Nuclear Fundamentals:
The science behind nuclear materials

By

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Mining Exposed 2009: Pier 21, Halifax
October 6, 2009

Overview

- A bit of history
- Atomic structure & radioactivity
- Sources of radiation
  - Natural
  - Man made
- Uranium
  - Isotopes
  - Decay chains
  - Fission & fission products
- Nuclear power reactors
- Risks of nuclear power

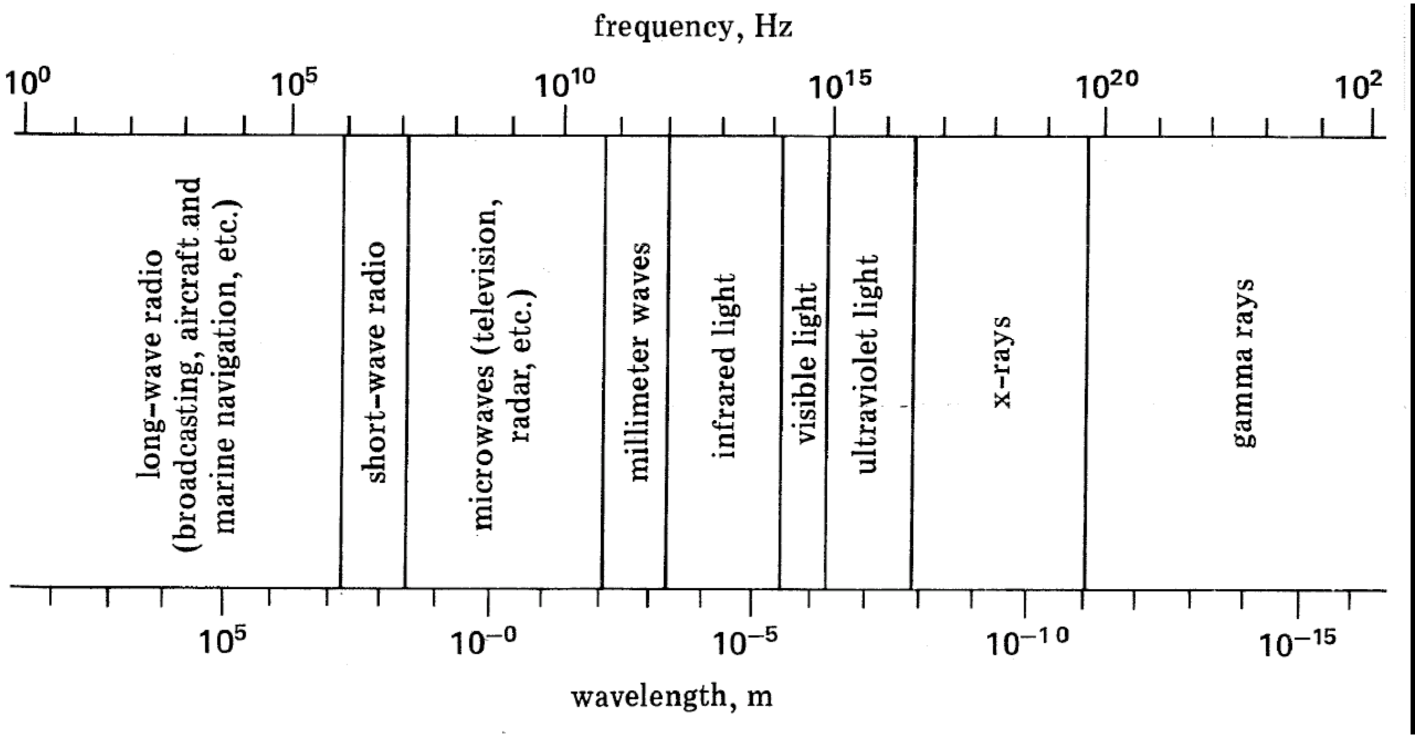
A bit of history …

- Radiation is a part of everyday life and, as such, it’s remarkable that what we call “ionizing” radiation was not discovered until just over 100 years ago.

- In the mid-to-end of the 19th century, the top scientists of the day were playing with electricity and magnetism and trying to find the bridge between them.

- In 1864, James Clark Maxwell proposed that the bridge was *electromagnetic waves* – a changing electric field has a changing magnetic field associated with it.

- Maxwell’s hypothesis was proven correct by Heinrich Hertz in 1888 and we now know the electromagnetic (EM) spectrum encompasses everything from radio waves (at the long wavelenth end) to gamma rays (short wavelength – high frequency).



- Yes, visible light is EM radiation …

- 1895 through 1945 saw unprecedented advances in the understanding of matter, particularly on the atomic scale.
- Noble prizes were won by many “nuclear” scientists who discovered, amongst other things:
    - X-Rays – Wilhelm Rontgen, 1895;
    - Radioactivity – Henri Becquerel, 1896;
    - The electron – J.J. Thompson, 1897;
    - Radioactive elements (polonium & radium) – Marie and Pierre Curie, 1898;
    - Spontaneous transmutation of elements – Ernest Rutherford & Frederick Soddy, 1902;
    - Theory of relativity, interchangability of mass & energy – Albert Einstein, 1905;
    - Atomic nucleus – Rutherford, 1911;
    - Preliminary structure of the atom – Neils Bohr, 1913;
    - The proton – Rutherford, 1919;
    - The neutron– James Chadwick, 1932
    - Demonstration of nuclear fission – Otto Hahn & Fritz Strassman, 1938
    - First man-made self-sustaining nuclear fission reaction – Enrico Fermi, 1942;
    - Atomic bombs dropped on Hiroshima & Nagasaki – 1945;
    - First commercial nuclear powered electricity plant – Shippingport, PA, 1957;

Ionizing Radiation

- Most EM radiation is more-or-less benign. Humans, animals and plants have always been exposed to the EM spectrum and have evolved in its presence.

