Imperial College London

Centre for Nuclear Engineering

Why Radionuclides are Good For You.

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**Centre for Nuclear Engineering (CNE)
and
Dept. of Materials.**

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Acknowledgements

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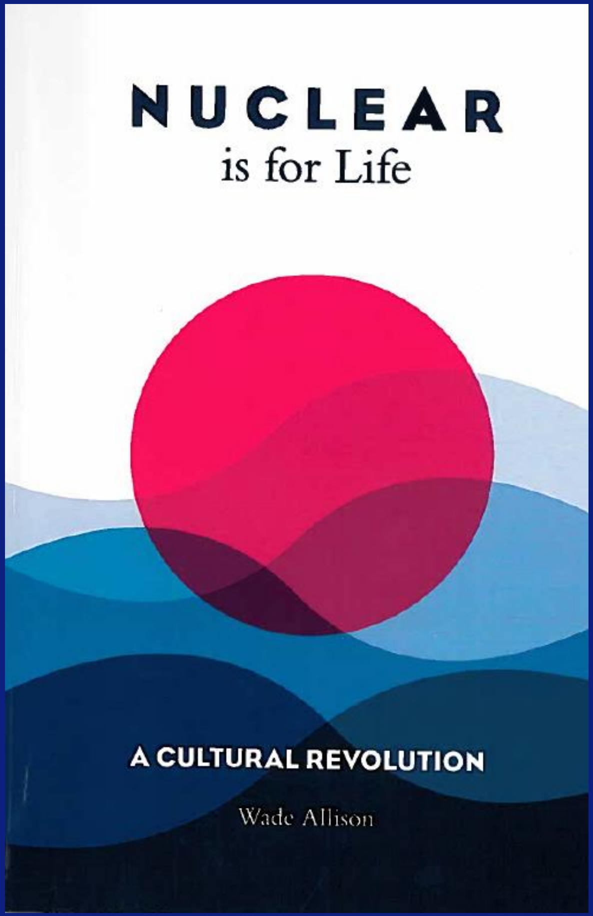

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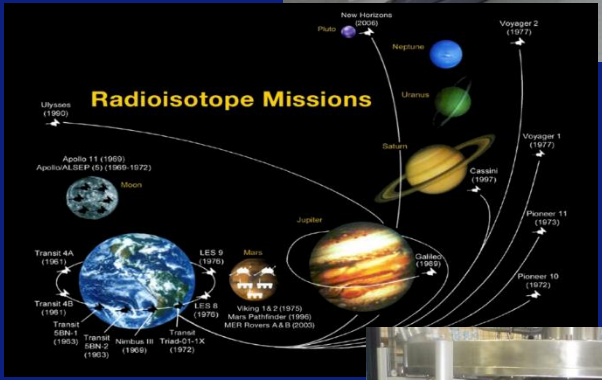
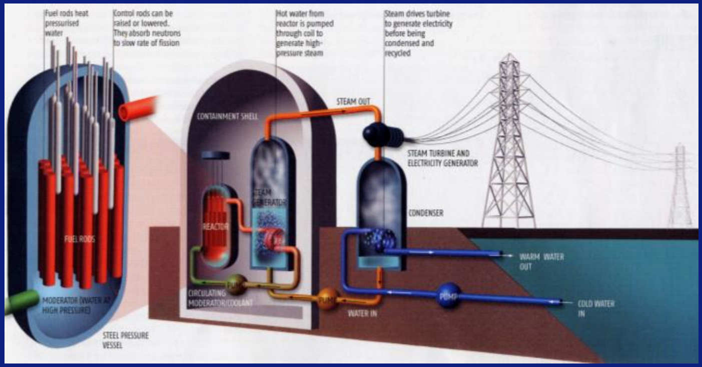
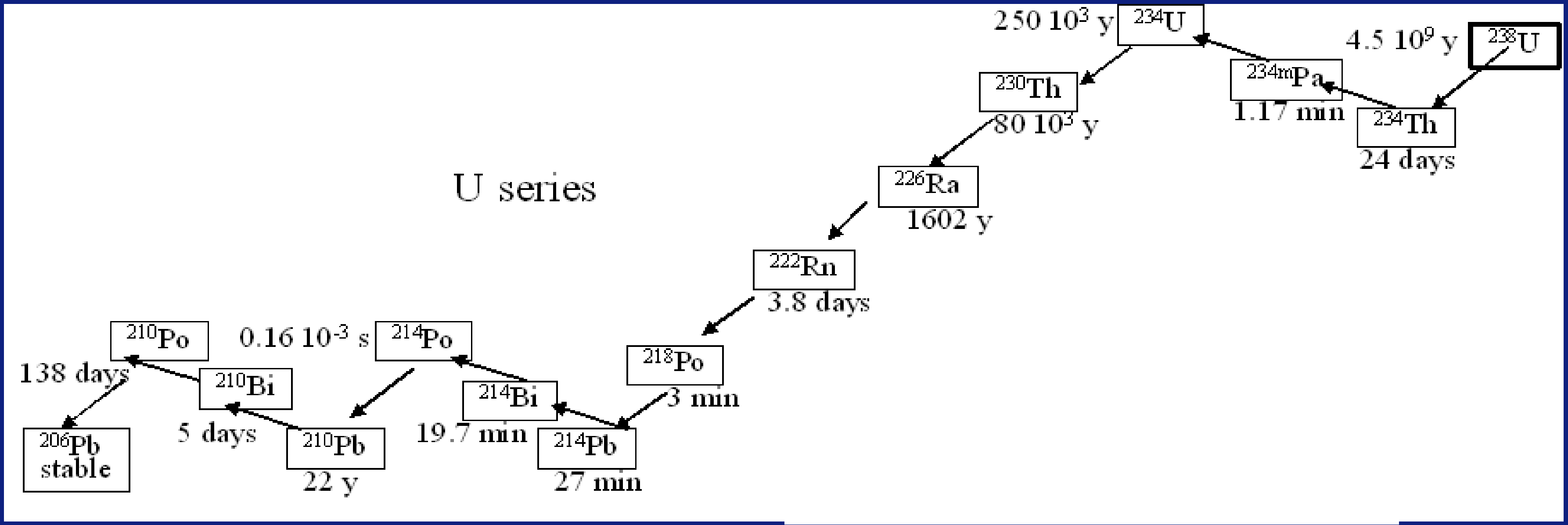
Outline

- Radionuclides.
- Radioactivity and its Uses.
  - Natural
  - Medical
  - Fission and Fusion Power
  - Space
- Perception of Risk.
- Take Home Messages.





What are Radionuclides?

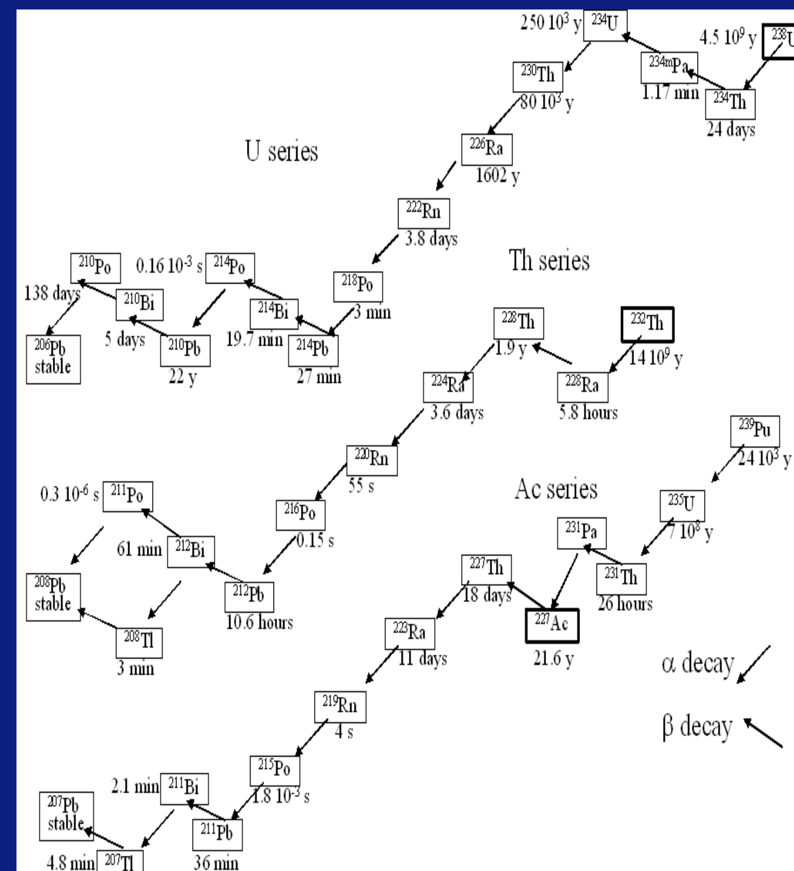


- A Radionuclide (radioactive nuclide, radioisotope or radioactive isotope) is an atom that has excess nuclear energy, making it unstable.
- Every radionuclide emits (α, β, γ) radiation at its own specific rate measured in terms of physical Half Life = time required for half of radioactive atoms to decay.
- Decay Series - A sequence of radioactive decay processes in which the decay of one element creates a new element that may itself be radioactive, and continuing until the sequence ends with stable, nonradioactive atoms.
- Unlike heavy metals (Pb, Hg etc.) radionuclides eventually go away.

Radioactivity is Natural

- Big Bang generated radiation and *primordial* radionuclides - part of everything in universe.
- More recent astronomical events (e.g. exploding supernovae) generate fresh radionuclides.

Exploding supernova



Radioactivity is Natural

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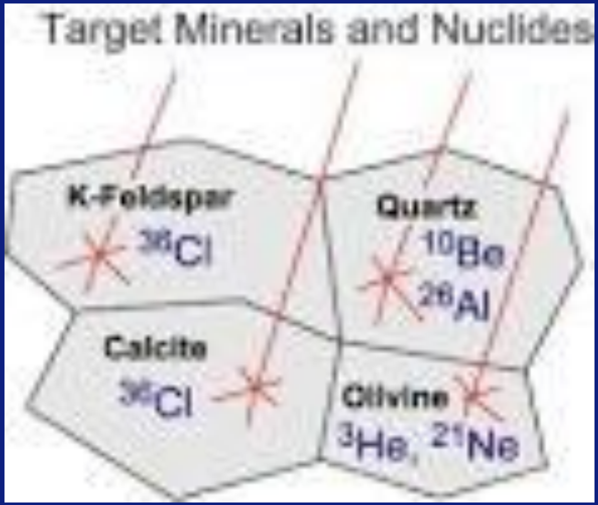
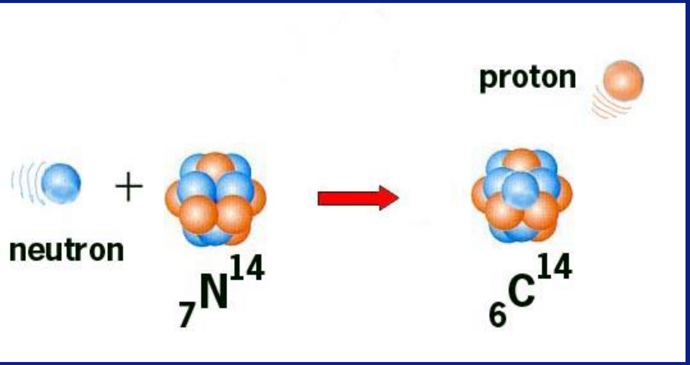
- *Cosmogenic* radionuclides produced by cosmic radiation from space e.g. high speed heavy particles, high energy neutrons.

