Iran
Pakistan
Slovenia
Netherlands
Armenia
Belarus
UAE
Bangladesh
Egypt
Indonesia
Jordan
Kazakhstan
Lithuania
Poland
Turkey
Vietnam

Public Perception of Nuclear Power

Fukushima nuclear accident

March 11, 2011



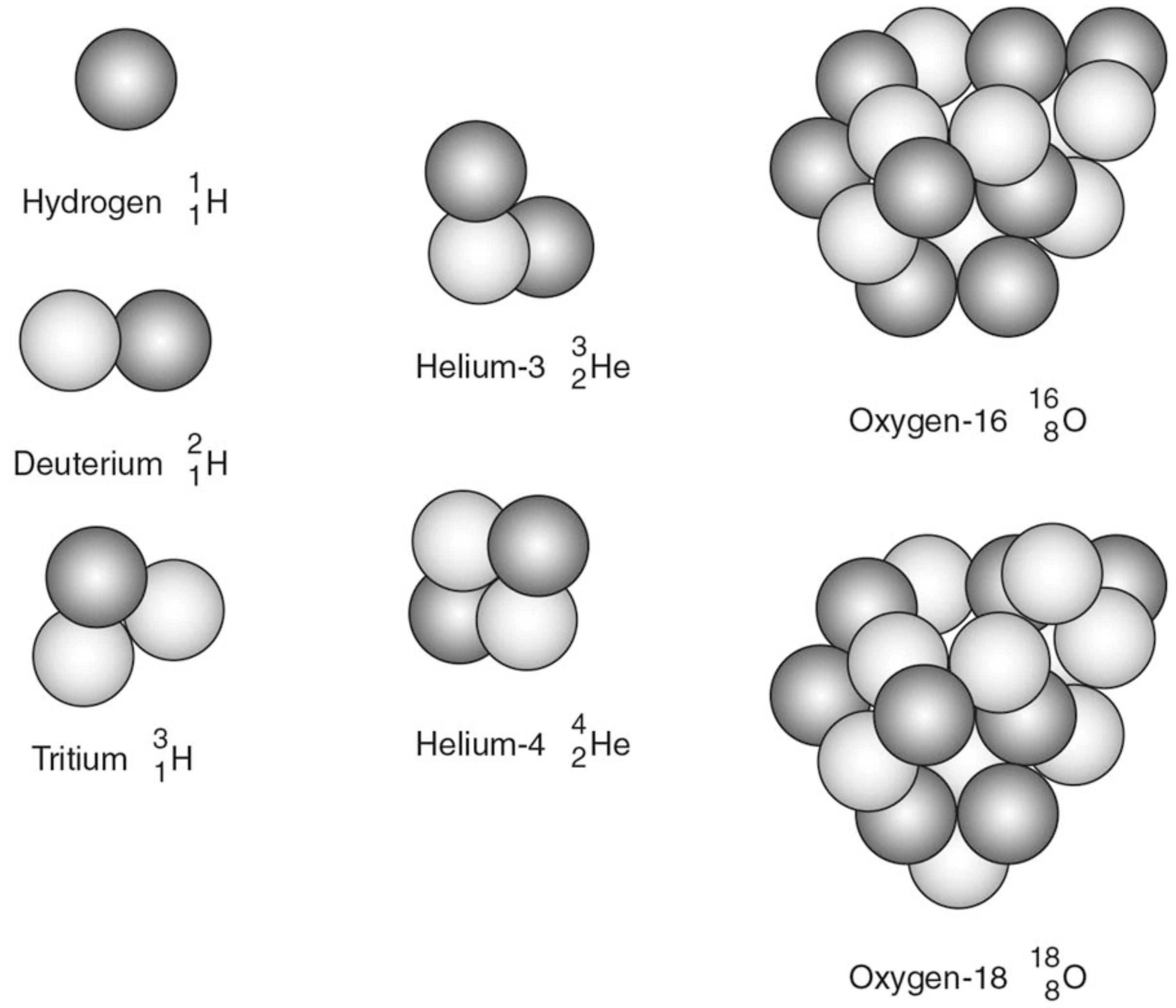
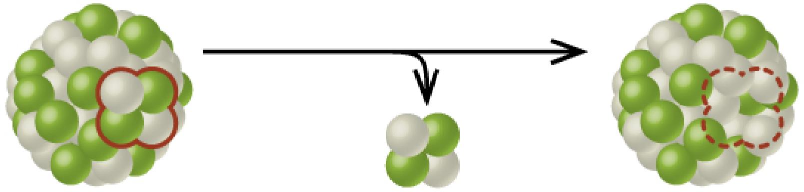
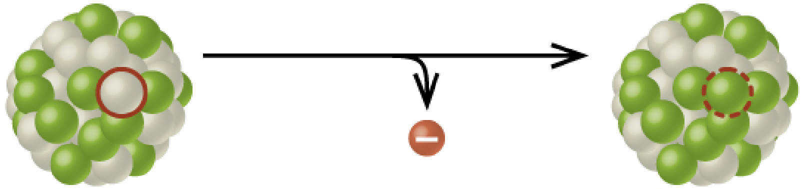
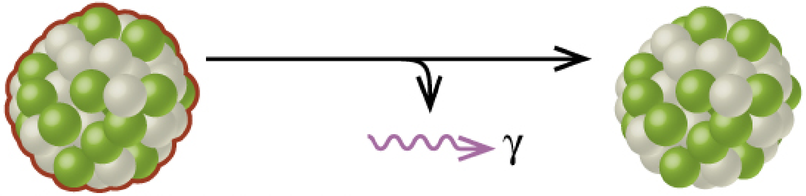
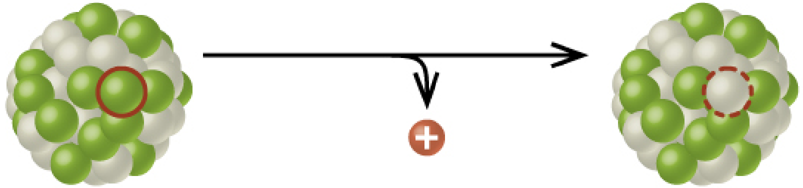
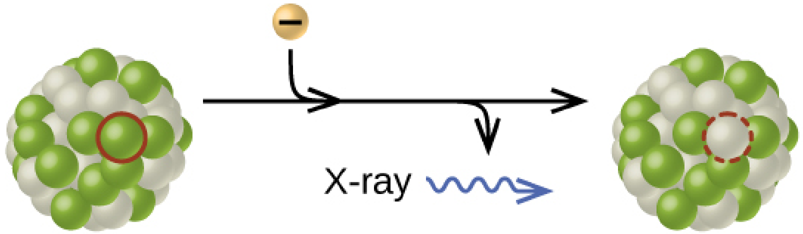


FIGURE 7.4

Isotopes of hydrogen, helium, and oxygen. Each isotope is designated by its element symbol (H, He, O, etc.), a preceding subscript giving the number of protons (darker spheres), and a preceding superscript giving the total number of nucleons. Only the hydrogen isotopes have their own names.