- *Ionizing radiation* emanates from the nucleus of the atom (or is generated in accelerators) and contains very high energy … essentially enough energy to ionize, or knock off electrons from the outer shell of other atoms as it passes by.

- To understand this further, let’s look at the structure of an atom …

Atomic Structure

- The structure of an atom has been well understood for about 75 years and is made up of the following primary particles:
  - Protons – positively charged particles contained in the nucleus of an atom.

    Mass = 1.007825 amu
  - Neutrons – particles containing no charge, typically found in the nucleus of the atom.

    Mass = 1.0086654 amu
  - Electrons – small, negatively-charged particles that orbit the atomic nucleus with well-defined structures and energies.

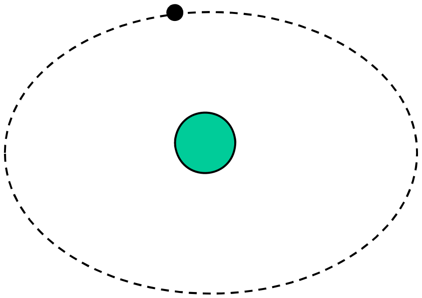
    Mass = 0.0005486 amu

amu = atomic mass unit = $1.673\mathrm{x}10^{-27}$ kg

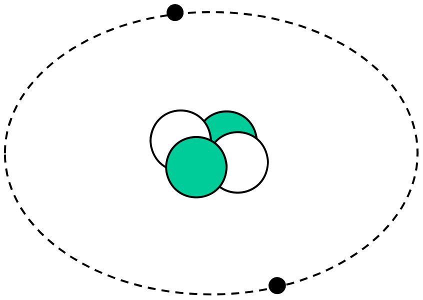
- The simplest element, hydrogen, has one proton in it’s nucleus and is circled by one electron that ensures charge neutrality.

- Adding a proton to the nucleus changes the element from hydrogen to helium (with another electron added as well to keep the charges balanced)

- However each proton must now be accompanied by a neutron to provide the necessary attractive nuclear force to offset the coulombic repulsion of the two protons



Hydrogen Atom



Helium Atom

● proton

○ neutron

• electron

- And so it goes … each element is uniquely defined by the number of protons it contains in its nucleus (and subsequently electrons in its orbital shells) .
- We commonly designate the element or atom by its chemical symbol and its Atomic number and Mass number, for example carbon-12:

$$C^{12}_{6}$$

Mass Number (A) – total number of particles in the nucleus (protons + neutrons)

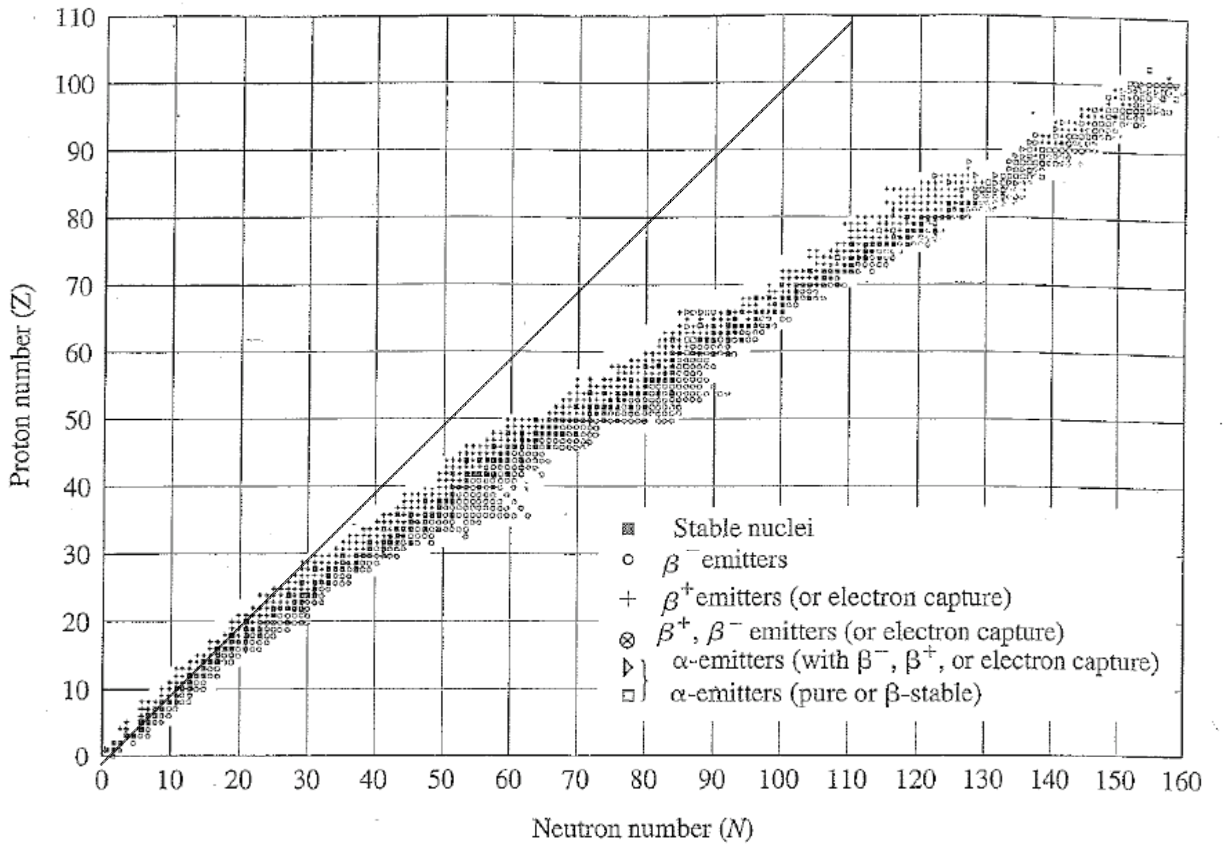
Atomic Number (Z) – number of protons in the nucleus

