Radiation Applications

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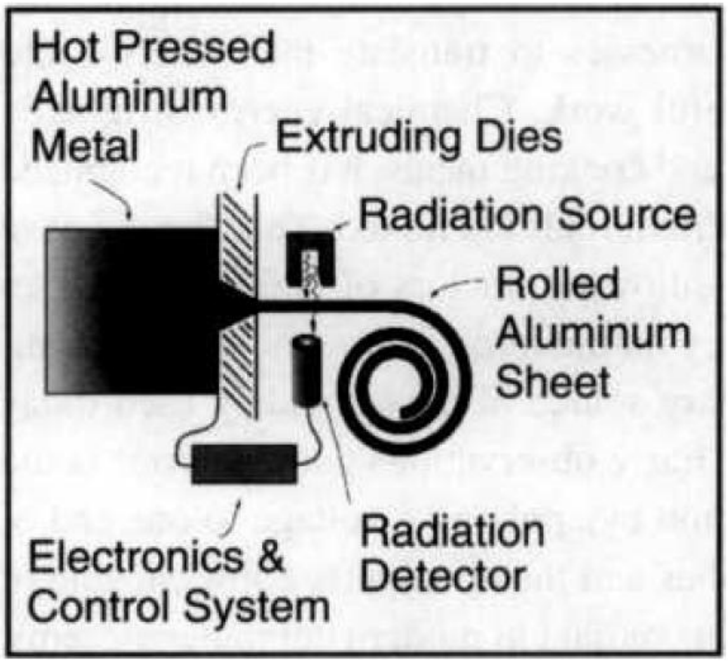
Material penetration

- Different types of particles emitted during radioactive decay have unique material penetration powers.
- If a beam of electrons (beta particles) of a known energy is focused upon a thin sheet of aluminum, the precise thickness of that sheet can be determined by measuring the reduction in the beam current on the other side of the metal.