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}X$ ${}^{4}_{2}He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}X$ ${}^{0}_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}X$ ${}^{0}_{0}\gamma + {}^{A}_{Z}Y$	 γ Excited nuclear state	A: unchanged Z: unchanged
Positron emission	${}^{A}_{Z}X$ ${}^{0}_{+1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	${}^{A}_{Z}X$ ${}^{0}_{-1}e + {}^{A}_{Y-1}Y$	 X-ray	A: unchanged Z: decrease by 1

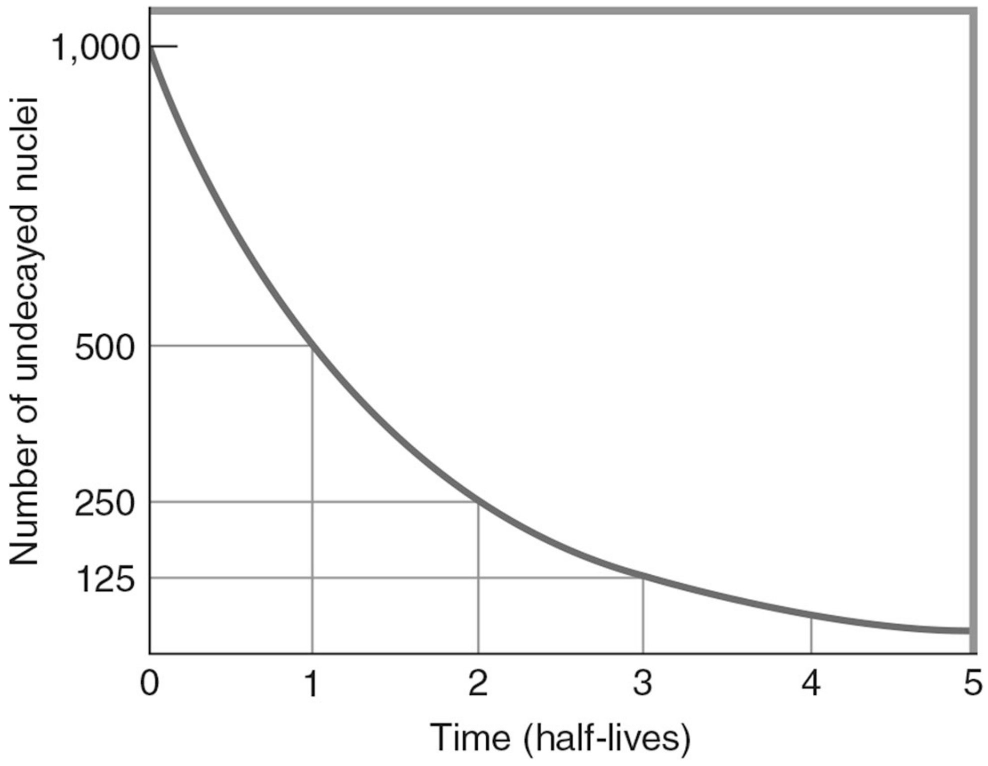


FIGURE 7.5

Decay of a radioactive sample initially containing 1,000 nuclei.

TABLE 7.1 | SOME IMPORTANT RADIOACTIVE ISOTOPES

Isotope	Half-life (approximate)	Significance
Carbon-14	5,730 years	Formed by cosmic rays; used in radiocarbon dating for objects up to 60,000 years old.
Iodine-131	8 days	Product of nuclear fission; released into the environment from nuclear weapons tests and reactor accidents. Lodges in the thyroid gland where it can cause cancer.
Potassium-40	1.25 billion years	Isotope constituting 0.012% of natural potassium and the dominant radiation source within the human body. Used for dating ancient rocks and to establish Earth's age.
Plutonium-239	24,000 years	Isotope produced in nuclear reactors from U-238. Can be used in nuclear weapons.
Radon-222	3.8 days	Gas formed by the decay of natural radium in rocks and soils, ultimately from uranium-238. Can be a health hazard when it seeps into buildings.
Cesium-137	30 years	Product of nuclear fission responsible for widespread land contamination at Chernobyl and Fukushima. Soluble in water; mimics potassium in the body.
Strontium-90	29 years	Product of nuclear fission that chemically mimics calcium, so it's absorbed into bone. Still at measurable levels in the environment following above-ground nuclear weapons tests of the mid-twentieth century.
Tritium (hydrogen-3)	12 years	Produced in nuclear reactors. Radioactive hydrogen isotope used to "tag" water and other molecules for biological studies. Used to boost the explosive yield of fission weapons.
Uranium-235	704 million years	Fissile isotope constituting 0.7% of natural uranium; fuel for nuclear reactors and some nuclear weapons.
Uranium-238	4.5 billion years	Dominant uranium isotope (99.3%). Cannot sustain a chain reaction, but boosts the yield of thermonuclear weapons. Depleted uranium—after removal of U-235—is used for armor-penetrating conventional weapons because of its high density.