Chemical Symbol

neutrons = A – Z = 12 - 6 = 6

- The number of neutrons contained in the nucleus of the atom may vary.
- We find that, as the elements get heavier (more protons and neutrons), the number of neutrons required to balance the increasing repulsive forces of the protons increases as well.
- This starts to occur around an atomic number of 20 – calcuim.

- Elements heavier than calcium tend to have more neutrons in their nuclei than protons.



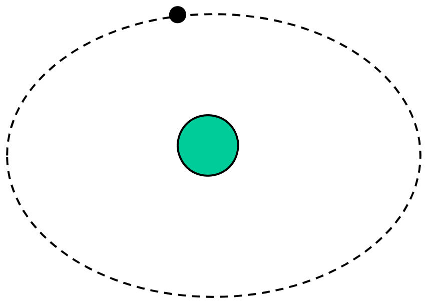
- As we see on the previous “Chart of the Nuclides”, there can also be a varying number of neutrons for a given element with atomic number, A.

- Obviously, this gives different masses to an atom of a particular element, we call these ***isotopes.***

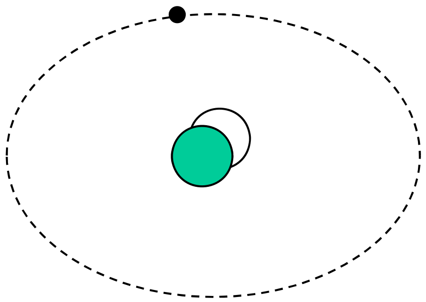
- Isotopes of an element behave more-or-less the same chemically but can show significant differences at the nuclear level.

Hydrogen, Deuterium and Tritium

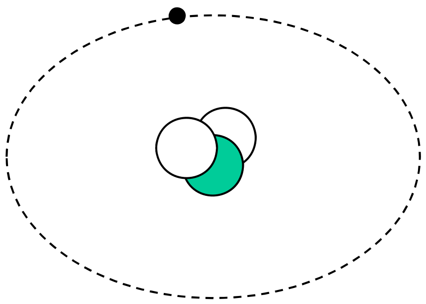
- All three are isotopes of hydrogen and have the atomic number A = 1;
- Deuterium has a neutron in its nucleus, still has atomic number A = 1 but has a mass number Z = 2. It is stable and has about 0.015% abundance in nature.
- Tritium has two neutrons in its nucleus, thus: A=1; Z=3. It is *radioactive* and decays by beta particle emission.



Hydrogen



Deuterium

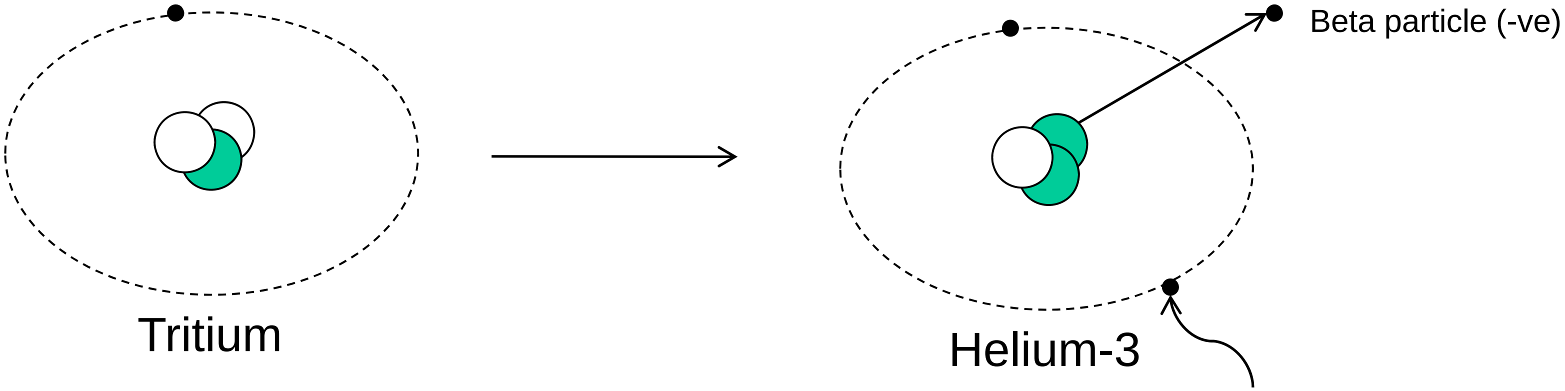


Tritium

- The spontaneous decay of a nuclide is its way of achieving a more stable energy state.

- If a nucleus has too many (or too few) neutrons, it will emit a particle (and sometimes excess EM energy – gamma rays) to try and achieve a more stable energy state.