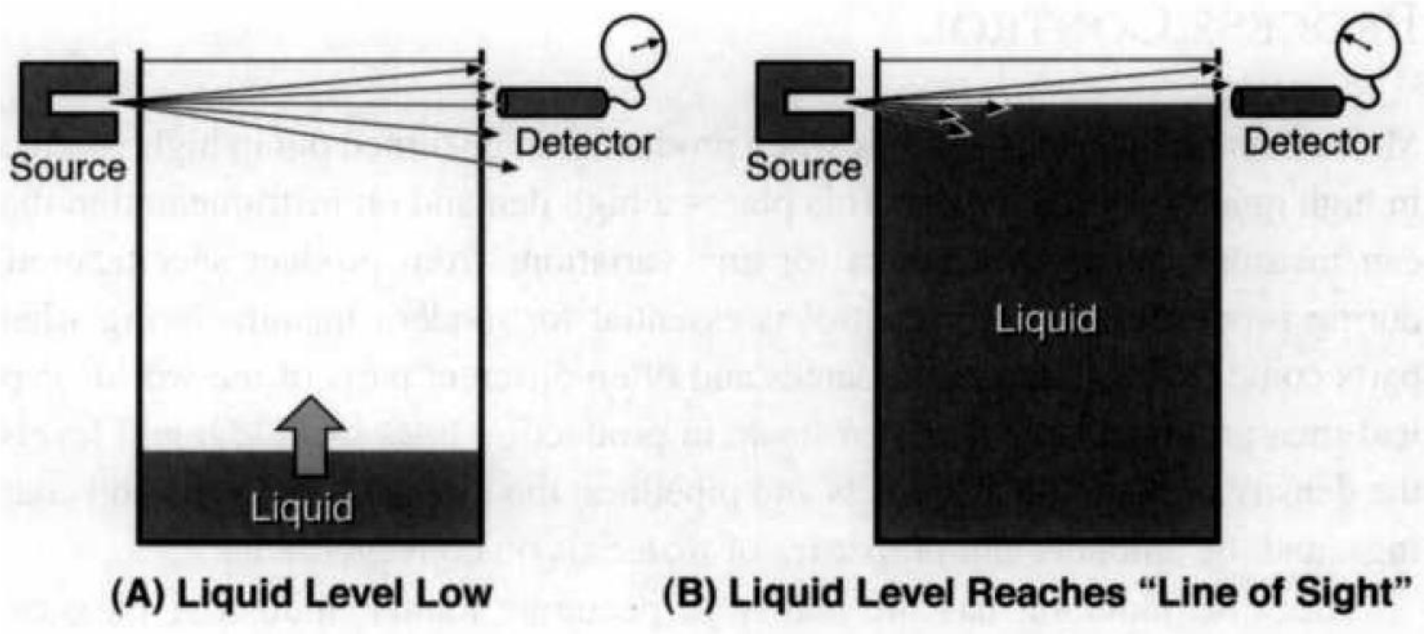


Thickness monitor

X-ray imaging

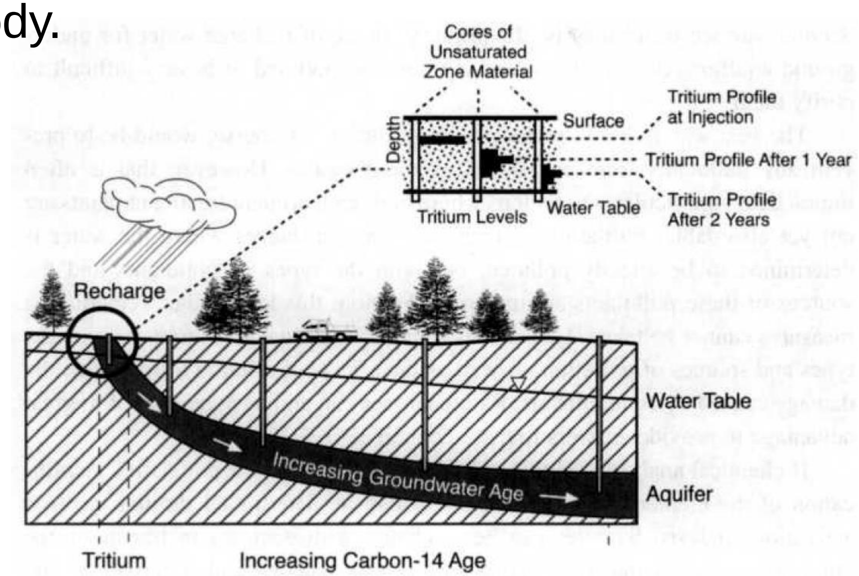
Material penetration

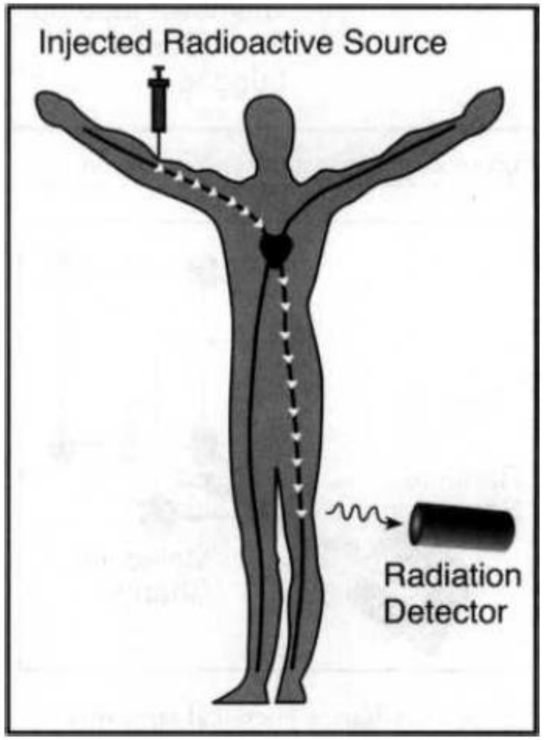
- Because radiation has the ability to penetrate matter, industrial measurements can be made using radioisotopes without the need for direct physical contact with either the source or the sensor. This allows on-line measurements to be made, nondestructively, while the material being measured is in motion.