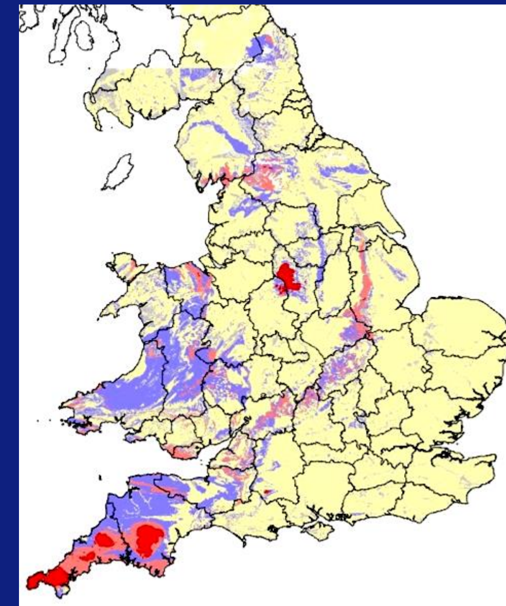
- Earth's upper atmosphere and some minerals interact with cosmic radiation producing radioactive nuclides such as ^{3}H, ^{7}Be, ^{14}C, ^{18}F, ^{22}Na, ^{26}Al, ^{31}Si, ^{32}Si, ^{32}P, ^{38}Cl, ^{38}Mg, ^{38}S, ^{39}Cl and ^{80}Kr.

- Most have short half-lives, except e.g. ^{14}C (5700 years).





Naturally Occurring Radioactive Materials (NORM)



Darker shading equals greater Rn in rocks

- Present in rocks, minerals and soils.
- Principally radium (Ra) and radon (Rn) from natural U and Th decay.
- Technological processes such as fossil fuel burning, oil, gas and mineral extraction and fertiliser application often increase NORM concentrations giving technologically-enhanced (TENORM).
- Since radioactivity is natural it occurs in food which we ingest and so remains in our bodies e.g. ^{40}K and ^{226}Rn in bananas, carrots and potatoes, and ^{228}Ra and ^{40}K in brazil nuts. As a result we irradiate people in our proximity all the time!
- ^{40}K etc. common in building materials (bricks, breeze blocks) so our houses irradiate us!

Short-Lived Radionuclides

Short-lived radionuclides have half-lives shorter than 30.2 years.

E.g.

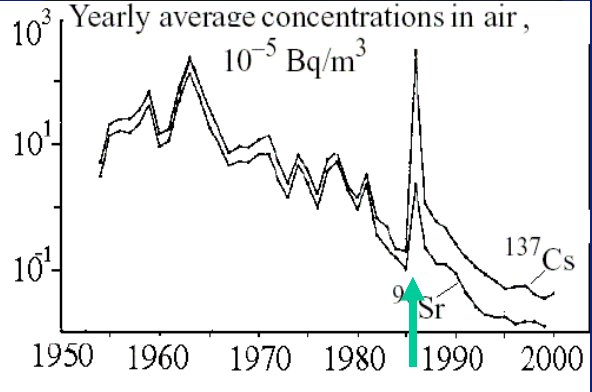
Tritium ^{3}H, 12.33 years.

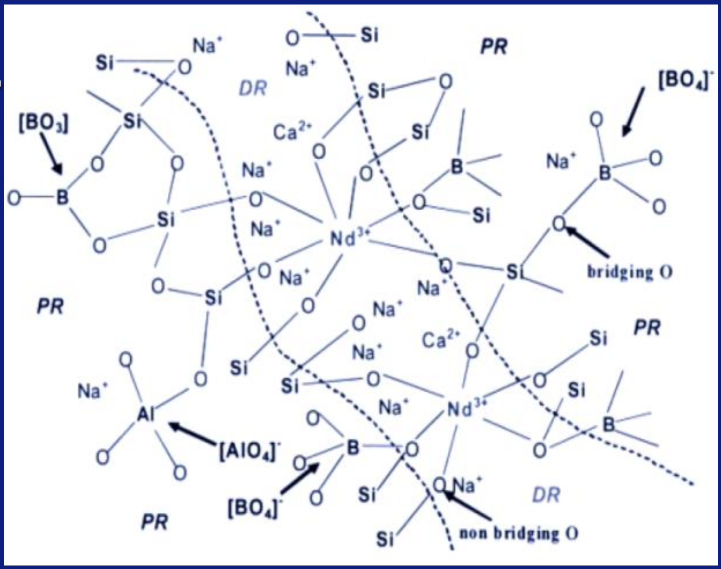
^{90}Sr, 28.5 years.

^{137}Cs, 30.17 years.

^{90}Sr

- Strontium present in natural minerals chiefly as celestite ($SrSO_4$) and strontianite ($SrCO_3$).
- Sr in nature is usually stable nuclide ^{88}Sr.
- ^{90}Sr not naturally-occurring, dispersed from 1950's/60's weapons testing and occasional accidents, can only decrease by radioactive decay.
- ^{90}Sr decays by high energy β emission (546keV).
- ^{90}Sr arises from fission of ^{235}U or other fissile nuclides with a yield of about 6%.
- ^{90}Sr is a major radionuclide in spent nuclear fuel (SNF), HLW resulting from the processing of SNF, and radioactive wastes associated with the operation of reactors & fuel reprocessing plants.
- Easily immobilised in glass HLW forms as ion is similar to Na a common element in glass structures.



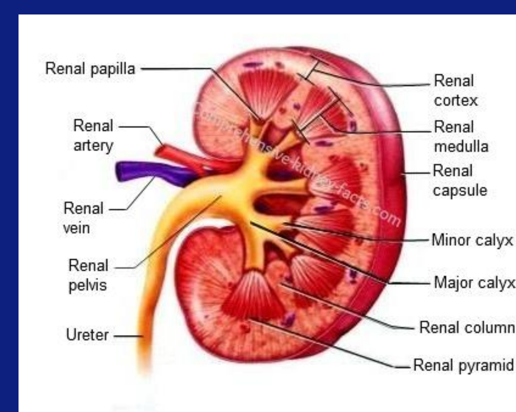


^{90}Sr in the Environment and the Human Body.

- Sr is soluble and transported readily in rain and groundwater deep into soils.
- Principal means of ^{90}Sr getting into food chain is via plant root uptake.
- Sr gets into body by eating food, drinking water, or breathing air.
- Sr behaves similarly to calcium and ~15% of that entering the bloodstream is deposited in bone.
- ^{90}Sr contamination in the proximity of blood-producing bone marrow, leads to reduction in the blood platelet production and the possibility of bone cancer.
- Remainder goes to soft tissue (mainly the kidney) and plasma extra-cellular fluid and is excreted in urine.

- Biological half-life (time for body to evacuate half of radioactive atoms) for ^{90}Sr is ~30 years.





Long-Lived Radionuclides

E.g.

^{14}C, 5730 years.

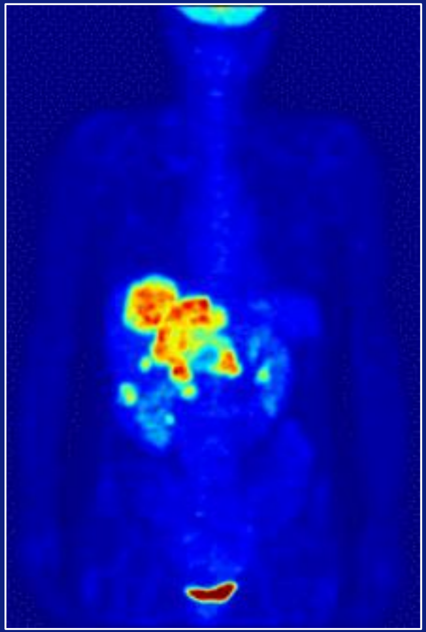
^{99}Tc, 213,000 years.

^{129}I, 15.7 million years.

^{239}Pu, 24,110 years.

^{99}Tc

- ^{99}Tc is not naturally-occurring. Produced by fission of uranium and plutonium.
- No stable isotopes of technetium but 10 radioisotopes including ^{99}Tc. Also meta states e.g. ^{99m}Tc (6 hour half life) which is an important medical isotope.
- ^{99}Tc decays by emitting (average 84.6keV) β particle to produce stable ^{99}Ru. Its very long half-life limits its radioactive hazard.
- ^{99}Tc is a key radionuclide in SNF and HLW resulting from processing spent fuel.
- ^{99}Tc present in soil in small concentrations due to fallout from past atmospheric nuclear weapons tests.

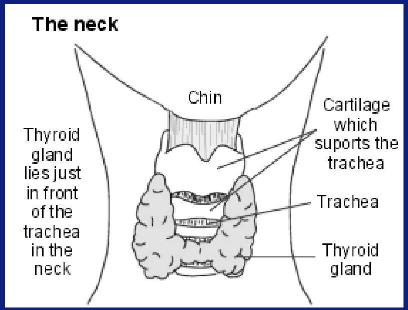


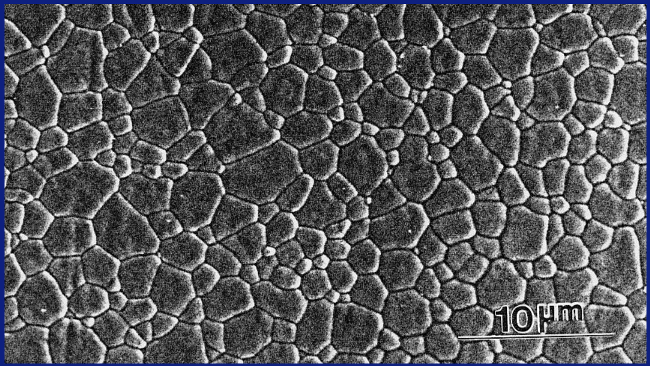
Whole body PET scan using ^{18}F – FDG.

Spent Nuclear Fuel (SNF) storage pond.

^{99}Tc in the Environment and Human Body

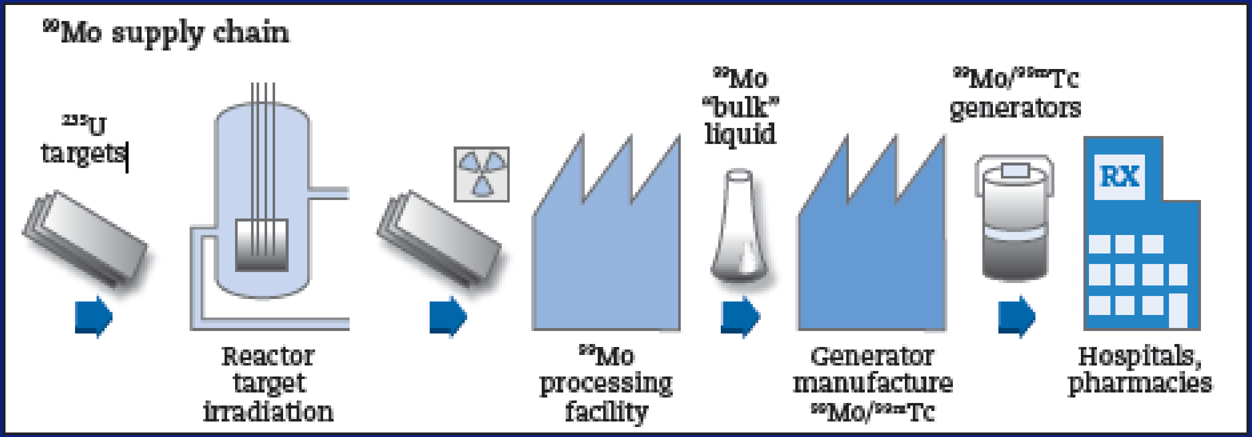
- ^{99}Tc very mobile in environment. Most technetium compounds do not bind well to soil particles.
- Predominant form of ^{99}Tc at disposal facilities is the pertechnetate ion TcO_4^-.
- TcO_4^- is highly mobile in groundwater and ^{99}Tc has a long half-life so its disposal presents a potential long-term hazard to the public.
- TcO_4^- is readily taken up from the intestines and lungs, with 50-80% of that ingested going to bloodstream. ~4% deposits in thyroid where it is retained with a biological half-life of 0.5 days.
- Wasteforms for TcO_4^- developed based on metals or pyrochlore ceramics.





^{99m}Tc Medical Isotope

- ^{99m}Tc used in 30 million procedures/year globally, ~85% of all diagnostic investigations using nuclear medicine techniques.
- Its 6 h physical half-life and 140 keV gamma emission make it ideally suited to act as a tracer enabling medical imaging of organs using conventional gamma cameras.
- ^{99m}Tc is derived from its parent radionuclide ^{99}Mo that has a physical half-life of 66 h.
- At present ^{99}Mo is derived almost exclusively from fission of ^{235}U targets irradiated in 6 old research reactors.
- Several of these reactors will shut down in next 2-3 years so precipitating global medical isotope shortage.