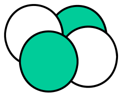
- The tritium atom emits a beta particle (electron) from its nucleus – in essence, one of the neutrons becomes a proton/electron pair – the electron is ejected from the nucleus.



- The atom that undergoes radioactive decay is no longer tritium, its atomic number is now A = 2.
- It is a helium isotope $\left(He_2^3\right)$ which is stable.

Forms of Radioactive Decay

ALPHA Particles 〈 (Helium nucleus)



- 2 protons, 2 neutrons;
- 4 amu;
- +2 charge;
- **Reason for decay: Nucleus is too large**

POSITRON emission – $®^{+}$ (positron)

- 1 positron (positive electron) ●
- 1/1840 amu;
- +1 charge;
- **Reason for decay: too many protons relative to neutrons**

BETA particles: $®^{-}$ (electron)

- 1 electron; ●
- 1/1840 amu;
- -1 charge;
- **Reason for decay: too many neutrons in nucleus relative to protons**

ELECTRON CAPTURE

- Electron absorbed by nucleus
- 1/1840 amu;
- -1 charge
- **Reason for capture: too many protons relative to neutrons**

GAMMA rays –© (high freq. EM radiation)

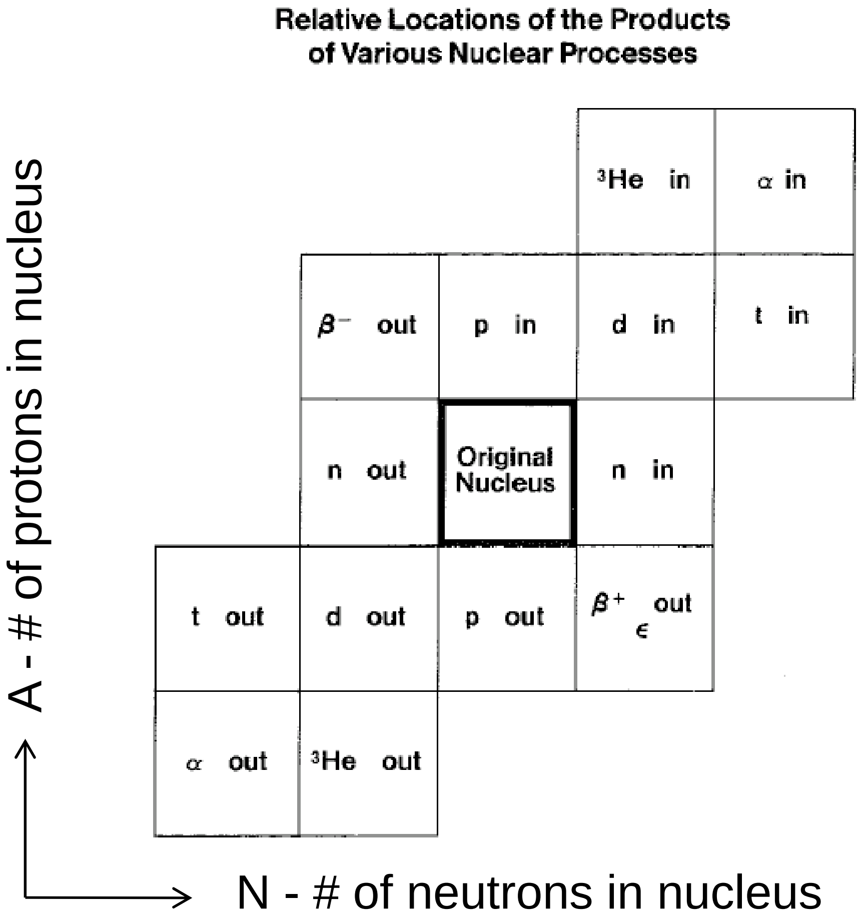
- electromagnetic radiation;
- 0 mass;
- 0 charge;
- **Reason for decay: excess energy in nucleus**

NEUTRON particles – **n**

- 1 amu; ○
- 0 charge;
- released in nuclear fission or directly by select nuclides

Transmutation

- An element that undergoes spontaneous radioactive decay is transformed into a new element, that may-or-may-not be stable itself.

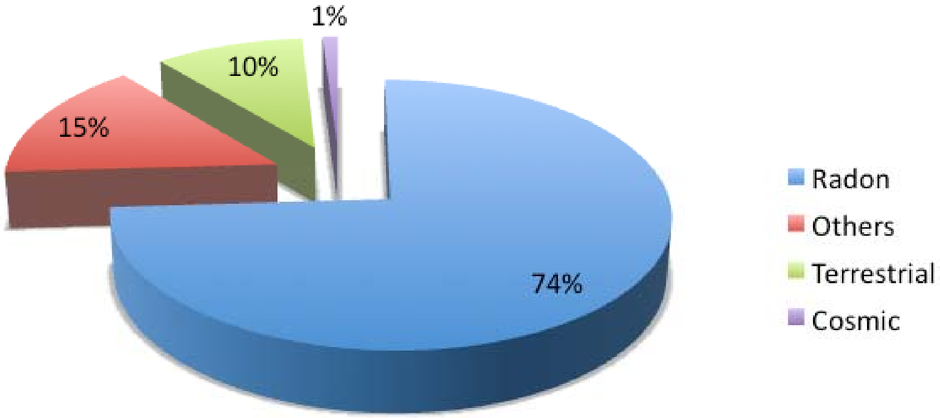


Relative Locations of the Products of Various Nuclear Processes

			^{3}He in	α in
	β^- out	p in	d in	t in
	n out	**Original Nucleus**	n in	
t out	d out	p out	β^+ out ϵ	
α out	^{3}He out			