Tracer

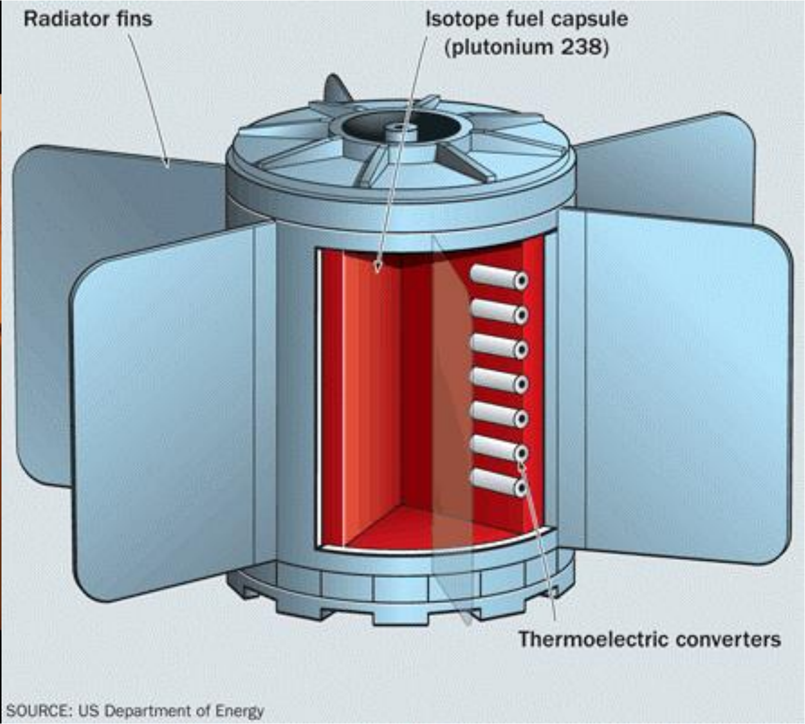
- Since gamma rays can penetrate through a relatively large mass, it is possible to attach specialty gamma emitters to materials via chemical means that can easily be transported by fluids.
- Such a linkage allows the gamma-emitting radioisotopes to flow through a set of pipelines or blood vessels, thus allowing the location of this radioactive material to be measured as a function of time.
- This tracer or labeling technique is routinely used to map groundwater movement, detect pipe leaks in the petroleum industry, and diagnose ailments in the human body.





Atomic batteries

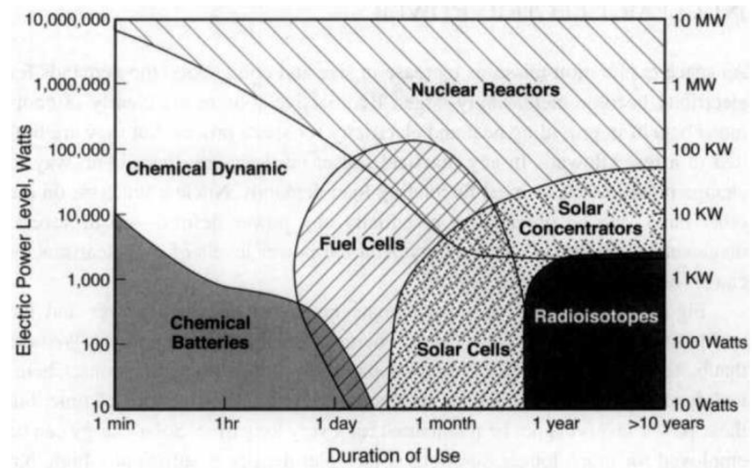
- Atomic batteries, nuclear batteries or radioisotope generators are devices that use energy from radioactive decay to generate electricity. Similar to nuclear reactors, they generate electricity from atomic energy, but differ in that they do not use chain reactions and instead use continual radioactive emissions to generate electricity.



RTG (Radioisotope thermoelectric generator)

Atomic batteries

- Figure illustrates the approximate ranges of electrical power and the usable lifetimes for the various energy sources available for space travel.
- Note that radioisotope sources can contribute a very long life, but the total power available is limited. Nuclear reactors, on the other hand, can produce a very high range of power and, properly designed, can also operate for quite long periods of time.