Radioactivity – alpha and beta particles, gamma rays

Alpha – relatively heavy particle, penetration depth ~ 1mm

Beta particle – light particle (electron), penetration depth several cm

Gamma ray – high energy EM radiation, penetration depth measured in meters

Decay rate and half-life

$N = N_O \exp(-kt)$ and $t_{1/2} = \ln 2/k$

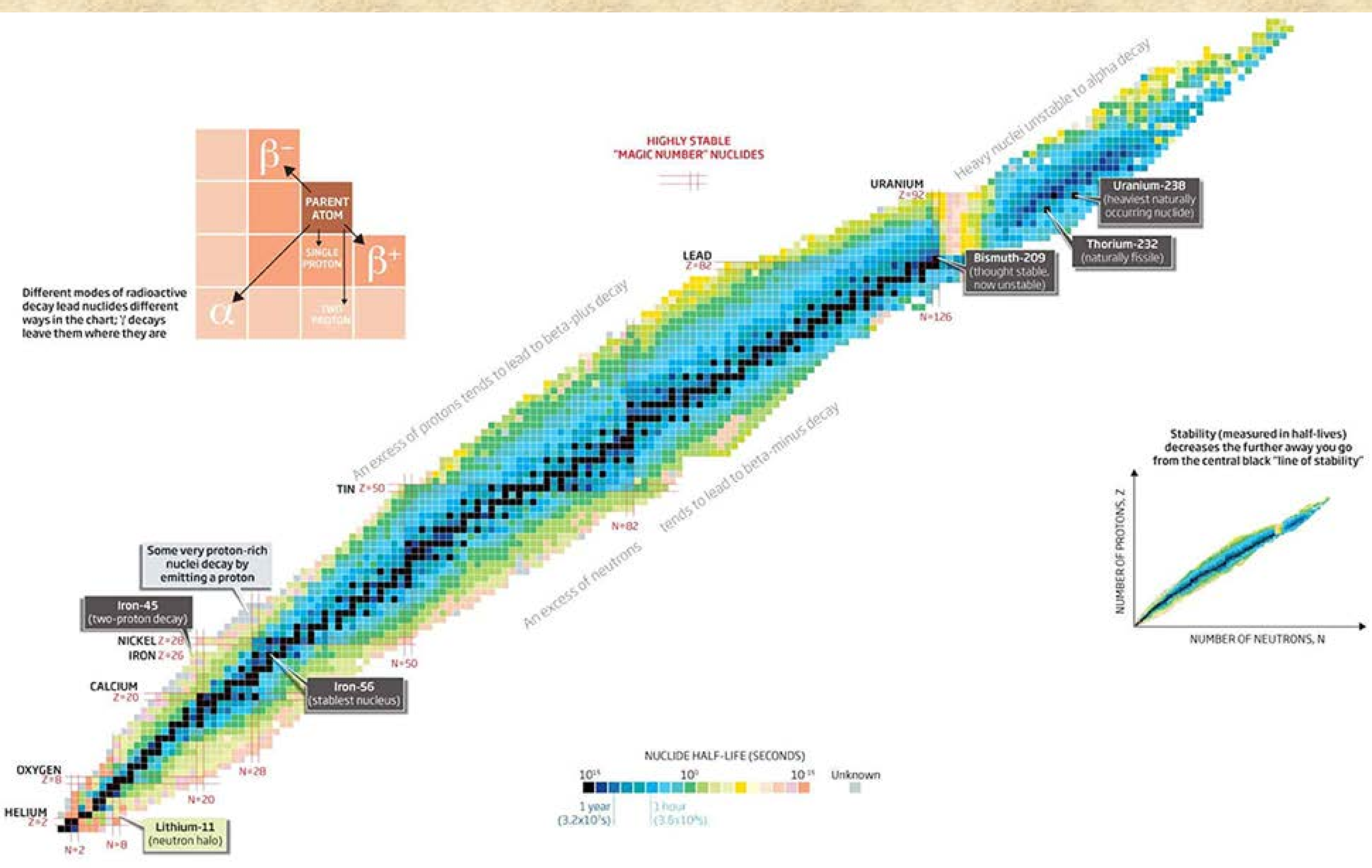
Measuring radioactivity

1 Ci = 3.7(E10) Bq, where Bq = 1 decay/second

1 Gy = 1 J of absorbed energy per Kg, also 1 rad = 0.001 Gy

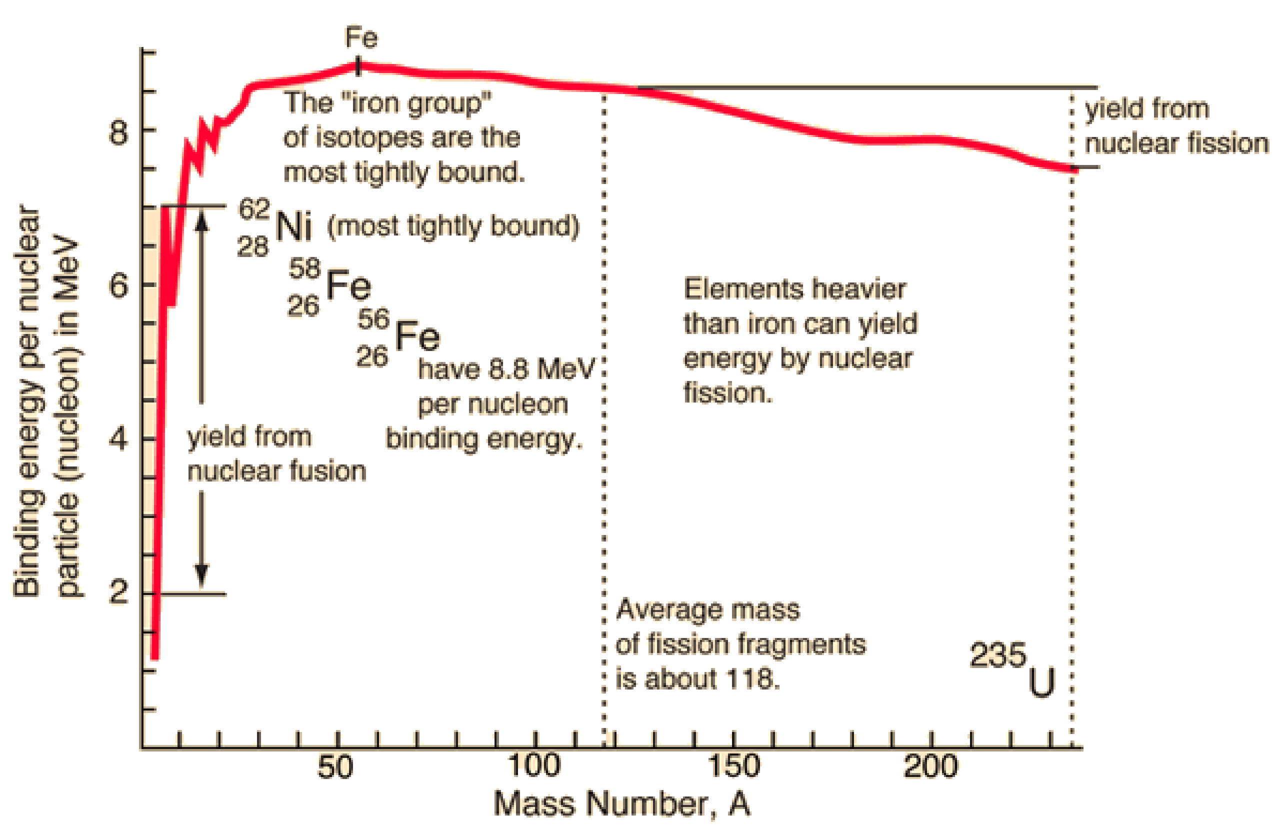
Seivert (Sv) is used to measure the dose equivalent which takes into account the quality (Q) of the absorbed radiation. Q = 1 for X-rays, γ-rays, and β particles, 10 for neutrons, and 20 for α particles.

1 rem (roentgen equivalent man) = 0.01 Sv and 1 millirem = 1E-5 Sv



β−
PARENT ATOM
SINGLE PROTON
β+
α
TWO PROTON
Different modes of radioactive decay lead nuclides different ways in the chart; γ decays leave them where they are
HIGHLY STABLE "MAGIC NUMBER" NUCLIDES
Heavy nuclei unstable to alpha decay
URANIUM Z=92
Uranium-238 (heaviest naturally occurring nuclide)
Thorium-232 (naturally fissile)
LEAD Z=82
Bismuth-209 (thought stable, now unstable)
N=126
An excess of protons tends to lead to beta-plus decay
An excess of neutrons tends to lead to beta-minus decay
TIN Z=50
N=82
Some very proton-rich nuclei decay by emitting a proton
Iron-45 (two-proton decay)
NICKEL Z=28
IRON Z=26
N=50
CALCIUM Z=20
Iron-56 (stablest nucleus)
OXYGEN Z=8
N=28
N=20
HELIUM Z=2
Lithium-11 (neutron halo)
N=2
N=8
NUCLIDE HALF-LIFE (SECONDS)
10^{15}
10^{0}
10^{-15}
Unknown
1 year (3.2×10^{7}s)
1 hour (3.6×10^{3}s)
Stability (measured in half-lives) decreases the further away you go from the central black "line of stability"
NUMBER OF PROTONS, Z
NUMBER OF NEUTRONS, N

Binding energy per nucleon of the isotopes



$^{235}U + {}^{1}n \rightarrow {}_{144}Ba + {}^{89}Kr + 3{}^{1}n + 177$ MeV (1 MeV = 1.6E-13 J)

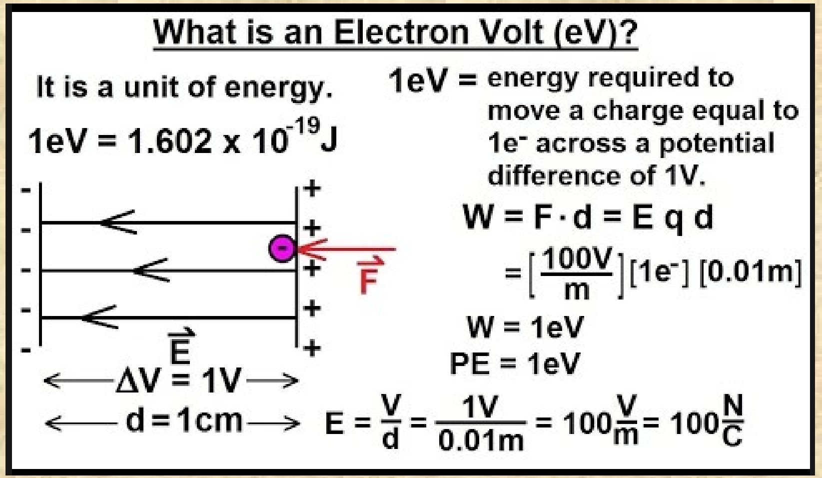
$^{238}U + {}^{1}n \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \beta \rightarrow {}^{239}Pu + \beta$