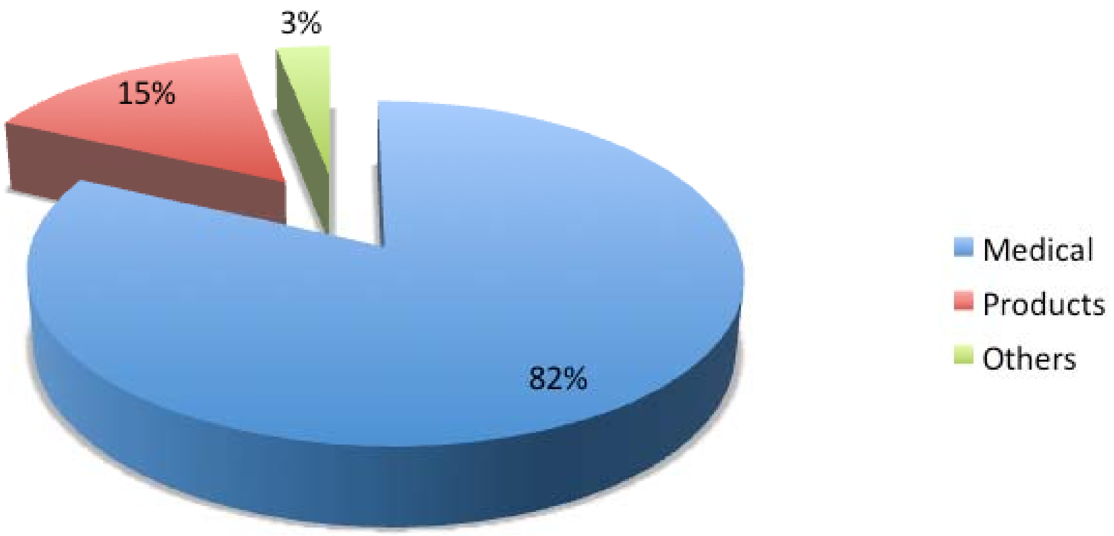
Natural Sources of Radiation

- Radiation is all around us … it emanates from the rocks under our feet, the air we breathe and from cosmic rays from outer space.
- On average, 74% of the population’s exposure from natural sources is through radon gas.
- Others include our internal body sources: uranium and thorium and their decay products and potassium-40 (0.012% naturally occurring).



Man-made sources of radiation exposure

- The biggest single source of the general population’s man-made radiation exposure comes from medical procedures (82%)!!
- Others include workplace radiation exposures, nuclear fallout from bomb tests and the nuclear power industry.



Average Population Equivalent Dose

Radiation Type	Source	Dose (µSv/yr)	Total (µSv/yr)
Natural Background:	Cosmic Rays	330	
	Radon & decay products	600	
	External Terresterial	440	
	Internal sources	200	1570
Man-made: Medical Exposure	Diagnostic X-Rays	300	
	Radiotherapy	50	
	Nuclear medicine	5	355
Fall out	Weapons testing	10	10
Occupational Doses	Medical	2	
	Dental	0.5	
	Research & Education	0.5	
	Industry (non-nuclear)	0.3	3
Miscellaneous Sources	TV, air travel etc.	3	3
Nuclear Power Generation	Uranium mining	1	
	Reactor operation	15	
	Other fuel processes	3	
	Transportation	0.01	
	Accidents	0.5	20
		Grand Total	2000