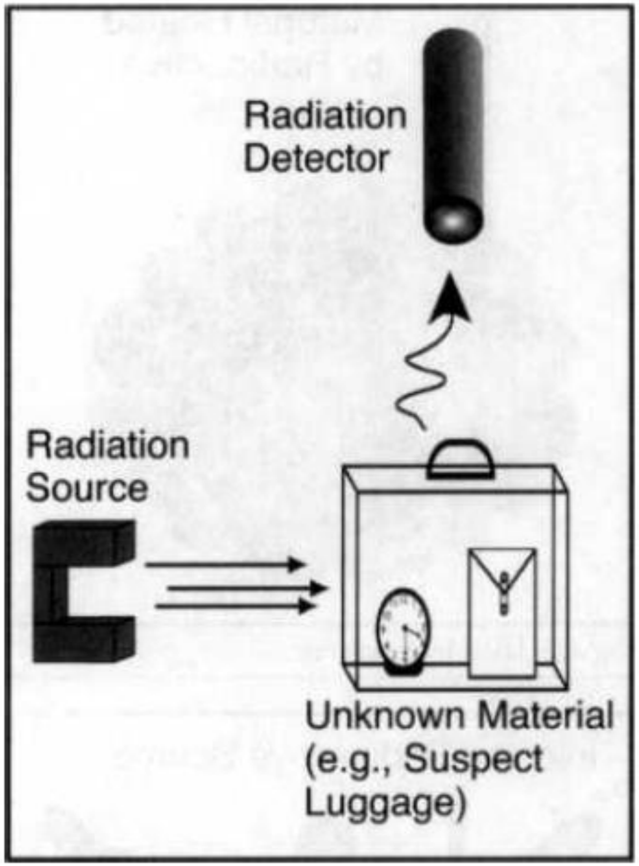


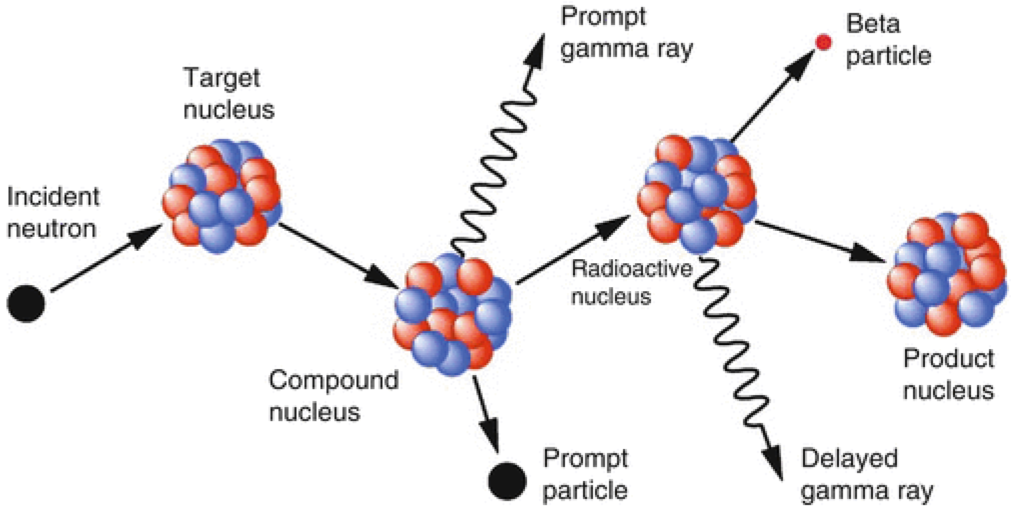
Material	Shielding	Power density (W/g)	Half-life (years)
^{238}Pu	Low	0.54	87.7
^{90}Sr	High	0.46	28.8
^{210}Po	Low	140	0.378
^{241}Am	Medium	0.114	432

Name and model	Used on (# of RTGs per user)	Maximum output		Radio-isotope	Max fuel used (kg)	Mass (kg)	Power/mass (Electrical W/kg)
		Electrical (W)	Heat (W)				
MMRTG	MSL/*Curiosity* rover	c. 110	c. 2000	^{238}Pu	c. 4	<45	2.4
GPHS-RTG	*Cassini* (3), *New Horizons* (1), *Galileo* (2), *Ulysses* (1)	300	4400	^{238}Pu	7.8	55.9–57.8[51]	5.2–5.4
MHW-RTG	LES-8/9, *Voyager 1* (3), *Voyager 2* (3)	160[51]	2400[52]	^{238}Pu	c. 4.5	37.7[51]	4.2
SNAP-3B	Transit-4A (1)	2.7[51]	52.5	^{238}Pu	?	2.1[51]	1.3
SNAP-9A	Transit 5BN1/2 (1)	25[51]	525[52]	^{238}Pu	c. 1	12.3[51]	2.0
SNAP-19	Nimbus-3 (2), Pioneer 10 (4), Pioneer 11 (4)	40.3[51]	525	^{238}Pu	c. 1	13.6[51]	2.9
modified SNAP-19	Viking 1 (2), Viking 2 (2)	42.7[51]	525	^{238}Pu	c. 1	15.2[51]	2.8
SNAP-27	Apollo 12–17 ALSEP (1)	73	1,480	^{238}Pu[53]	3.8	20	3.65
(fission reactor) Buk (BES-5)**	US-As (1)	3000	100,000	highly enriched ^{235}U	30	1000	3.0
(fission reactor) SNAP-10A***	SNAP-10A (1)	600[54]	30,000	highly enriched ^{235}U		431	1.4
ASRG****	prototype design (not launched), Discovery Program	c. 140 (2x70)	c. 500	^{238}Pu	1	34	4.1