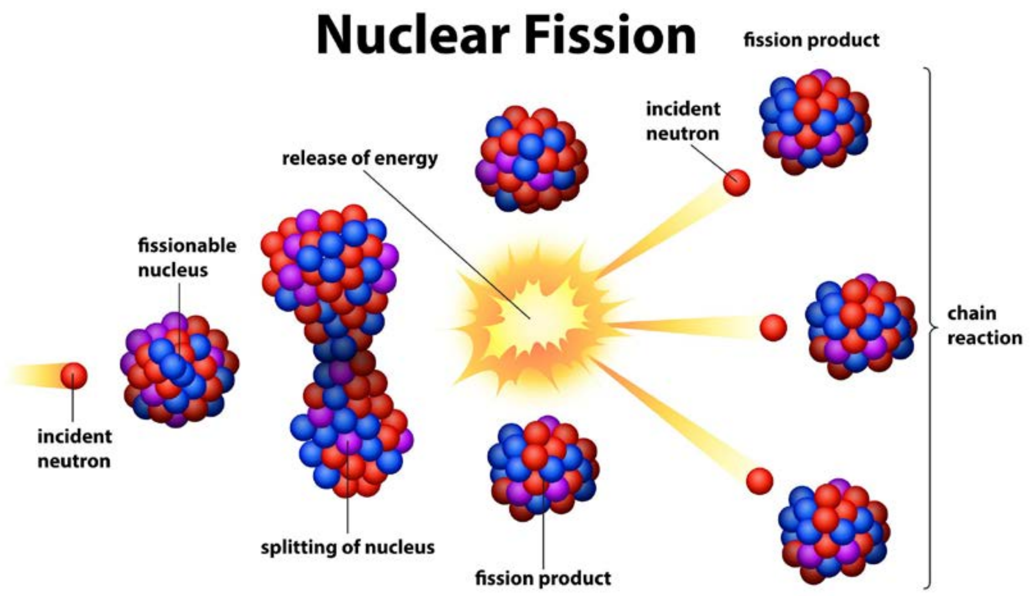
Fissile nuclei (split after absorbing thermal neutron) = ^{233}U, ^{235}U, ^{239}Pu

Fertile nuclei (absorb fast neutron and convert into fissile nuclei) = ^{232}Th, ^{238}U

Nuclear fission reactors

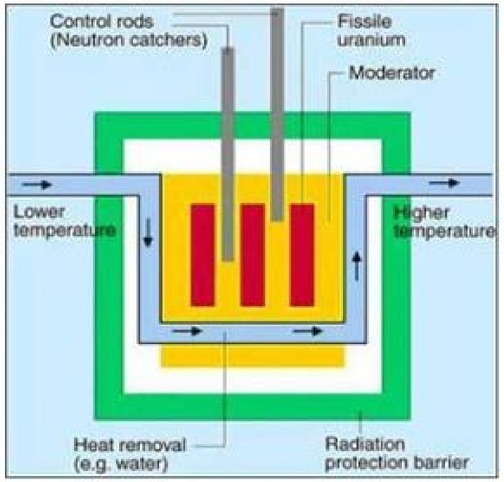
- Natural U is 99.3% U-238 and 0.7% U-235
- U-235 is the fissionable isotope
- For reactor fuel enrich U-235 to 4.0%
- The neutrons emitted during the fission event have an energy of 2.0 MeV. Lower energy neutrons (2 eV) are much more effective at inducing fission (capture cross-sections)
- A moderator is used to slow down the neutrons
- A control rod made of a neutron absorber is used to control the reaction
- Criticality is achieved when the reaction is at equilibrium



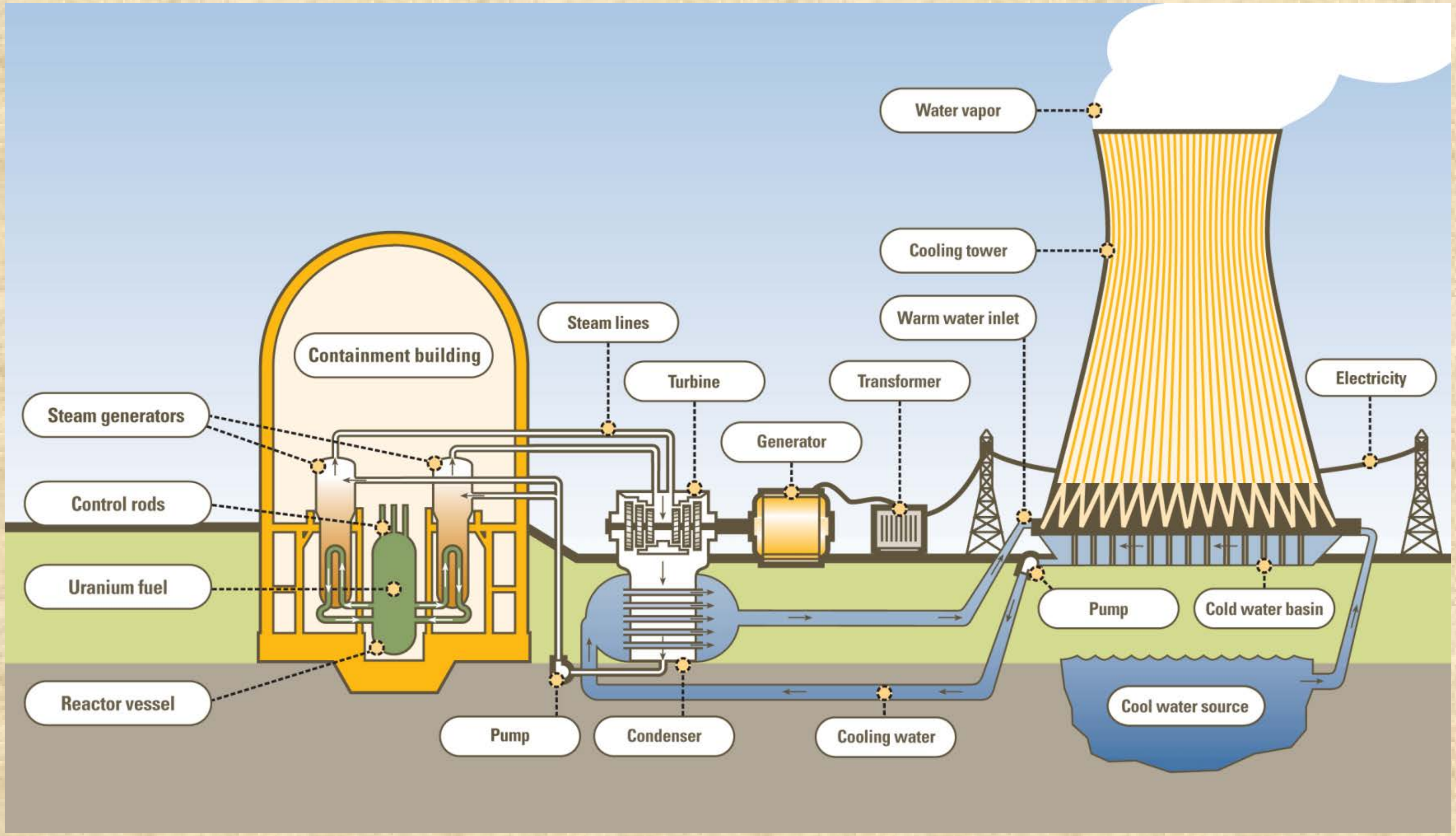


Controlling the Nuclear Reaction

- **Control rods:** Keep reaction from going too fast by absorbing some of the neutrons; often made of cadmium
- **Moderator:** slows down neutrons so that the reactor fuel (^{235}U or ^{239}Pu) can capture them; water and graphite are good moderators