Terrestrial Radiation

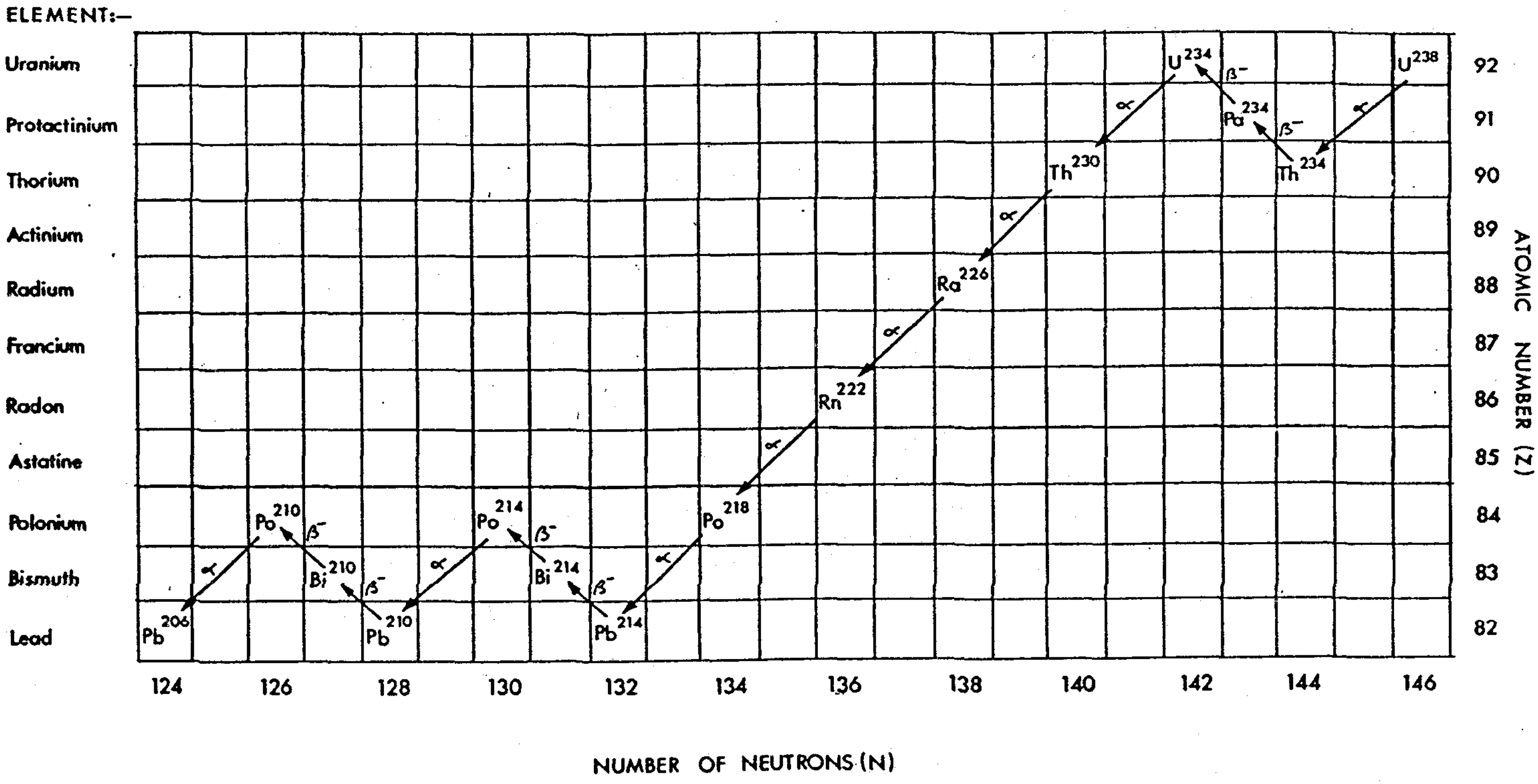
- Most naturally occurring radioactive isotopes stem from four parent elements proceeding in a long decay-chain:

Parent Element	**Half-life (years)**	**Stable end-product (daughter)**
Thorium 232	13.9 Billion	Lead-208
Neptunium 237	2.25 Million	Bismuth-209
Uranium 238	4.51 Billion	Lead-206
Uranium 235	0.707 Billion	Lead-207

- Half-life is the time required, through radioactive decay, for the number of atoms originally present to be ½ their original value. In practice, after ~ 10 half-lives the element has essentially disappeared completely.

- Note the relatively short half-life of Np-209 … none of its decay products (nor itself for that matter) are found naturally on Earth today.