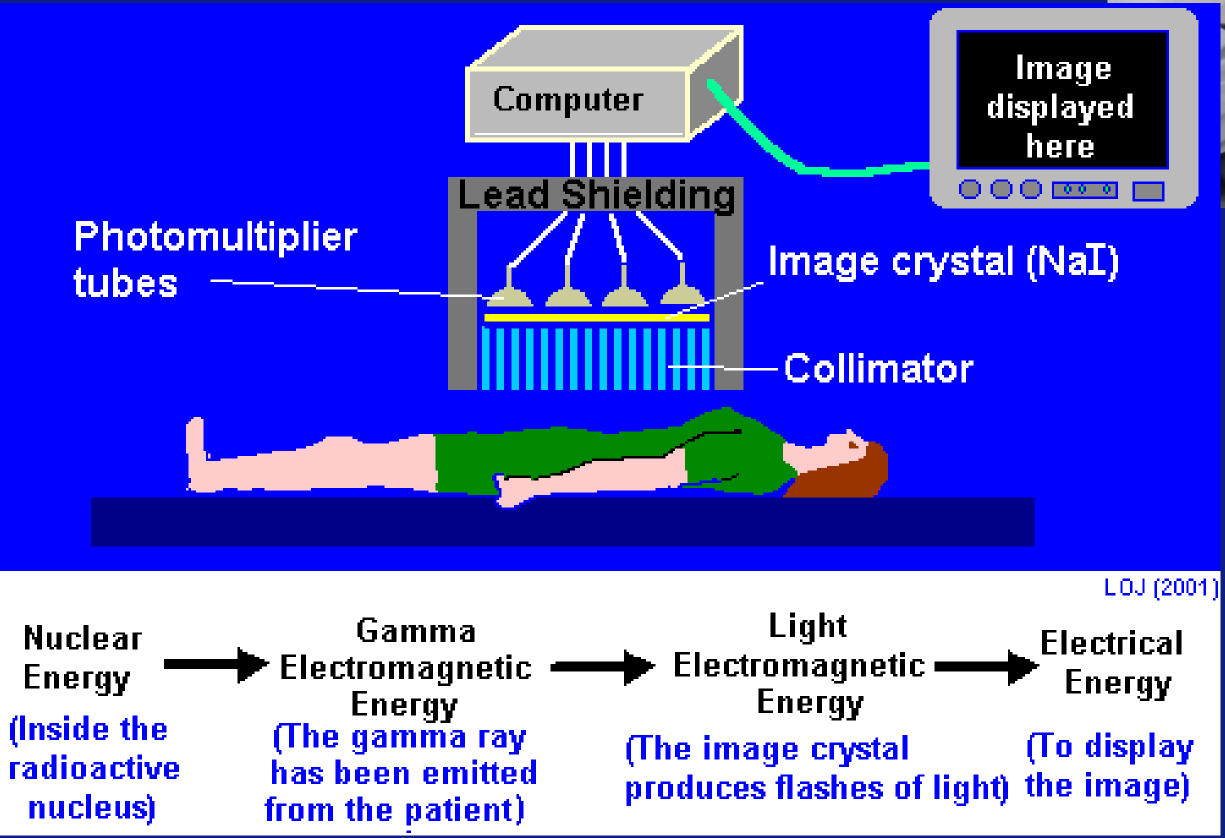


Radioactivity is Good For You.

- Natural radioactivity discovered - Becquerel 1896.
- First artificial radioactive materials produced by Curie's in 1930's and ever since utilized for society's benefit in science, medicine, industry and agriculture.
- Nuclear medicine defined as using radioactive isotopes for diagnosis and treatment.
- Radioisotopes attached to chemicals that have an affinity for particular organs, bones etc.
- Often inject a small amount as a tracer to follow a physiological process, find out where it goes using *emission* e.g. of γ rays.
- Differs from radiology where energy (X-rays, ultrasound, magnetic field) is passed through patient to interact with tissue so using *transmission*.

Nuclear Medicine.

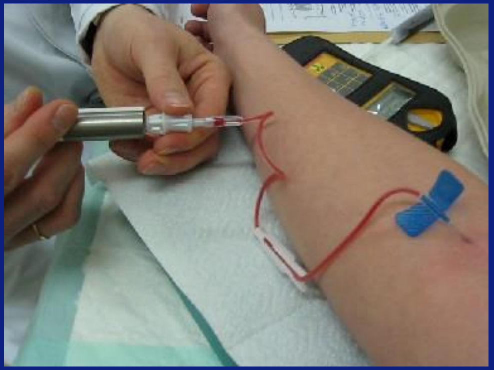
Real PET Scanner



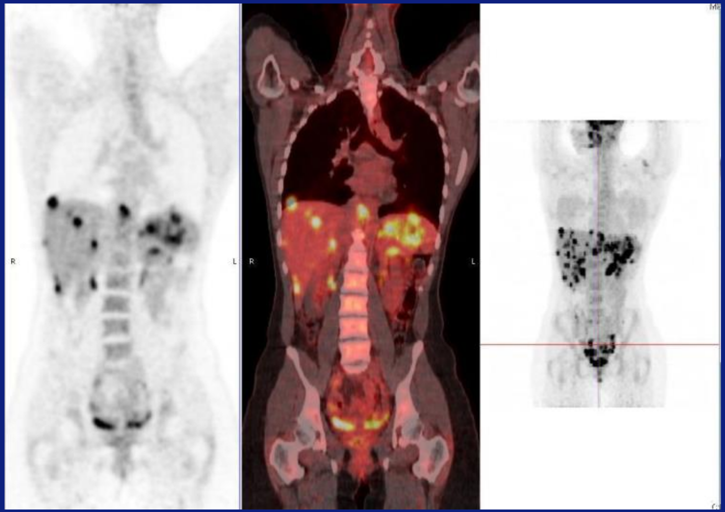
Schematic Gamma camera

Positron Emission Tomography (PET) Scanners

- Positrons = positively charged electrons generated from radionuclide tracer injected in patient.
- Travel 0.001-1mm hit electron and annihilate, producing two 511keV γ rays which are detected.
- Make image from trace and assemble in 3D.
- PET tracers have range applications in detecting cancers and affects of heart attacks and brain abnormalities:
  - F-18 FDG metabolism
  - C-11 methionine cell turnover
  - F-18 FMISO hypoxia
  - C-11 metomidate Conn's tumours
  - F-18 FLT protein synthesis
  - O-15 blood flow to heart



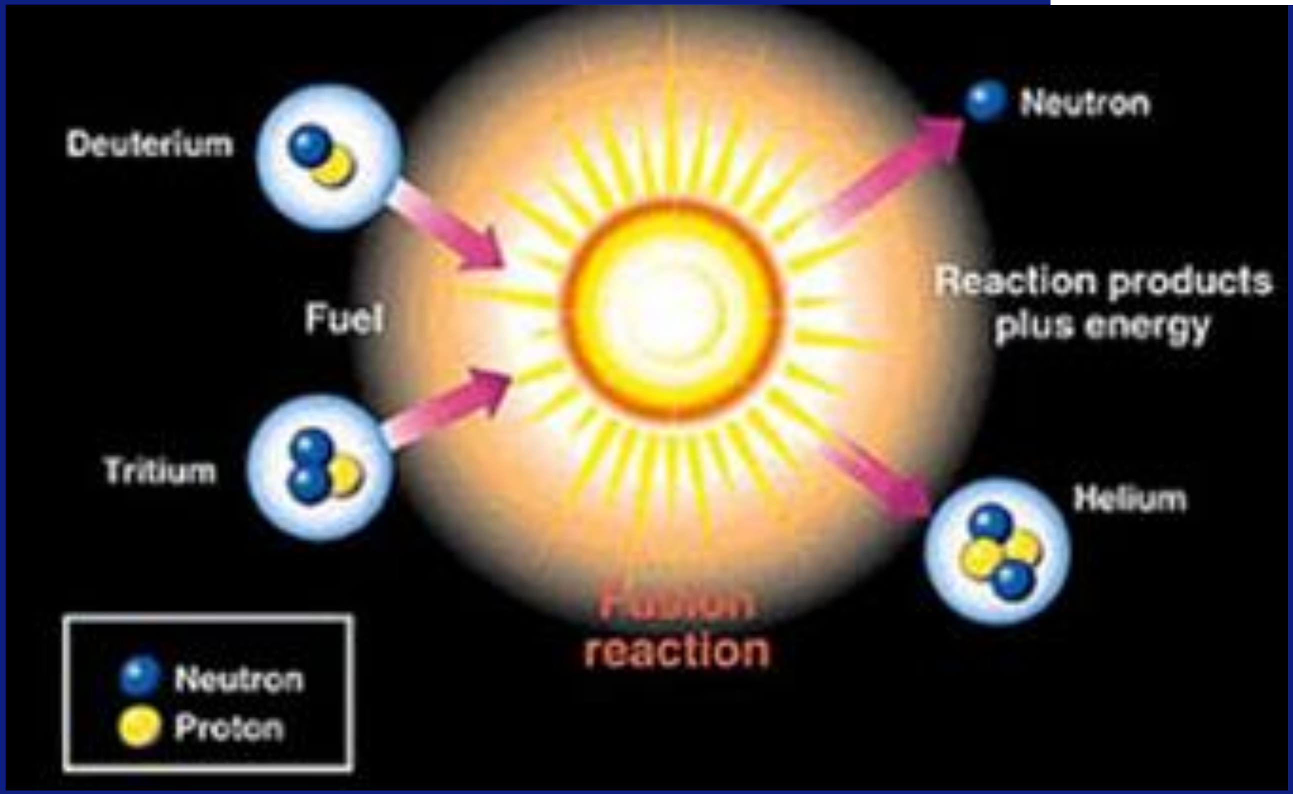
Injecting ^{99m}Tc tracer using shielded syringe



Some Nuclear Medicine Imaging Radioisotopes

Radionuclide	Symbol	Physical half-life	Chemical Form	Diagnostic Use
Indium	^{111}In	67.4h	OncoScint	Colorectal or ovarian cancer
			ProstaScint	Prostate cancer
Iodine	^{123}I	13.3h	Sodium Iodide	Thyroid Function/ Imaging
Technetium	^{99m}Tc	6h	Sodium Pertechnatate	Imaging of brain, scrotum, kidneys, heart etc.
			Tetrofosmin	Cardiovascular Imaging
			IDA	Gall Bladder Imaging
Thallium	^{201}Tl	73.5h	Thallous Chloride	Myocardial Imaging

Nuclear Fusion



$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \longrightarrow ^{4}_{2}\mathrm{He}\ (3.5\ \mathrm{MeV}) + ^{0}_{1}\mathrm{n}\ (14.1\ \mathrm{MeV})$$

- **Need T > 20 million K, like in sun which uses same process.**
- **Difficult engineering and materials problems associated with containing plasma at this temperature and accessing energy.**