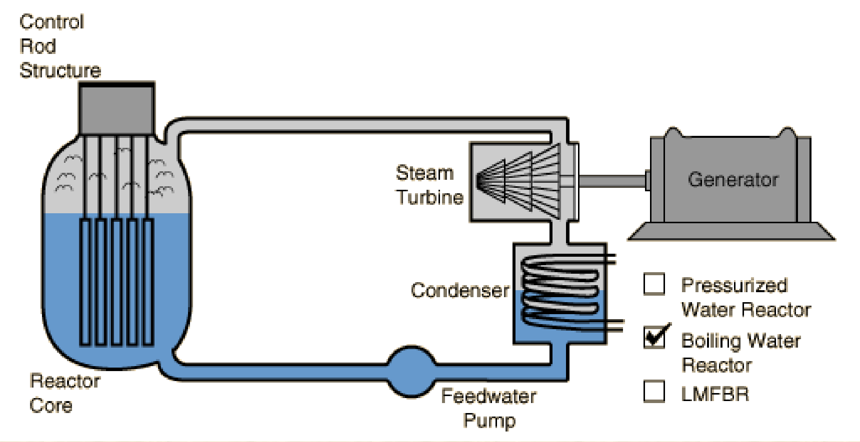
Nuclear Power Plant

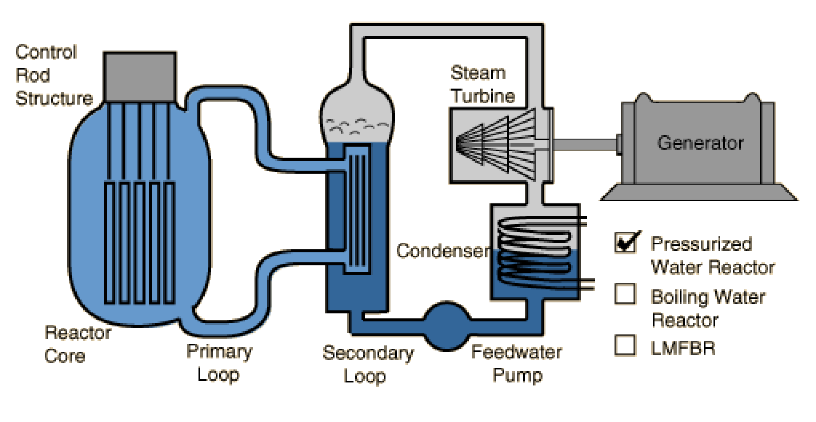


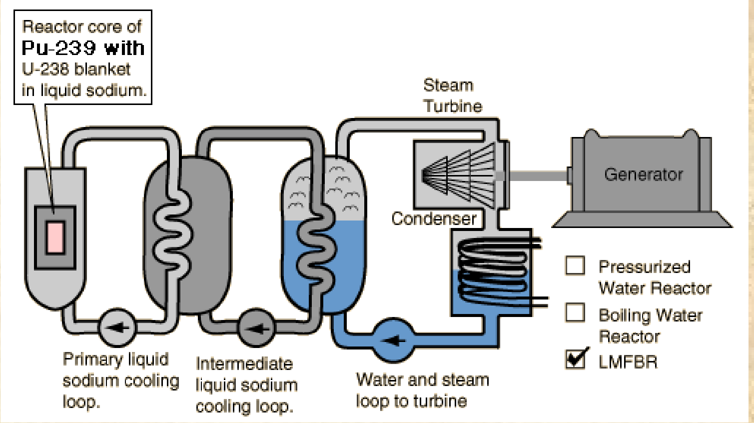
Components:

- Fuel rods (elements)
- Moderator
- Control rods
- Coolant

Types of fission reactors

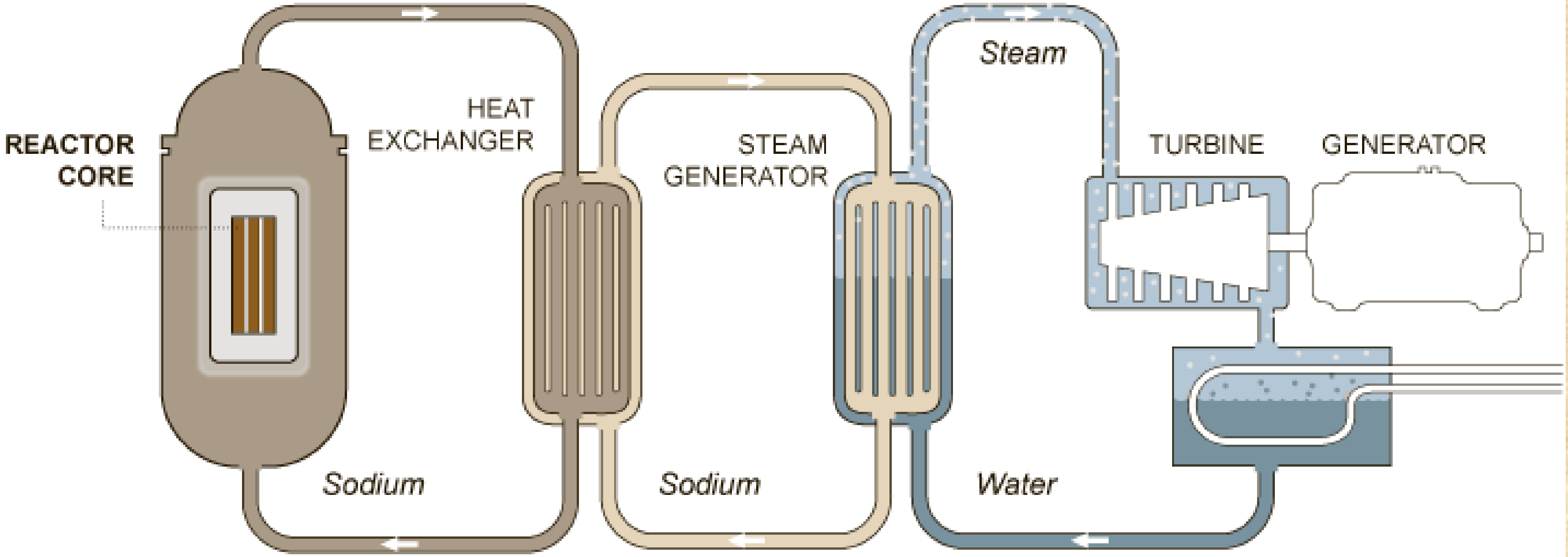






1 The core of a breeder reactor contains fissile uranium and plutonium, atoms that split easily and release energy as heat and radiation. Neutrons released during this reaction are absorbed by a "blanket" of fertile uranium surrounding the core. Fertile uranium, harder to split than fissile uranium, turns into plutonium when it absorbs neutrons.

Unlike conventional reactors that use water to transfer heat, a breeder uses liquid sodium. The sodium does not slow the neutrons like water, and high-energy neutrons are more readily absorbed by the fertile uranium to create plutonium.



2 The sodium surrounding the core flows through a heat exchanger, a cluster of thin-walled metal tubes, and transfers its energy to a separate stream of sodium.

3 The heat then passes through a steam generator. If there is a leak and the sodium comes into contact with water or air, the sodium burns. A 1995 fire caused by a sodium leak shut down the Monju breeder reactor for 14 years.