Decay Series for U238

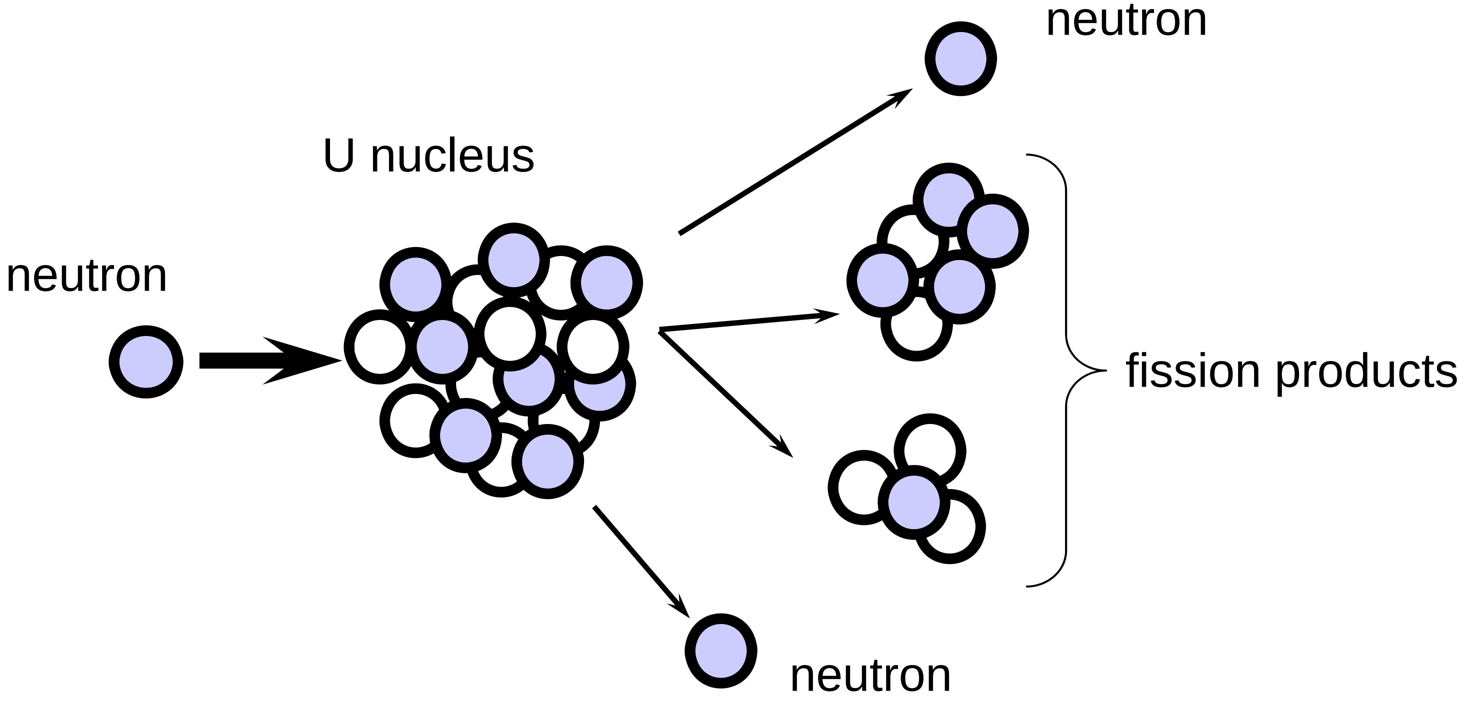


Another property of nuclear materials – Nuclear Fission

- Some heavy elements can undergo another form of radioactive decay … An unstable heavy nucleus can split into into two lighter nuclei … a process called ***nuclear fission***.

- Fission can (and does) occur spontaneously, like the other forms of radioactive decay, but its probability is greatly enhanced by forcing the heavy nucleus to absorb an additional neutron.

- Fission of U-235 …



$$U_{92}^{235} + n_{0}^{1} \rightarrow U_{92}^{236} \rightarrow Ba_{56}^{137} + Kr_{36}^{97} + 2n_{0}^{1}$$

- Balancing the protons and neutrons in this reaction:
  - Before: U-235 (92 protons; 143 neutrons)

    \+ 1 neutron

    Total: 92 protons; 144 neutrons

  - After: Ba-137 (56 protons; 81 neutrons)

    Kr-97 (36 protons; 61 neutrons)

    \+ 2 neutrons

    Total: 92 protons; 144 neutrons

- However, calculating the actual masses before and after the nuclear reaction gives:

$$235.0439 + 1.00867 \rightarrow 136.9061 + 96.9212 + 2 \times 1.00867$$

or

$$236.052 \rightarrow 235.8446$$

- This shows a loss of mass of 0.2082 amu … which has been converted to energy through Einstein’s famous relation $E = mc^2$.

- The loss of 0.2082 amu represents the release of 193 MeV (Mega-electron volts or ~ $3.1\mathrm{x}10^{-11}$ Joules).

- For each fission reaction, additional energy is obtained from the radioactive decay of the fission fragments and non-fission capture of some neutrons.

- On average, each fission reaction will release about 200 MeV of energy (~3.2×10^{-11} Joules).

- If we consider that 1 gram of uranium-235 will contain 2.6×10^{21} atoms of uranium, complete fissioning results in:
  - 8.32×10^{10} Joules of energy released
  - 23110 kW-hr of energy (enough for the average household for well over a year!)
  - You would need to burn around 1300 kg of coal or around 1400 litres of oil for the same energy release!

- The probability (called *cross-section* by nuclear physicists) of inducing a *fissile element* to fission is greatly enhanced when the neutrons are moving slowly, i.e. they have low energy, are ***thermal*** or have been ***moderated***.

- Fissile elements (elements that may be fissioned by thermal neutrons) include:
  - U-235 (0.7% naturally occurring with U-238)
  - U-233 (artificially produced from Th-232)
  - Pu-239 (artificially produced from U-238)
  - Pu-241 (artificially produced from Pu-239)

- Nuclear power reactors employ a ***moderator*** to slow down the fast-moving neutrons produced from the fission reaction.

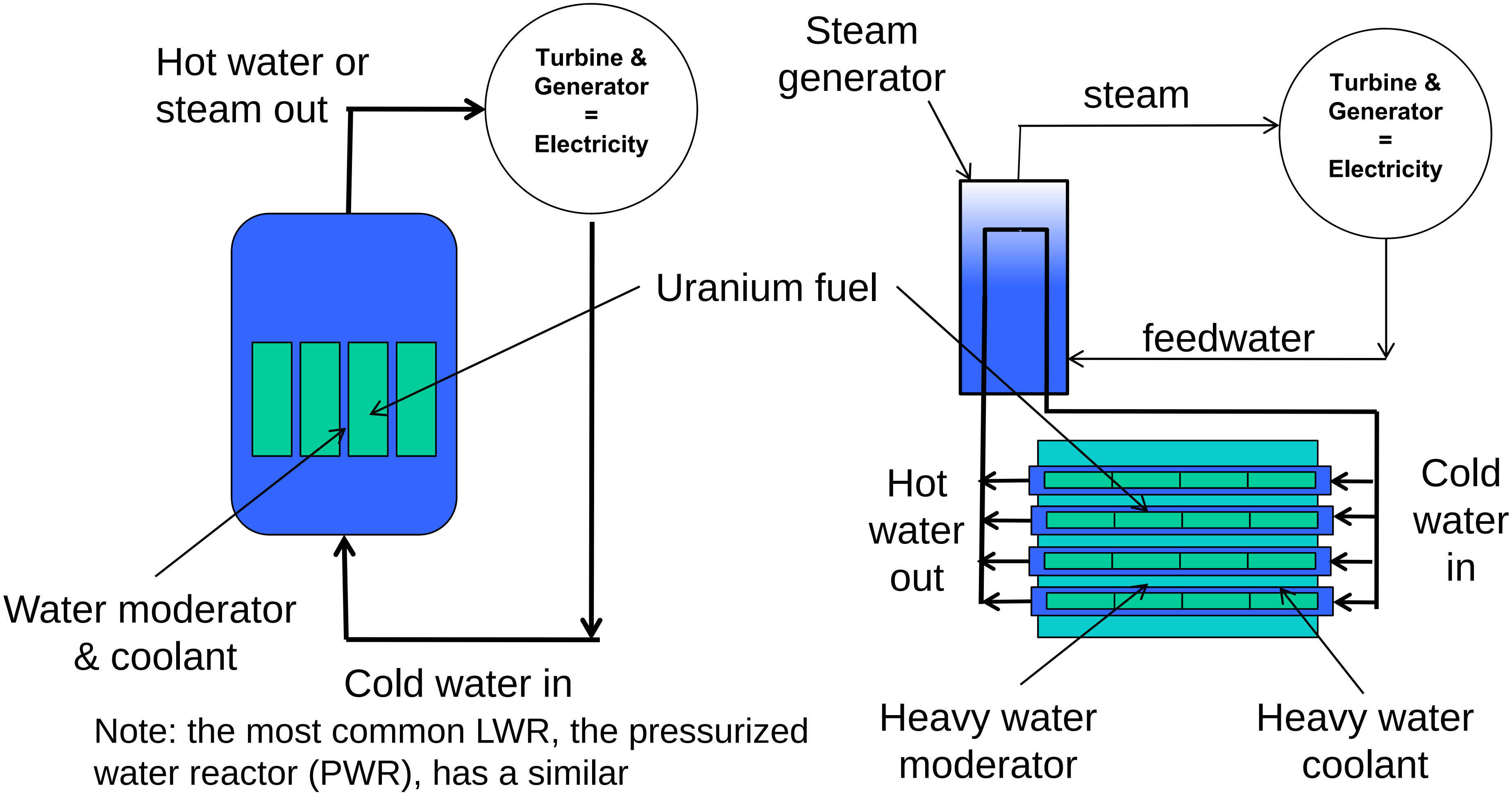
- Good moderators are materials that have about the same mass as the neutron, this provides efficient momentum and energy transfer.