Fusion

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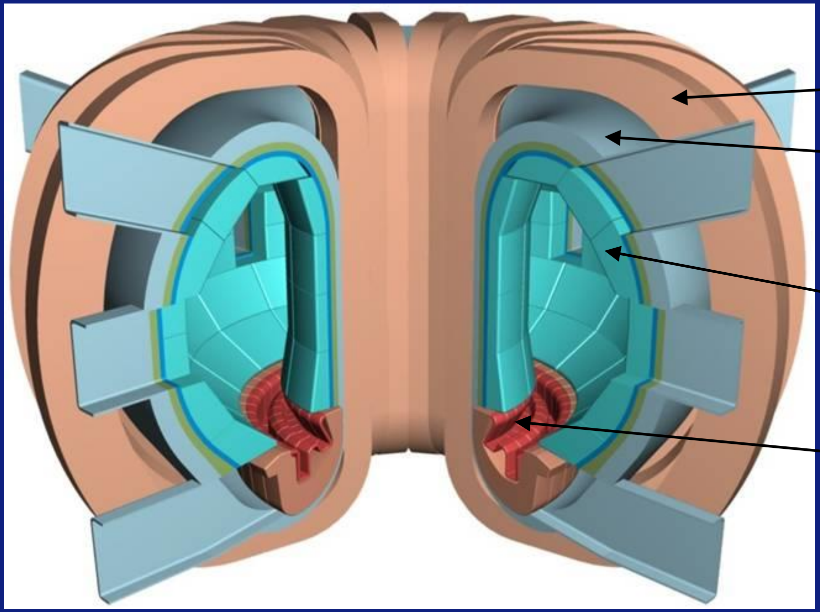
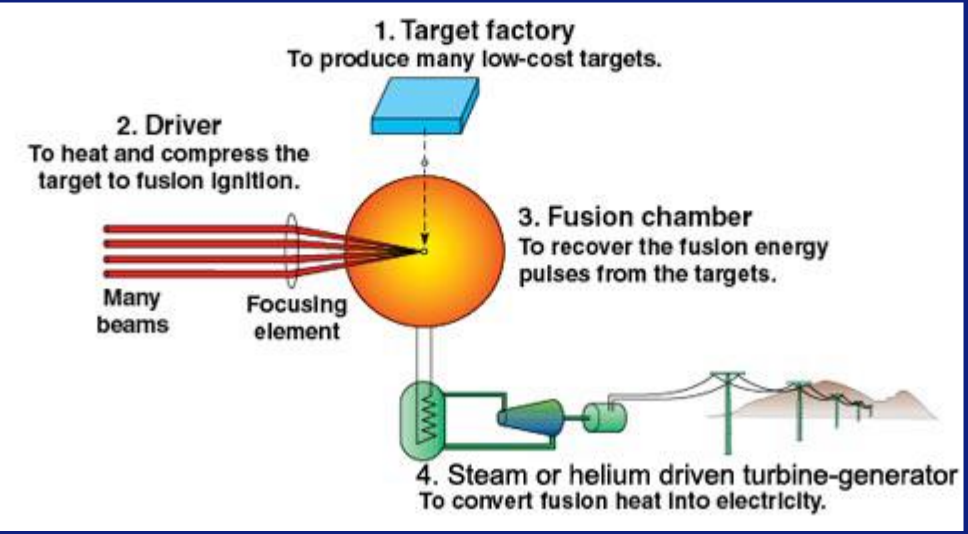
Two techniques:

- *Steady state* magnetic confinement of plasma (Tokamak e.g. ITER France)
- *Pulsed* power laser fusion (National Ignition Facility USA and Laser Megajoule France).

Massive international R&D effort.





Uranium Fission

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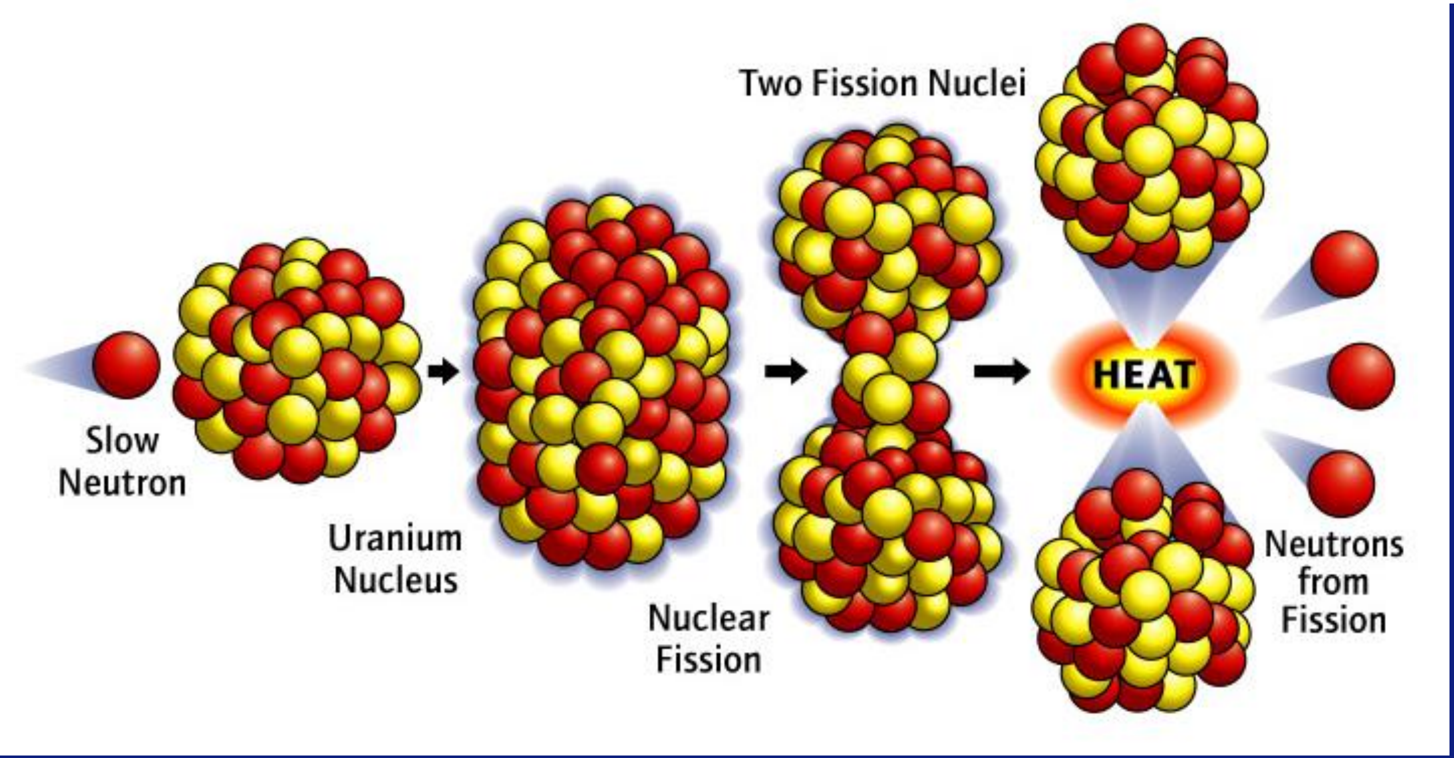
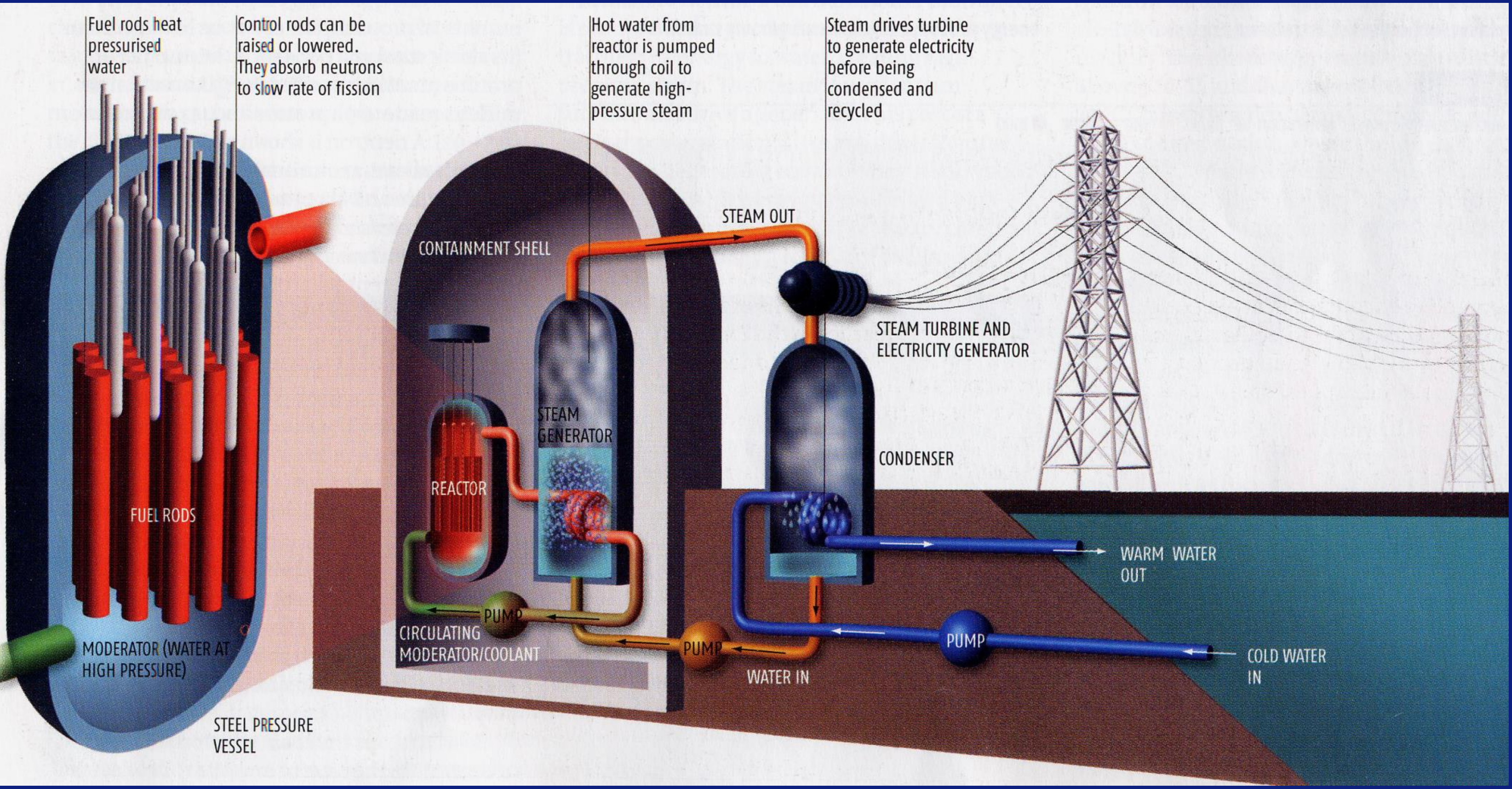


Nuclear fuel is a very compact energy source.

- **Neutron splits nucleus, so 2 fission products repel and flay apart with great velocity.**
- **Collisions of heavy ion fission fragments with host matrix (UO_2) causes damage and other processes that lead to phonons (lattice vibrations or heat).**
- **A fission event releases 170,000,000 eV of energy**

  e.g. $^{235}U + n \longrightarrow {}^{141}Ba + {}^{92}Kr + 3n + 170\ MeV$
- **A chemical reaction releases ~ 1 eV of energy**

Nuclear Power Generation.



- 60% current reactors PWR (Pressurised Water Reactors).
- Fuel: U oxide ceramic clad in zircaloy metal.
- Control rods contain n absorbers e.g. B or Hf.
- Water heat transfer medium & moderator (to slow fast n's).