4 The steam drives a turbine, generating electricity.

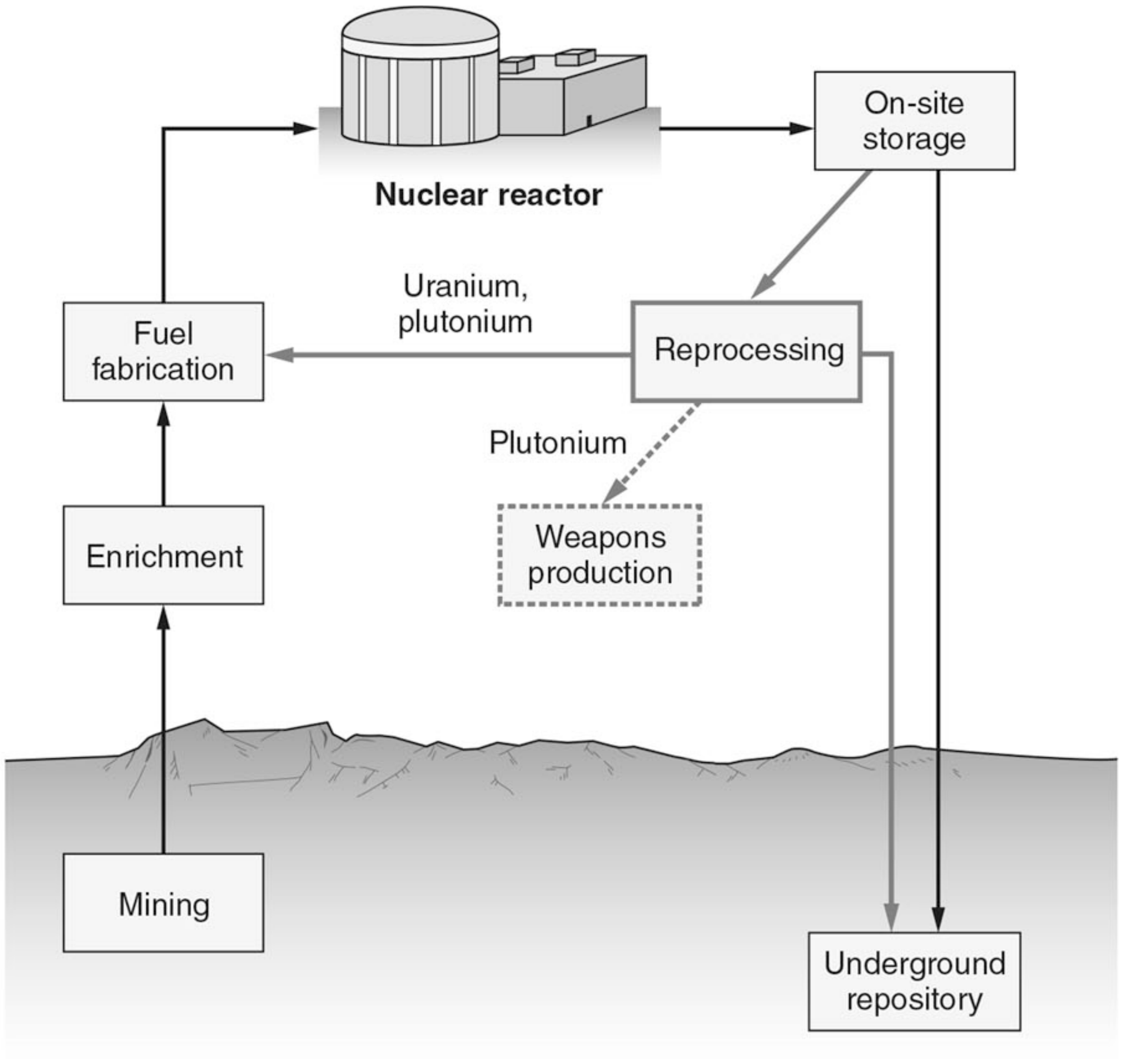


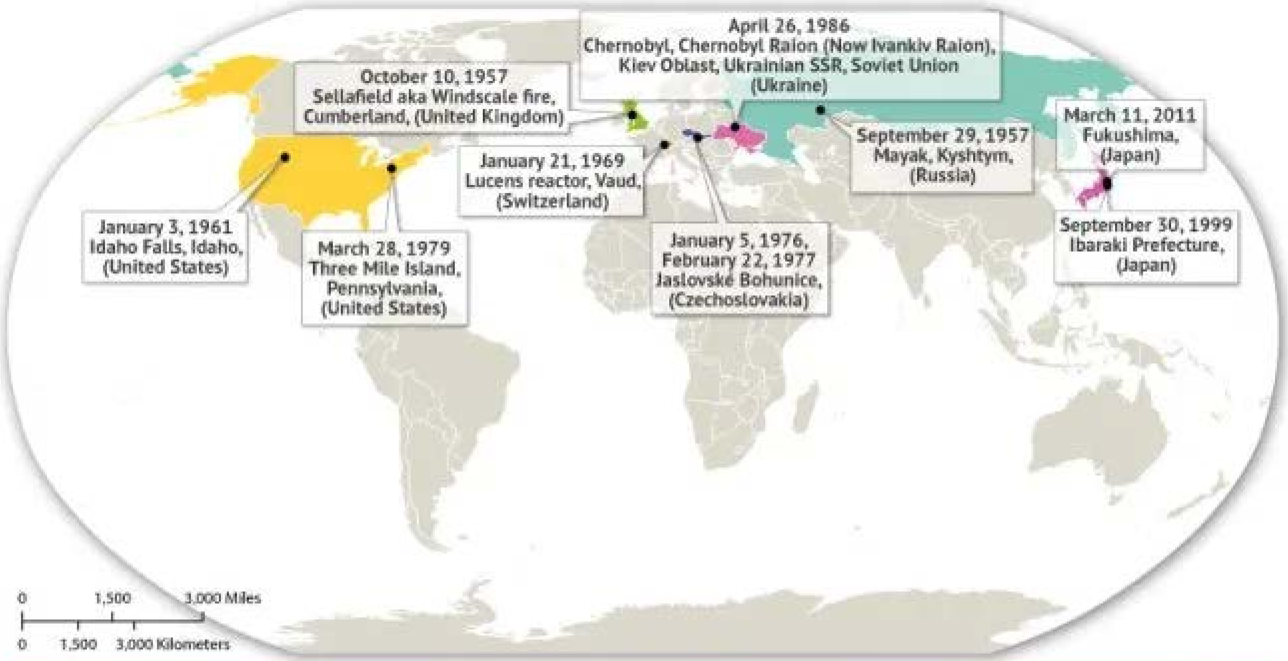
FIGURE 7.14

Nuclear fuel cycles. A once-through cycle is shown in black; additional steps in a reprocessing cycle are shown in gray. On-site storage involves pools of water for short-term storage of fresh, highly radioactive waste, followed by longer-term dry-cask storage.

TABLE 7.2 | SOME OPTIONS FOR NUCLEAR WASTE DISPOSAL

Option	Advantages	Disadvantages
Dry-cask storage	Available short-term option. Waste kept on site; no need to transport.	Most nuclear plants are near population centers and waterways.
Shallow burial (~1 km)	Relatively easy construction and access. Waste is recoverable and easily monitored.	Proximity to groundwater poses contamination risk. Subject to geological disturbance.
Sub-seabed burial	Keeps waste far from population centers.	Probably not recoverable. Requires international regulatory structure. Currently banned by treaty.
Deep-hole burial (~10 km)	Keeps waste well below groundwater.	Not recoverable. Behavior of waste at high temperature and pressure not well understood. Subject to geological disturbance.
Space disposal (dropped into Sun or stored on Moon)	Permanent removal from Earth environment.	Impractical and economically prohibitive. Risk of launch accidents.
Ice-sheet disposal	Keeps waste far from population centers.	Expensive due to remoteness and weather. Recovery difficult. Global climate change is diminishing ice sheets. Treaty bans radioactive waste from Antarctica.
Island disposal	Burial under remote islands keeps waste away from population centers.	Ocean transport poses safety issues. Possible seawater leakage into waste repository. Seismic and volcanic activity common at island sites.
Liquid-waste injection	Waste locked in porous rock below impermeable rock.	Requires processing waste to liquid form. Movement of liquid waste might result in radiation release. Liquid injection can increase seismic activity.
Transmutation	Advanced reactor designs, high-energy particle accelerators, or “fusion torches” induce nuclear reactions that render waste non-radioactive or very short-lived.	Technology not proven or available. Requires shorter-term recoverable storage option until technology is operational.