- Typical moderators used include:
  - Water (H_2O)
  - Heavy water (D_2O)
  - Graphite (Carbon)

Schematic of Nuclear Power Reactors

Light Water Reactors

Heavy Water Reactors (CANDU)



Hot water or steam out

Turbine & Generator = Electricity

Uranium fuel

Water moderator & coolant

Cold water in

Steam generator

steam

Turbine & Generator = Electricity

feedwater

Hot water out

Cold water in

Heavy water moderator

Heavy water coolant

Note: the most common LWR, the pressurized water reactor (PWR), has a similar configuration as the CANDU and includes a steam generator

Used fuel

- The fission products are highly radioactive when the used fuel is first removed from the nuclear power reactor.

- However, the fission products decay very quickly and shielding is easily accomplished by ~ 3 metres of water or ~ 1 metre of concrete. Currently, in Canada, all used fuel stored on-site.

- After 300 – 500 years, the used nuclear fuel has an activity about equal to the original uranium ore that it originally came from.

Risks associated with nuclear power

- Two major nuclear accidents have occurred over the past half century:
  - Three Mile Island – 1979:
    - Minimal radiation release;
    - No casualties besides thousands of anxious people who were evacuated from the vicinity of the plant.
  - Chernobyl – 1986:
    - Large radiation release;
    - 28 casualties within 4 months of the accident;
    - Another 19 subsequently;
    - 9 due to thyroid cancer.
    - UN report 2000 (& 2005-06) concluded that no significant radiation-related health effects to most of the people exposed have been observed.

* Figures from World Nuclear Association (WNA) webpage

Risks in society

- Beside these two cases, the operational and safety record of the world’s nuclear power reactors is exemplary.

- Compare these relatively small casualties to what occurs with other power generation technologies, other industries or life in general …

- Bernard Cohen (Professor Emeritus of Physics, University of Pittsburgh) has ranked societal risks according to the averaged loss-of-life-expectancy (LLE) … here’s what he finds:

Activity or Risk	LLE (days)
Living in Poverty	3500
Being Male (vs female)	2800
Cigarettes (male)	2300
Heart Disease	2100
Being unmarried	2000
Being black (vs white)	2000
Socio-economic status	1500
Working as a coal miner	1100
Cancer	980
30 lb. overweight	900
Grade school dropout	800
Sub-optimal medical care	550
Stroke	520
15 lb. overweight	450
All accidents	400
Vietnam army service	400
Living in southeast US	350
Mining construction	320
Alcohol	230
Motor vehicle accidents	180

Activity or Risk	LLE (days)
Pneumonia, influenza	130
Drug abuse	100
Suicide	95
Homicide	90
Air pollution	80
Married to smoker	50
Speed limit (65 mph vs 55 mph)	40
Falls	39
Poison+suffocation_ asphyxia	37
Radon in homes	35
Fire, burns	27
Coffee (2.5 cups per day)	26
Radiation worker (aged 18 to 65)	25
Firearms	11
Birth control pills	5
Peanut butter (1 Tbsp/day)	1.1
Hurricanes, tornadoes	1
Airline crashes	1
Living near a nuclear plant	0.4
All nuclear electricity	0.04

Conclusions

- Radiation and nuclear materials are a significant part of our everyday lives.

- Nuclear power reactors currently account for about 15% of the world's total electricity generation.

- Depleting fossil fuel reserves and the need to reduce our industrial carbon dioxide emissions means an alternative for mass-produced electricity is needed … now.

- Nuclear power is a mature technology, has a excellent safety record and will provide for our future energy needs.