Global Fission Nuclear Scene

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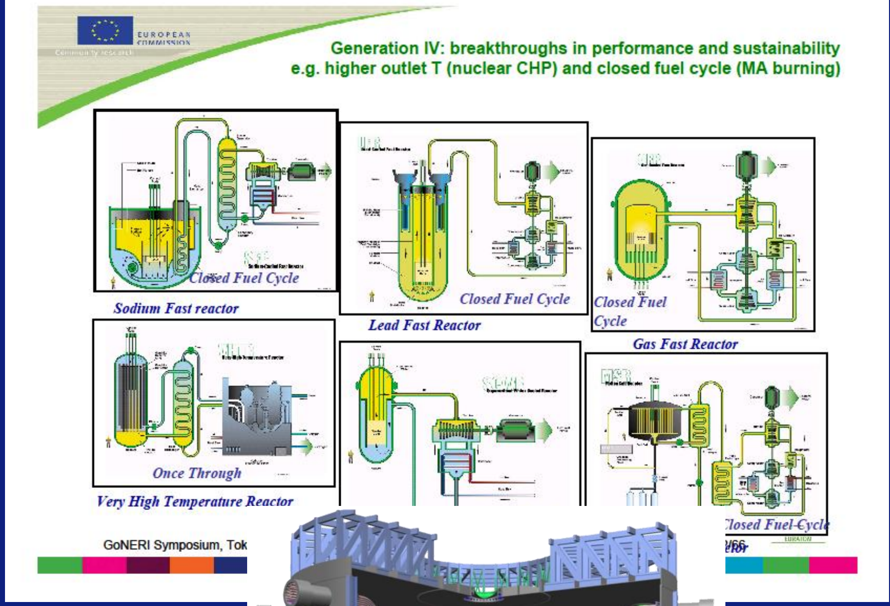
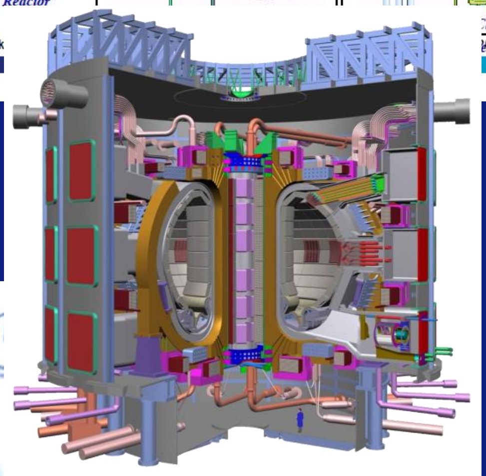
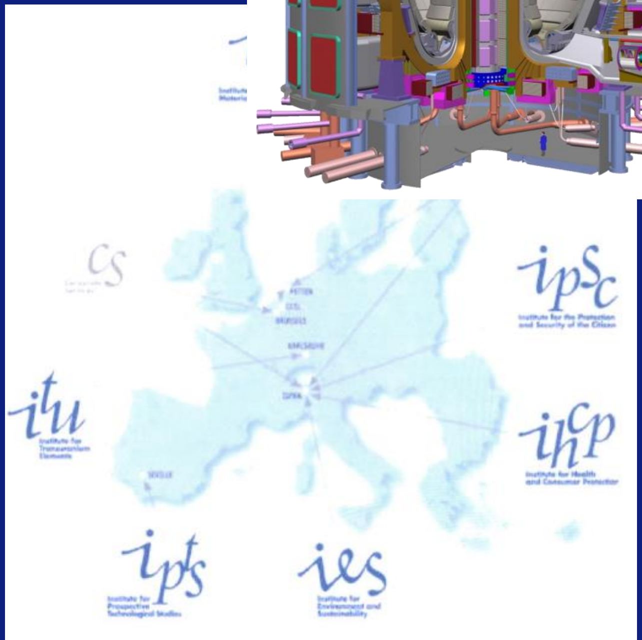
- Benefits of nuclear fission power recognised
  - Environment: low CO_2
  - Security of supply
  - Confidence from decades of stable, safe and reliable operation.
- Globally
  - 438 reactors currently in operation (375 GWe), 67 under construction
  - Installed capacity expected to grow 1.25-2 times by 2030
  - 80% of increased capacity will be in countries with existing nuclear power: South Korea , India, China, Russia
  - Several new nuclear countries in advanced planning/construction: UAE, Turkey, Saudi Arabia and Vietnam.
- Europe
  - France replacement strategy (40 units)
  - Finland expansion, construction in Romania and Slovakia
  - Plans in UK, Bulgaria, Hungary, Czech Republic, Romania, Slovenia and Poland.

Global Nuclear Vision.

- **Increased globalisation and international schemes**
  - Innovative Nuclear Reactors and Fuel Cycles (Gen IV)
  - International Thermonuclear Experimental Reactor (ITER)
  - Japan's planned International Collaborative Research Center on Decommissioning.
- **Sharing and open access to expensive infrastructure such as research reactors, hot cells**
  - Advanced Test Reactor National Scientific User Facility INL USA
  - EC Joint Research Centre: ITU, Ispra, Petten etc.
  - Jules Horowitz Reactor, France.

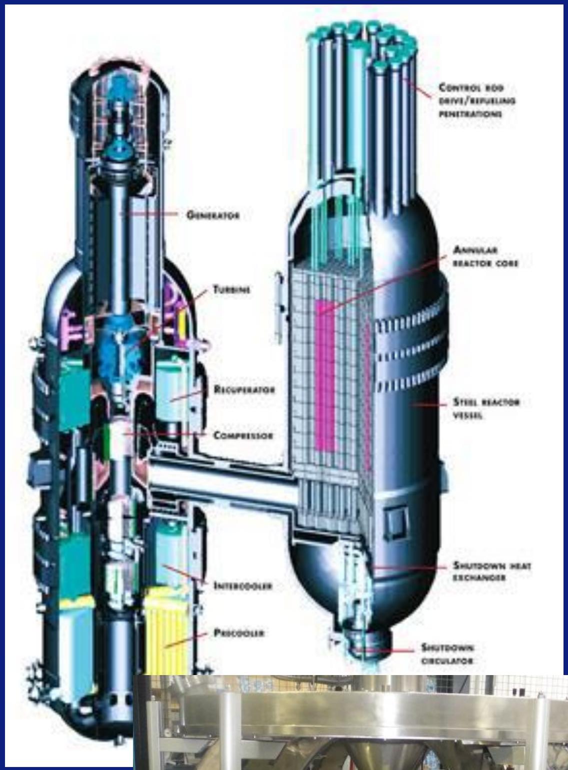




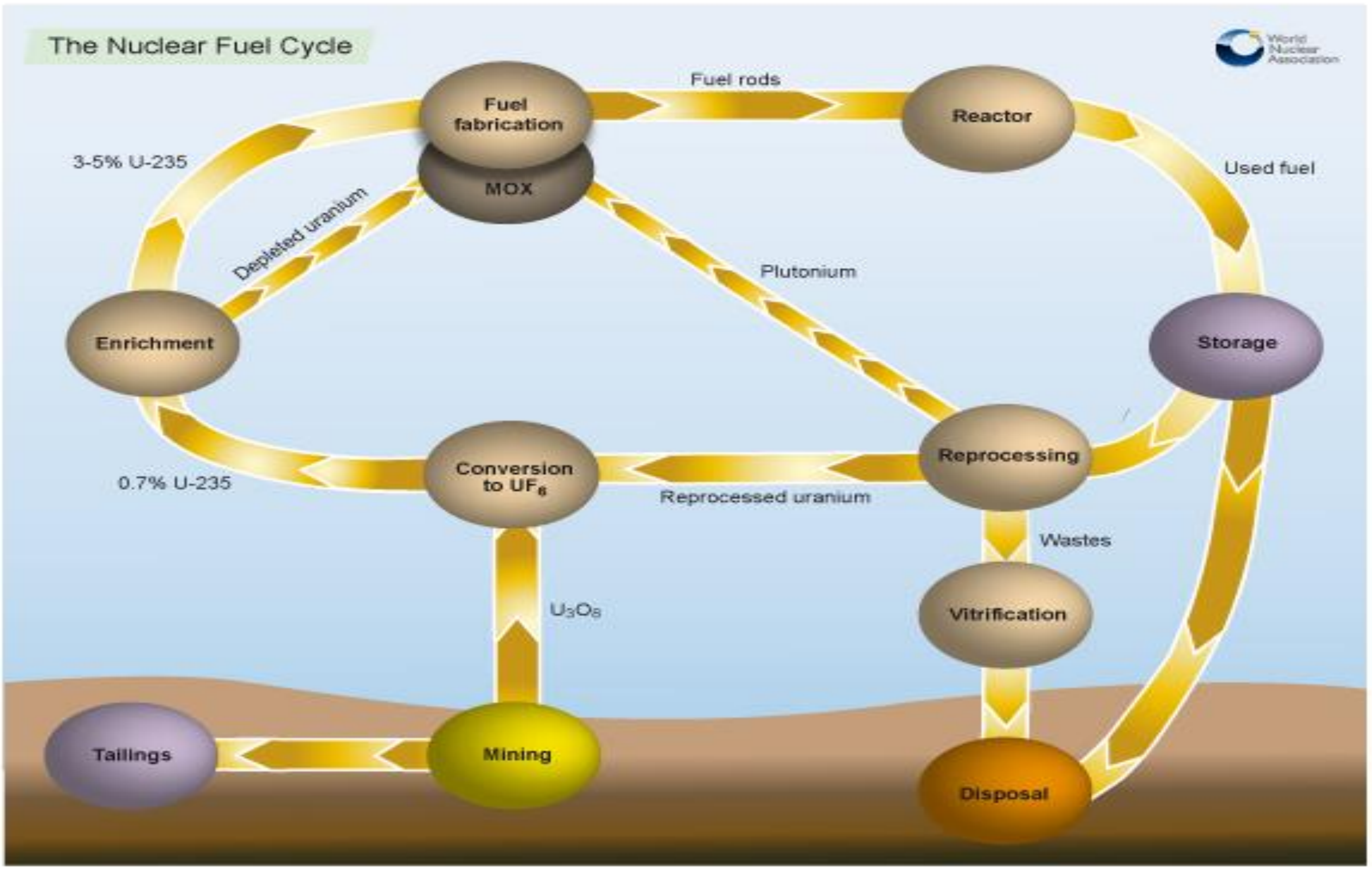


Small is Beautiful.

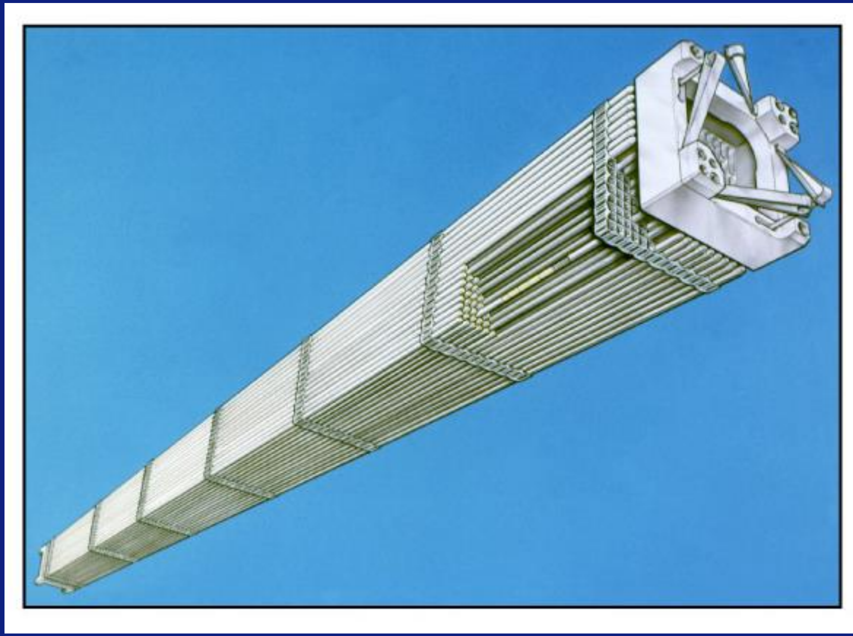
- **In both fission and fusion global trend away from large, high capital cost, reactors.**
- **Fission: Generation 3 to small modular reactors (SMRs)**
    - **Extend nuclear adoption to developing states with limited grid capacity**
    - **Will include greater safety conditions, proliferation-resistance through e.g. lifetime cores**
    - **E.g. NuScale (USA), mPower (Babcock and Wilcox, Bechtel USA), AREVA SMR (France), U Battery (URENCO, UK).**
- **Fusion: ITER to small spherical tokamaks (SSTs).**