Major Nuclear Disasters Around the World



Date	Location of Accident	Dead	INES Level
March 11, 2011	Fukushima, Japan	2	7
April 26, 1986	Chernobyl, Chernobyl Raion (Now Ivankiv Raion), Kiev Oblast, Ukrainian SSR, Soviet Union	53	7
September 29, 1957	Mayak, Kyshtym, Russia	NA	6
October 10, 1957	Sellafield aka Windscale fire, Cumberland, United Kingdom	0	5
January 21, 1969	Lucens reactor, Vaud, Switzerland	0	5
March 28, 1979	Three Mile Island, Pennsylvania, United States	0	5
February 22, 1977	Jaslovské Bohunice, Czechoslovakia	0	4
January 5, 1976	Jaslovské Bohunice, Czechoslovakia	2	4
September 30, 1999	Ibaraki Prefecture, Japan	2	4
January 3, 1961	Idaho Falls, Idaho, United States	3	4

Robinson Projection

TABLE 7.3 | IMPACTS OF TYPICAL 1-GWe COAL AND NUCLEAR POWER PLANTS

Impact	Coal	Nuclear
Fuel consumption	360 tons coal per hour	30 tons uranium per year
Air pollutants	400,000 tons per year	6,000 tons per year
Carbon dioxide	1,000 tons per hour	0
Solid waste	30 tons ash per hour	20 tons high-level radioactive waste per year
Land use (includes mining)	17,000 acres	1,900 acres
Radiation release	1 MBq per minute from uranium, thorium, and their decay products, but varies with composition of coal	50 MBq per minute from tritium, carbon-14, inert gases, iodine-131
Mining deaths	1.5 per year from accidents; 4 per year from black lung disease	0.1 per year from radon-induced lung cancer
Deaths among general public	30 premature deaths per year from air pollution	0.1–10 deaths per year from radiation-induced cancer

D-T fusion reaction

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{4}_{2}He + \ ^{1}_{0}N + 2.8\ pJ$$

pJ = 10^{-12} J

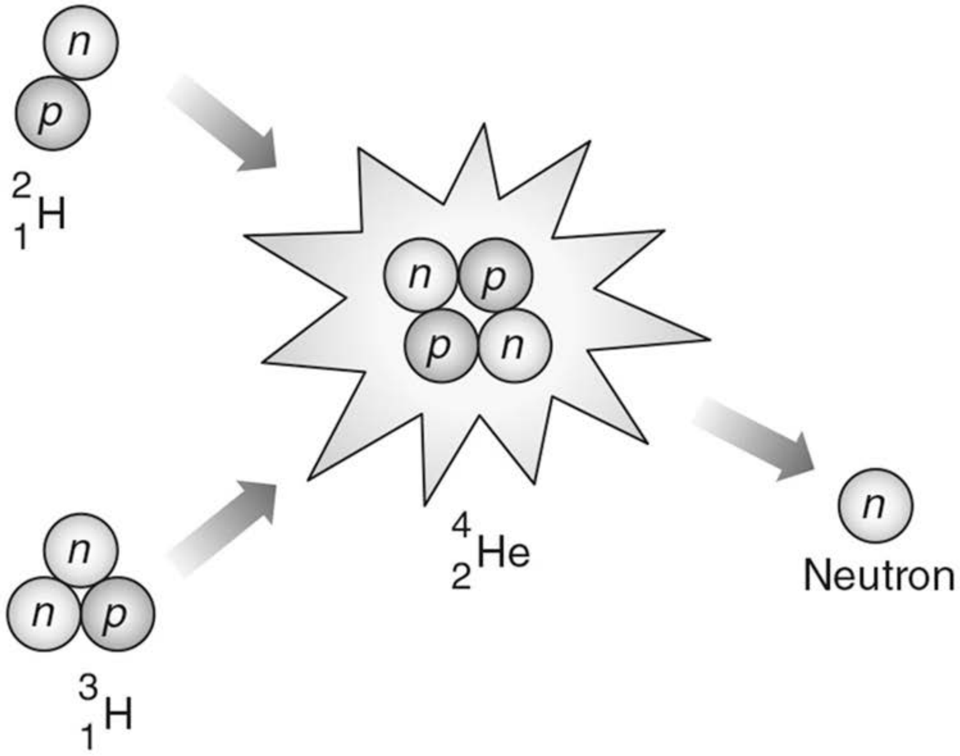
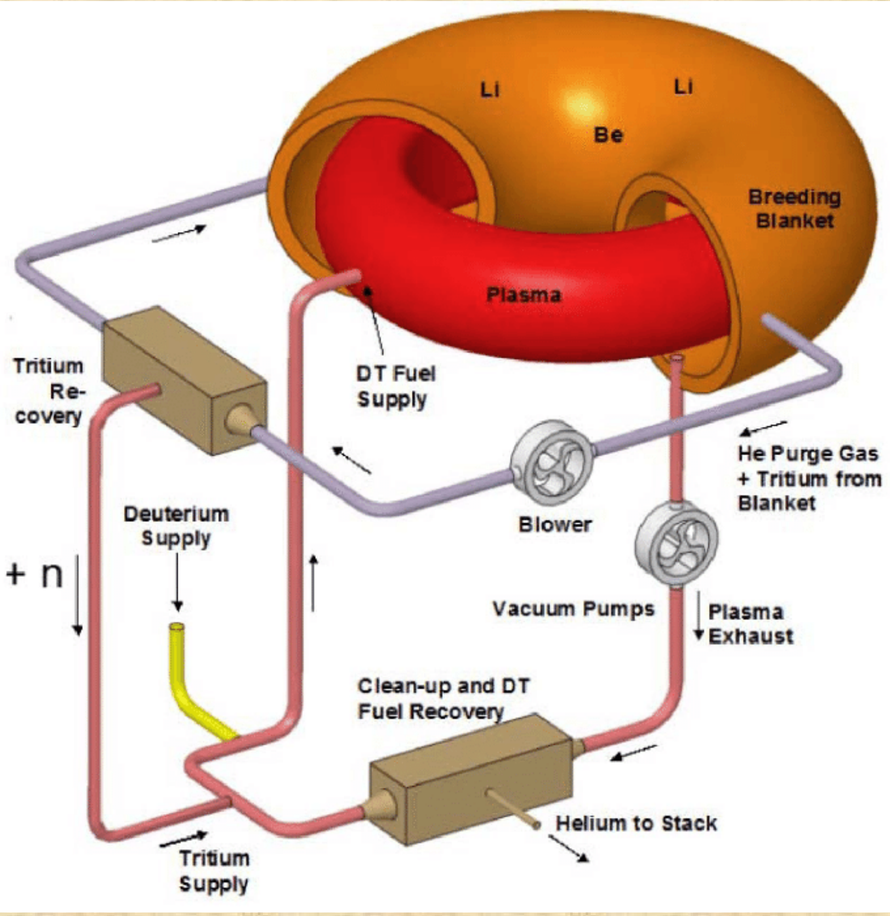


FIGURE 7.24

The deuterium-tritium (D–T) fusion reaction of Equation 7.3 produces a helium nucleus ($^{4}_{2}He$), a neutron, and energy.

Nuclear Fusion – Magnetic Confinement

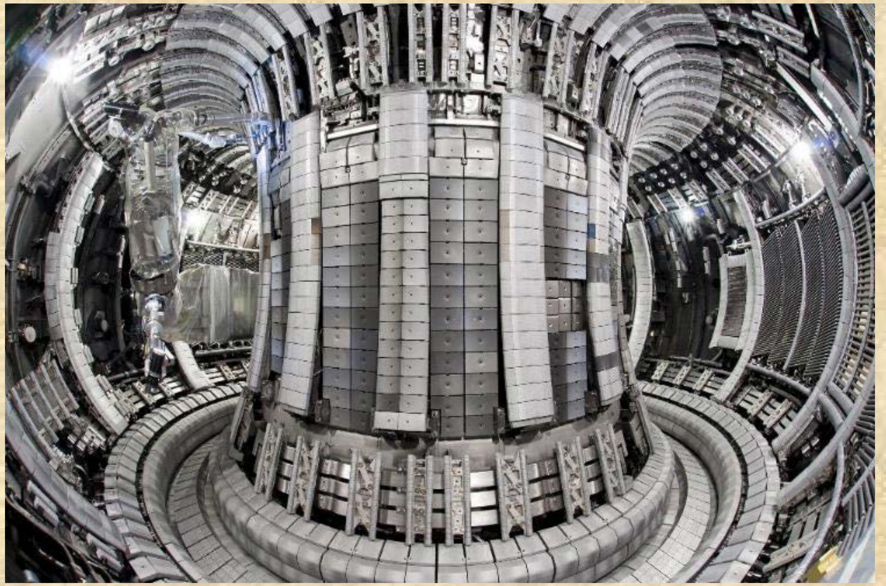


Fusion reactions require:

- High temperature (100E6 ^{o}C)
- High particle density
- Relatively small energy loss per unit time