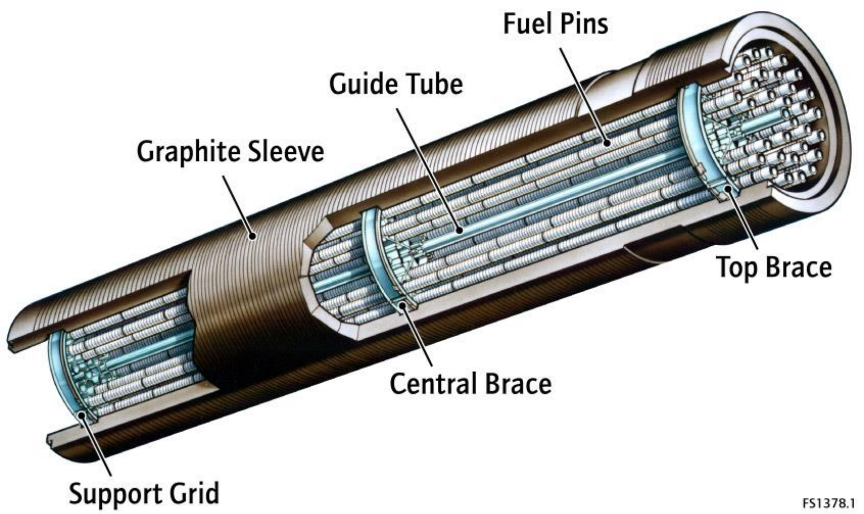
The Nuclear Fuel Cycle



Types of Fuel Element



Pressurised Water Reactor
Fuel Assembly



Advanced Gas-cooled Reactor
Fuel Assembly

Individual ceramic pellets for insertion into metal tubes (pins) to put together to make fuel assembly

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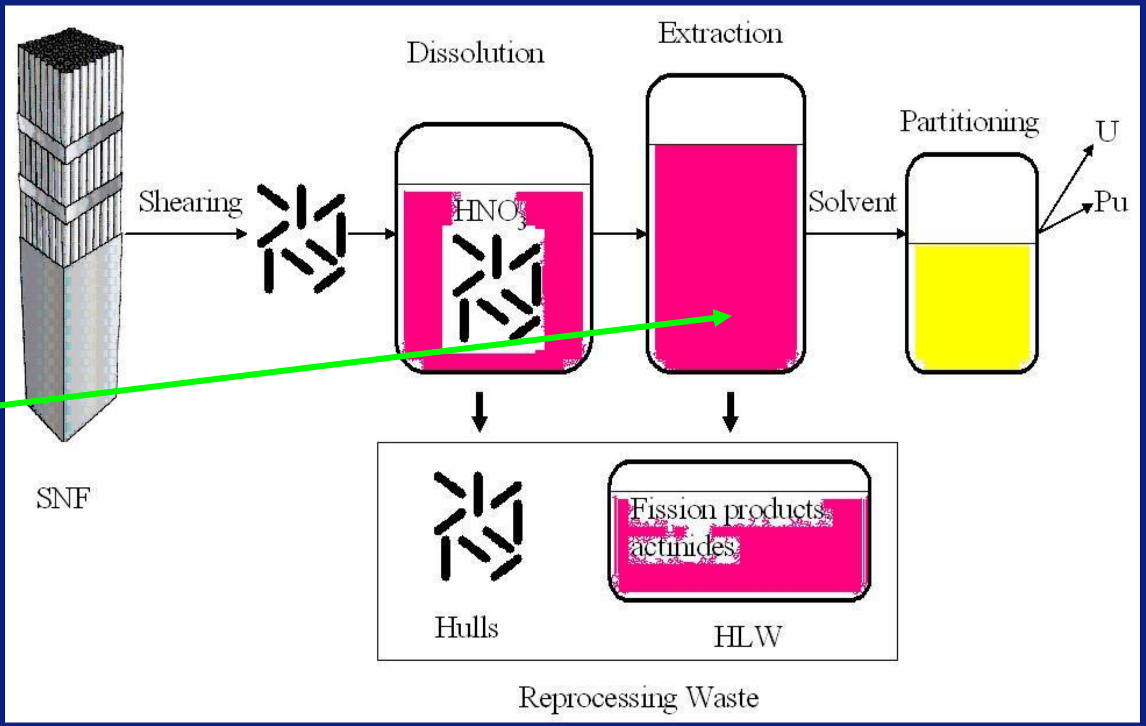
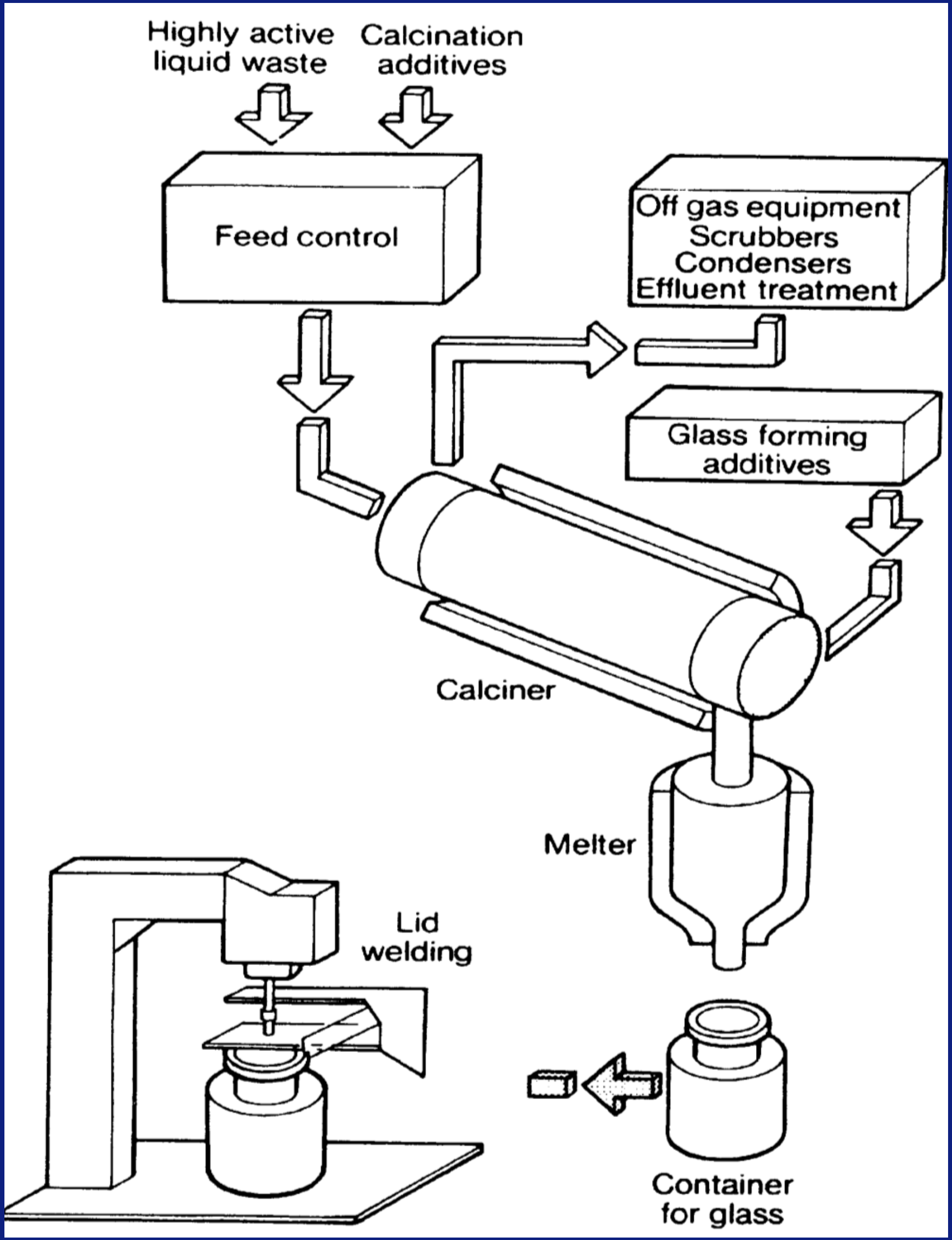
Plutonium and Uranium Extraction (Purex) Process.

Used at La Hague, France; THORP, Sellafield UK; Mayak, Russia; Rokkaso-mura, Japan.

Highly Active Liquor, HAL



- **Remove metal cladding and dissolve ceramic fuel in nitric acid.**
- **Pu & U chemically extracted, recycled in MOX (Mixed U/Pu OXide) fuel.**
- **Remnant HAL dried to form granulated HLW calcine.**



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HLW Vitrification Process

- HAL calcined to granular solid.
- Maximum calcination temp. ~500ºC.
- Discharge granular calcine to Inconel melter + borosilicate glass frit.
- Melt several hours at 1050ºC.
- Pour into SS canisters and allow to cool.

Temporary Storage of Canisters at Sellafield.

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- >5000 containers HLW currently stored at Sellafield.

ILW Encapsulation.

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- **Encapsulate solid, liquid or slurry wastes in cements.**

ILW Temporary Storage at Sellafield.

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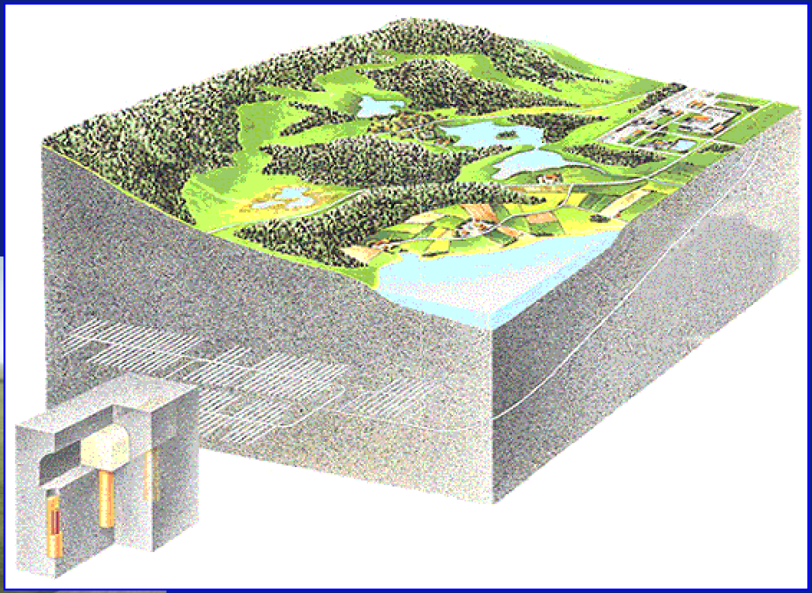
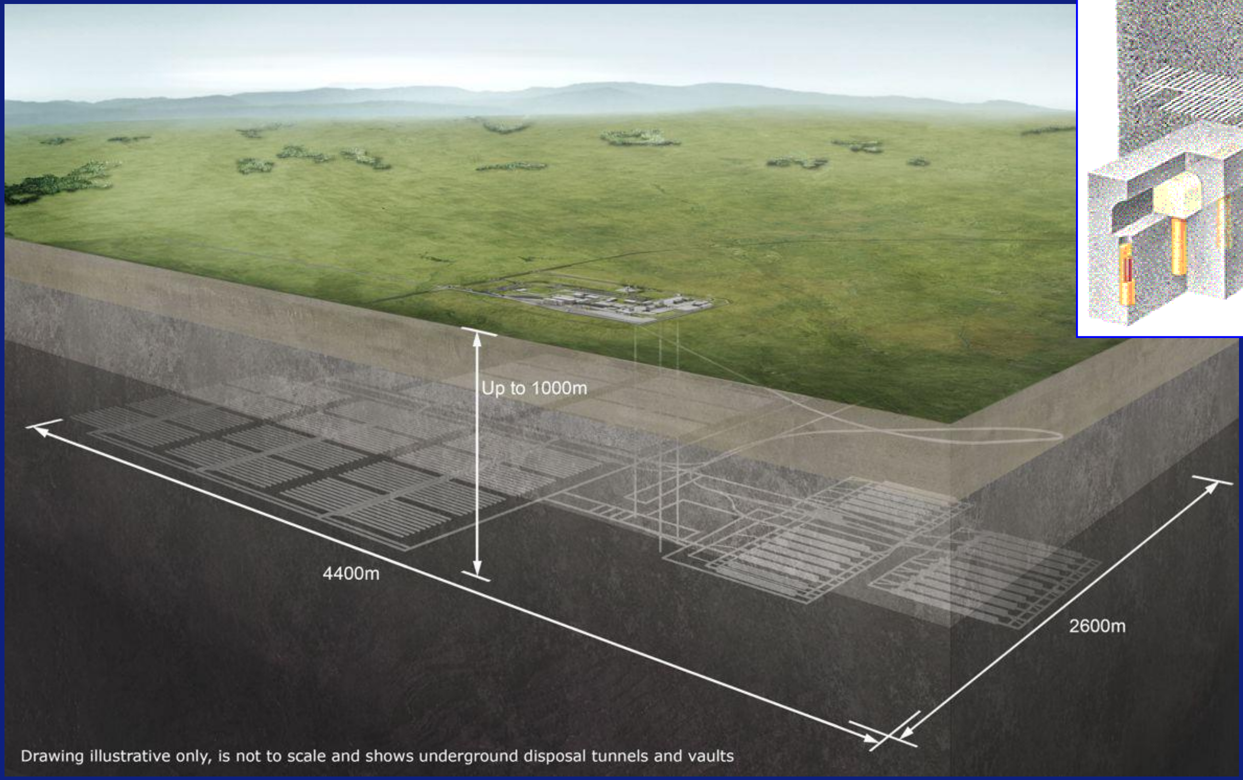
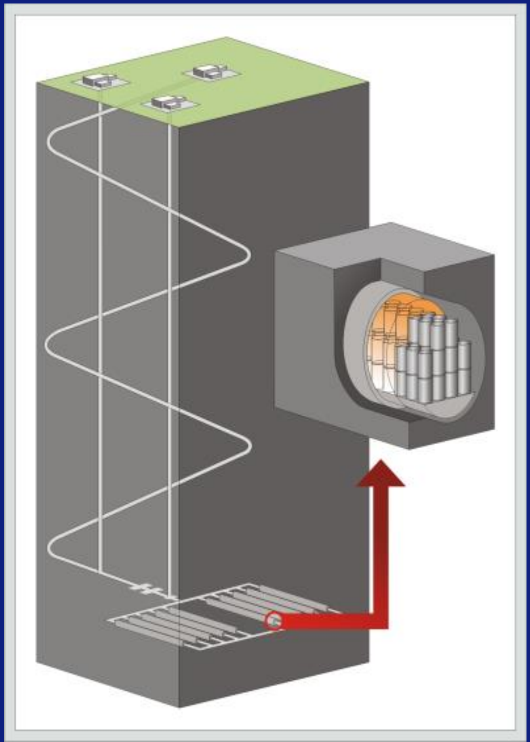
- 17000 cemented ILW containers currently stored at Sellafield