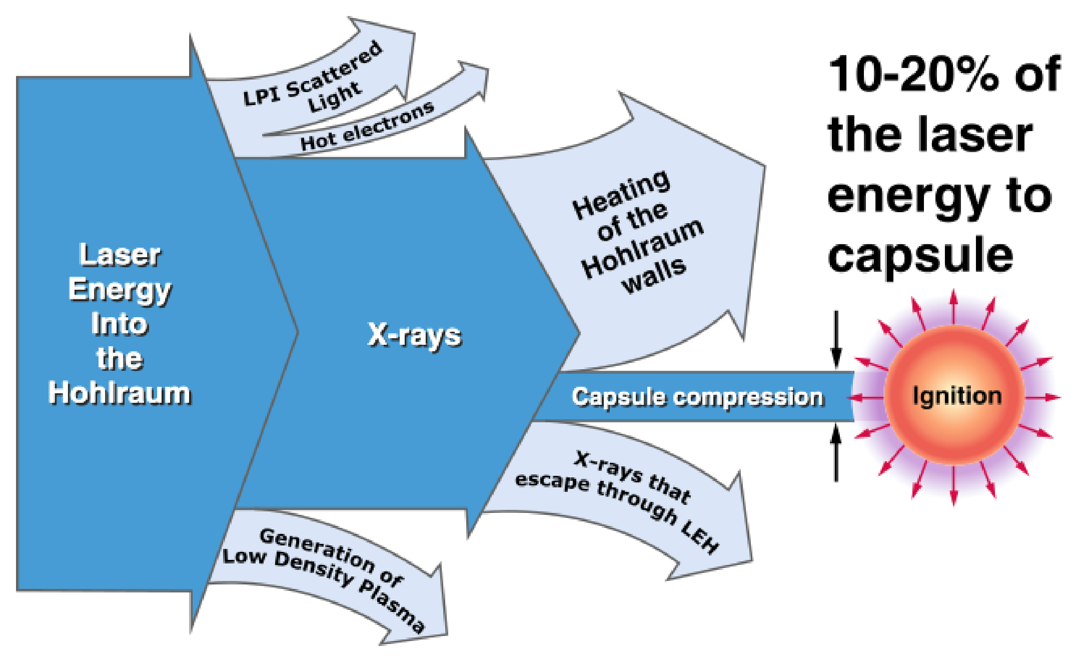
The above three items comprise the Lawson Criterion.

Fuel is deuterium and tritium



Lithium in the walls of the chamber react with fast neutrons to produce additional tritium (half-life = 12.3 years)

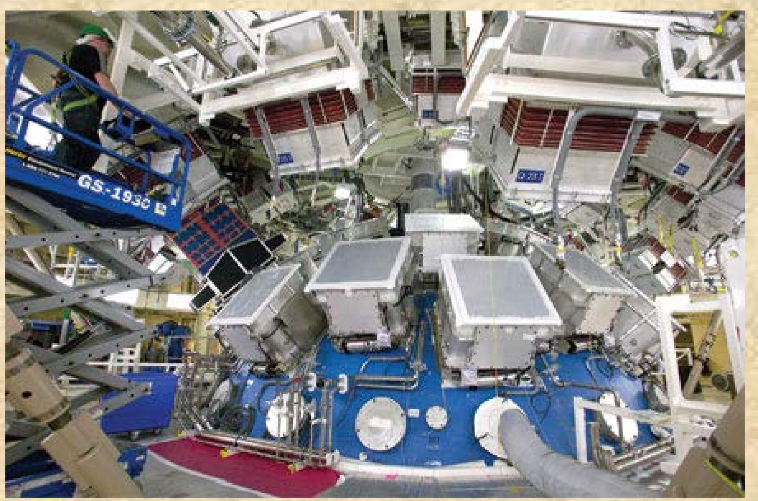
Nuclear Fusion – Laser Ignition



Fuel is a mix of deuterium and tritium. In most designs laser beams directly compress the target. In this design X-rays, generated by lasers, compress the target.

National Ignition Facility (NIF) – use lasers to initiate fusion

View of upper 1/3 of target chamber



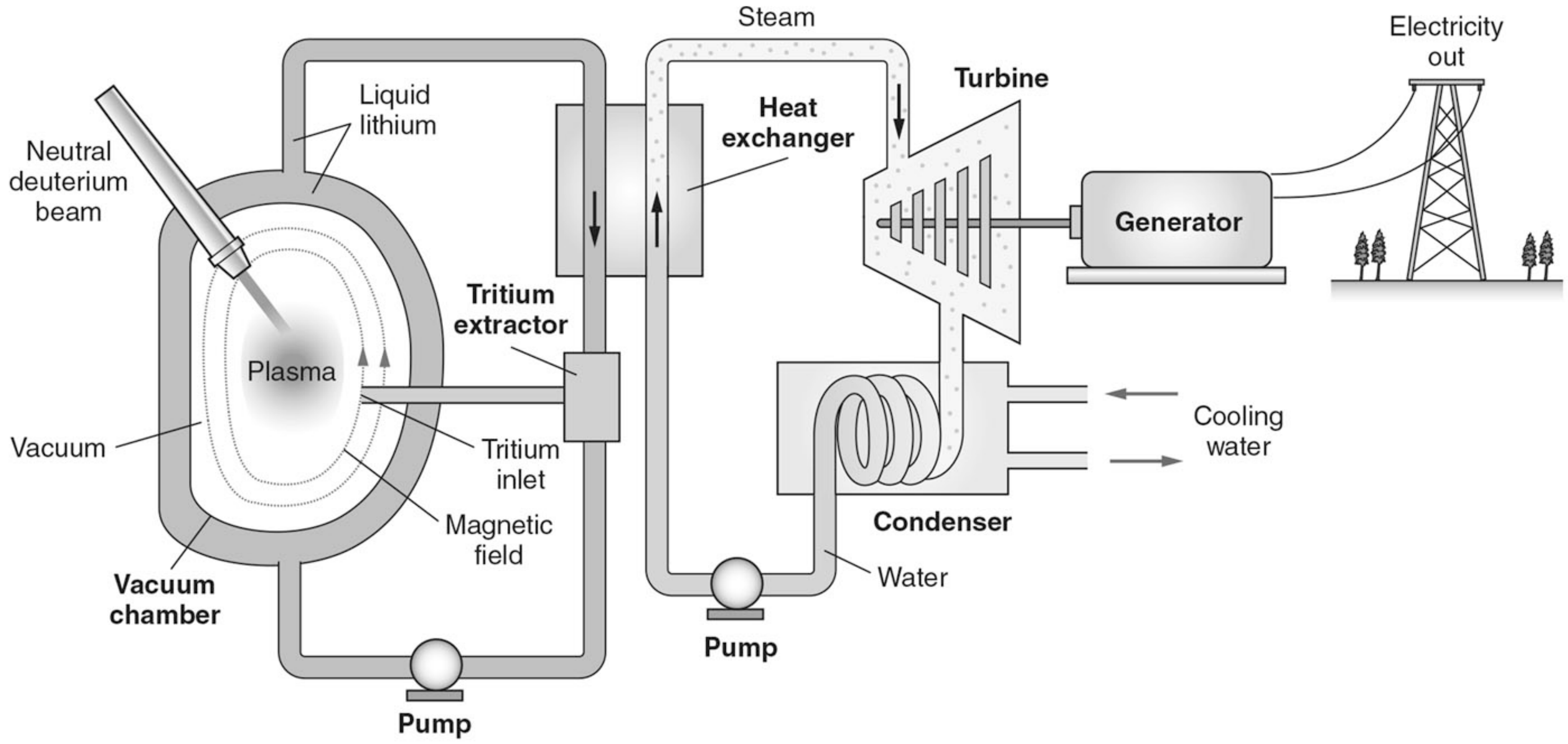


FIGURE 7.27

Possible design for a D–T fusion power plant with a tokamak fusion reactor. The D-shaped structure at left is a cross section through the tokamak. The neutral deuterium beam supplies both fuel and energy to heat the plasma.