Geological Disposal of HLW/ILW.





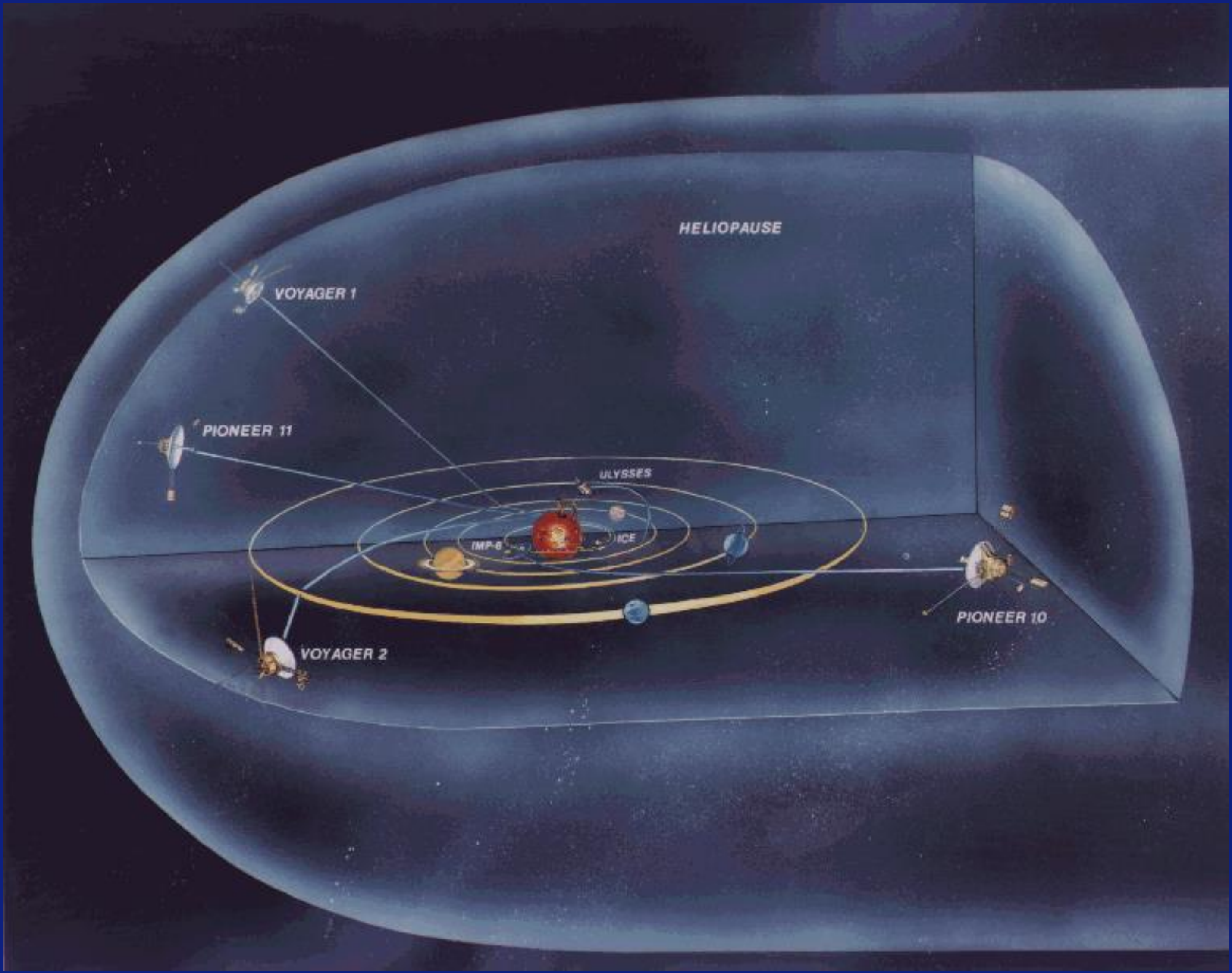


- **Is this a Mistake? What will Future Generations Think?**

Space Applications of Radionuclides

- Heat and Power.
- Used extensively but surreptitiously in space programmes.
- Even in Star Trek Into Darkness….exposure from ships nuclear reactor killed Captain Kirk.

Space, it's big



Romantic vision of space thanks to films, in reality it is:

- **Cold**
- **Unforgiving**
- **Full of intense radiation.**

Image courtesy of NASA

Space Power Options

- Chemical
  - Don’t last very long
  - Fuel cells need fuel
- Solar
  - Beyond Mars becomes ineffective
  - Orbit dependent
  - Easily damaged with large and complex deployment
  - Proven and cheap
- Nuclear
  - Expensive with limited supply
  - Launch safety challenge
  - Independent of orbit and location
  - Proven and reliable

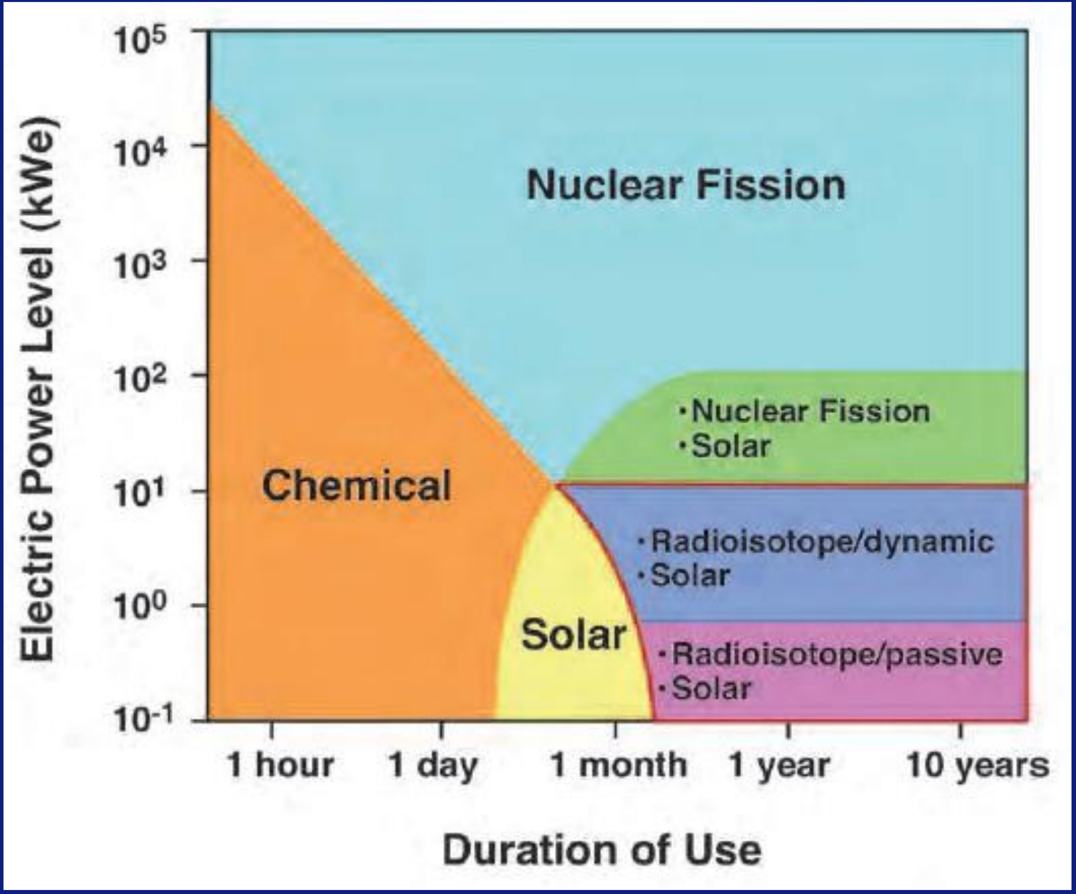


Image courtesy of NASA

Nuclear Systems used in Space

- Direct production of heat by radioactive decay (Radioisotope Heater Unit, RHU)
- Electrical power generation via radioactive decay heat (Radioisotope Power System, RPS)
  - Radioisotope Thermoelectric Generator (RTG)
- Nuclear reactor system
  - Electrical power & Electrical Propulsion (NEP)
  - Thermal Propulsion (NTP)

Radioisotope Heater Units (RHU)

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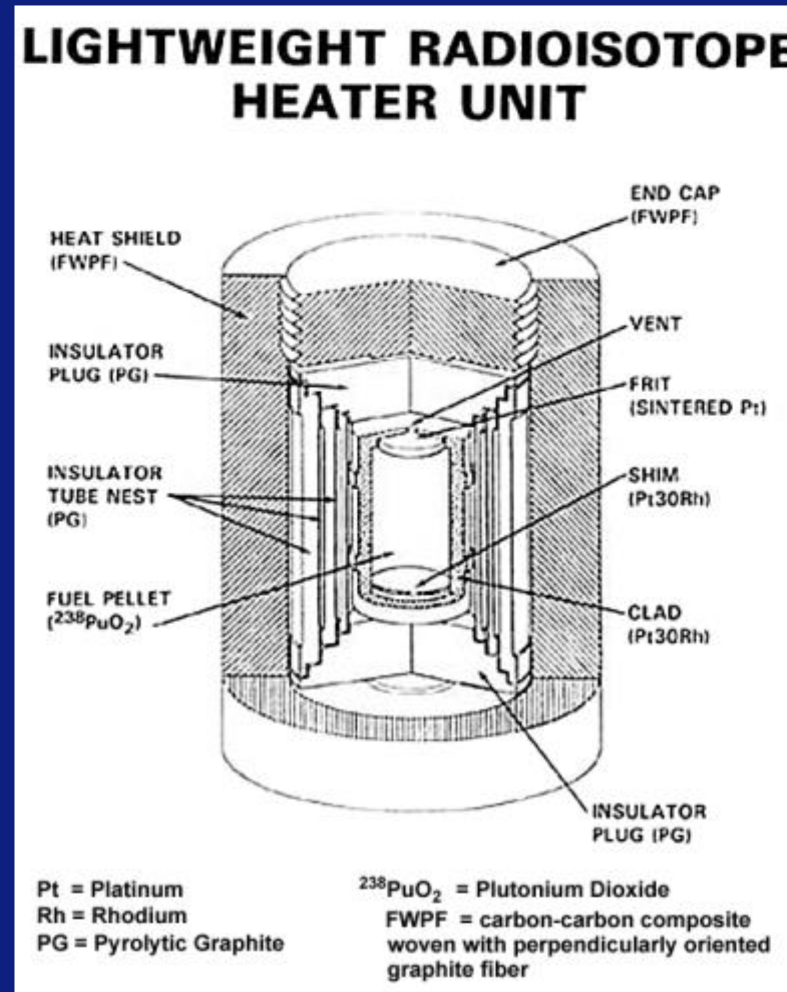
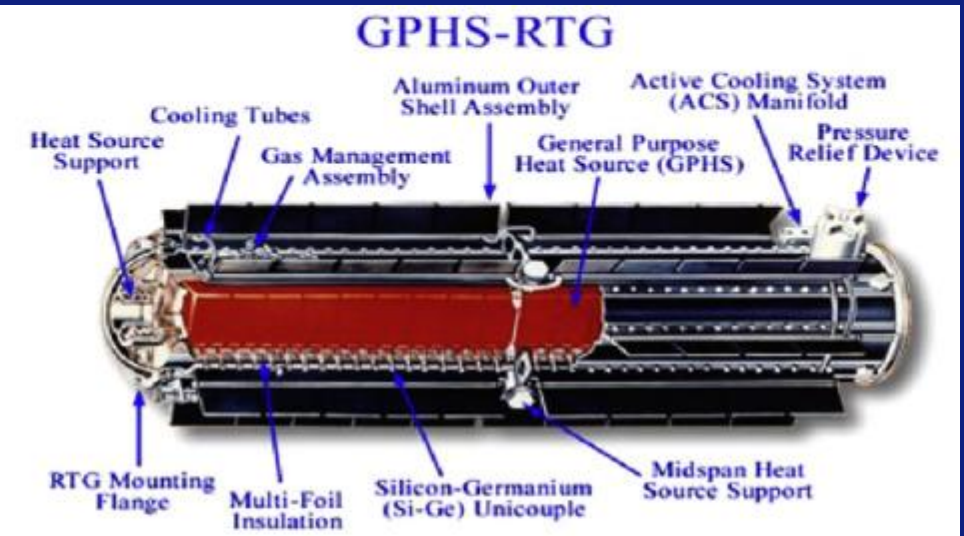
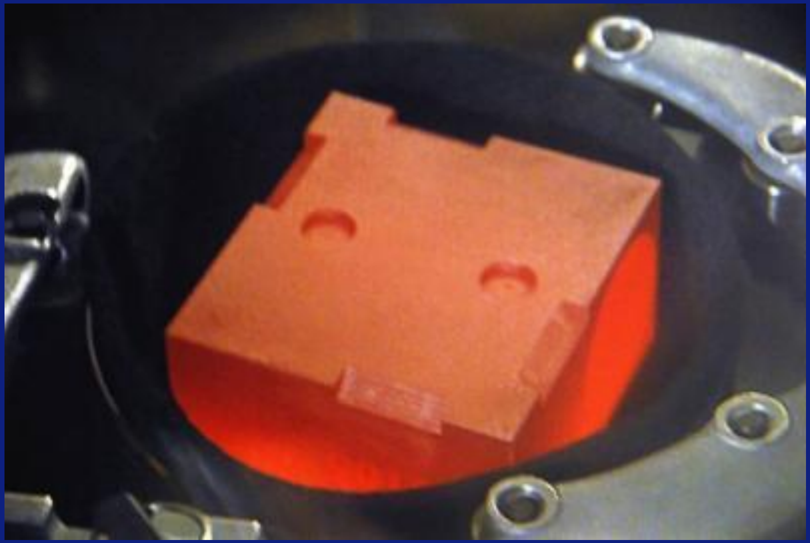
- Simple devices that use directly the heat from the decay of radioactive material
- RHU's are small (size of pencil top eraser) pellets of encapsulated radioactive material (e.g. PuO_2) within a protective capsule
- Used to keep vital spacecraft systems warm



Radioisotope Power Systems (RPS)?



- With no moving parts, Radioisotope Thermoelectric Generators (RTGs) convert heat from ^{238}Pu decay into electricity using thermoelectrics or other methods.



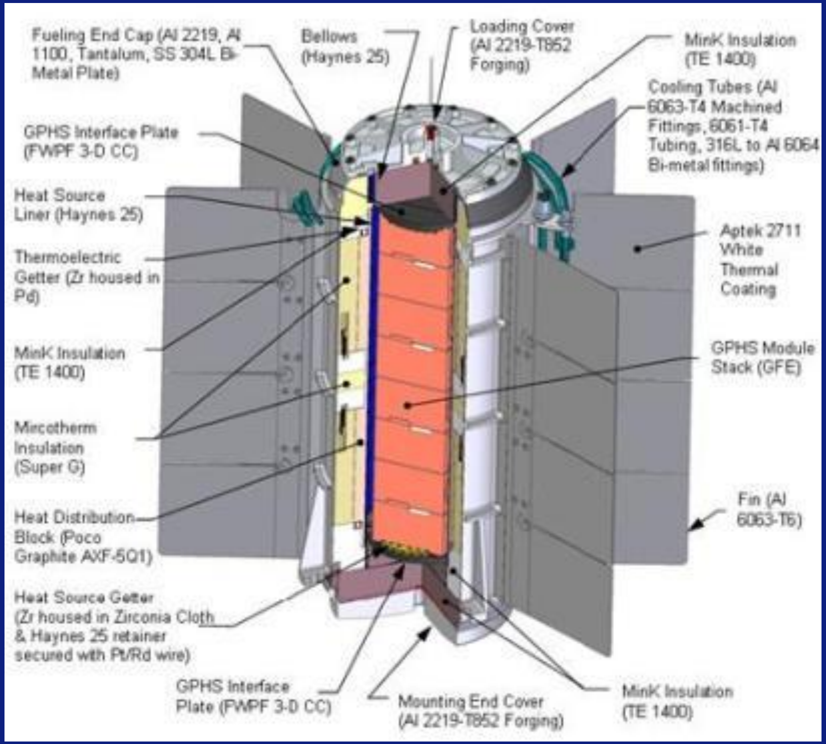


Image courtesy of NASA and US DoE

Radioisotope Power Missions

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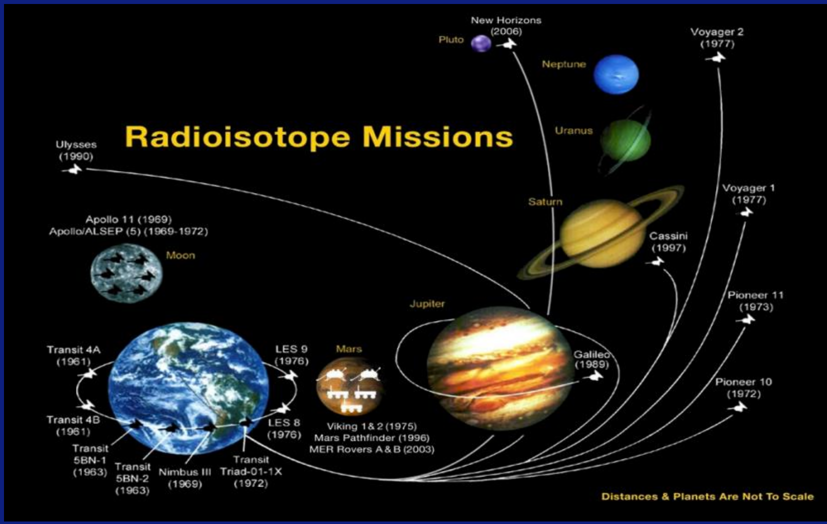
- 1961 first use US Navy transit 4A (System for Nuclear Auxiliary Power; SNAP 3)
- 1964 first failure, SNAP 9A did not make orbit (~1kg of Pu^{238})
- 1968 Nimbus B1 failure, Pu^{238} material recovered
- 1969 Apollo missions
- 1970 Lunokhod lunar rover (Solar & RHUs Po^{210})
- 1972-73 Pioneer 10, 11
- 1975 Viking landers
- 1976 LES-8&9
- 1977 Voyager 1, 2
- 1989 Galileo
- 1990 Ulysses
- 1996 Mars Pathfinder (USA) Mars 96 (failed Russian launch)
- 1997 largest mass of Pu^{238} launched, Cassini-Huygens (33kgs)
- 2003 MER Mars rovers A&B
- 2006 New Horizons
- 2011 Mars Science Lab (Curiosity Rover)
- 2013 China became 3rd country to launch (RHUs)



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Mars Landers

- Viking 1 and 2 (1975)
- First space “selfie” by Viking 2
- Design life 60 days
- Mission life 4-6 years
- Heavier RTG to manage atmosphere and temperature changes

- 19 RTG’s provided Systems for Auxiliary Nuclear Power (SNAP)

Image courtesy of NASA

Perception of Risk: Health Effects of Energy Production

Deaths and illness expressed as per TW (W^{12})/h for different sources of energy

	Deaths from accidents		Air pollution-related effects		
	Among the public	Occupational	Deaths*	Serious illness†	Minor illness‡
Lignite[30]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	32·6 (8·2–130)	298 (74·6–1193)	17 676 (4419–70 704)
Coal[31]	0·02 (0·005–0·08)	0·10 (0·025–0·4)	24·5 (6·1–98·0)	225 (56·2–899)	13 288 (3322–53 150)
Gas[31]	0·02 (0·005–0·08)	0·001 (0·0003–0·004)	2·8 (0·70–11·2)	30 (7·48–120)	703 (176–2813)
Oil[31]	0·03 (0·008–0·12)	..	18·4 (4·6–73·6)	161 (40·4–645·6)	9551 (2388–38 204)
Biomass[31]	..	..	4·63 (1·16–18·5)	43 (10·8–172·6)	2276 (569–9104)
Nuclear[31,32]	0·003	0·019	0·052	0·22	..

Markandya and Wilkinson, Lancet (2007) 370: 979-90

Risks of Radiation Compared with Other Health Risks

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Exposure scenario	Exposure	Health endpoint	Approximate lifetime increased mortality
Living in Central London compared to Inverness.	Mix of air pollutants indicated by average $PM_{2.5}$ = 6.9 μg m^{-3} higher.	Mortality	**2.8 %** Postulated 2.8% higher air pollution related mortality in central London compared to Inverness (see text).
N.B. Extrapolates from data in the US. May be confounding factors which, if accounted for, would change the excess risk. Time-lag between exposure and effect is uncertain.			
Passive smoking – risk to non-smoker at home if spouse smokes.	Mix of pollutants in secondhand smoke.	Mortality	**1.7 %** 1.7% lifetime excess IHD mortality risk from passive smoking: average for men and women [36].
N.B. Heart disease risk: does not include strokes or the (significantly lower) risk from lung cancer or other illnesses. May be confounding factors/ limitations of meta-analysis data.			
Chernobyl emergency workers in the 30-km Zone 1986–87.	Radiation exposure: 100 mSv 250 mSv	Mortality	 **0.4 %** **1.0 %**

Smith BMC Public Health 2007 7:49

Take Home Messages

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- Radionuclides are ubiquitous, pervasive and perfectly natural.
- We have evolved to be tolerant of radiation.
- Radionuclides use in medicine saves and extends life.
- All types of energy generation have risks and benefits.
- How we generate energy affects climate change and effects of climate change may kill 150,000 per year.
- Nuclear is a safe, reliable and low C form of base-load electricity.
- We can deal with radioactive waste but need community buy-in.
- Without radionuclides forget about space exploration.
- Don't believe everything you read on the internet or in the media – look at the evidence for yourself.

- E.g. watch Pandora's Promise: http://pandoraspromise.com