Transmission/activation

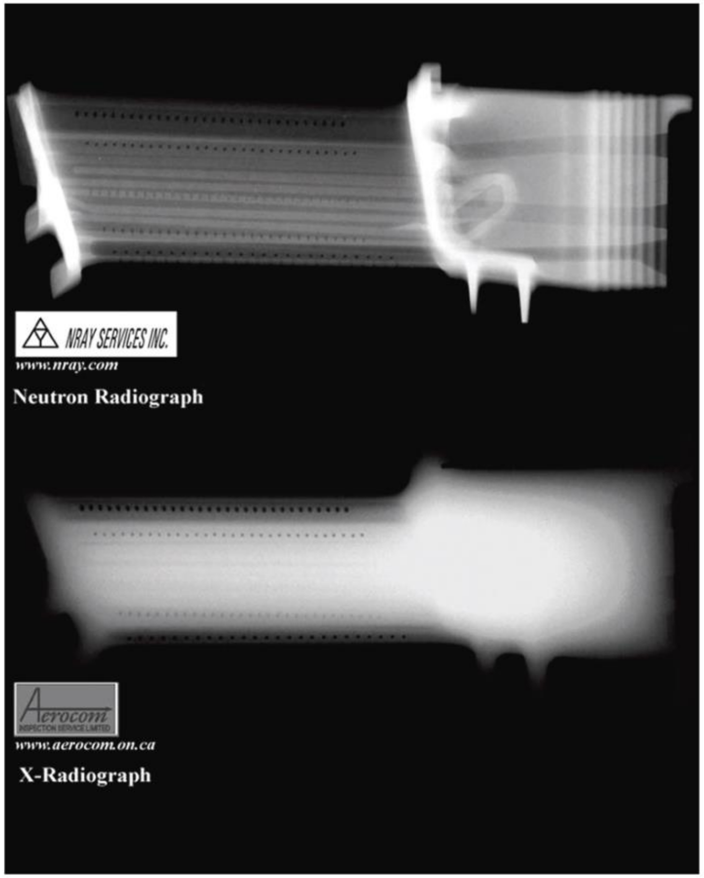
- By focusing a beam of neutrons on unknown materials, it is possible to transmute (fundamentally change) the target material into another isotope (or possibly an isotope of a different element). If this new isotope is radioactive, it will emit a radioactive signature that uniquely determines its identity.



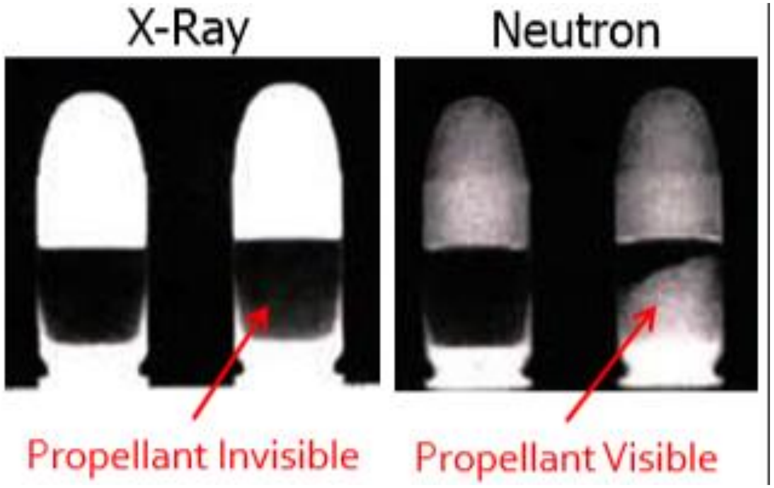


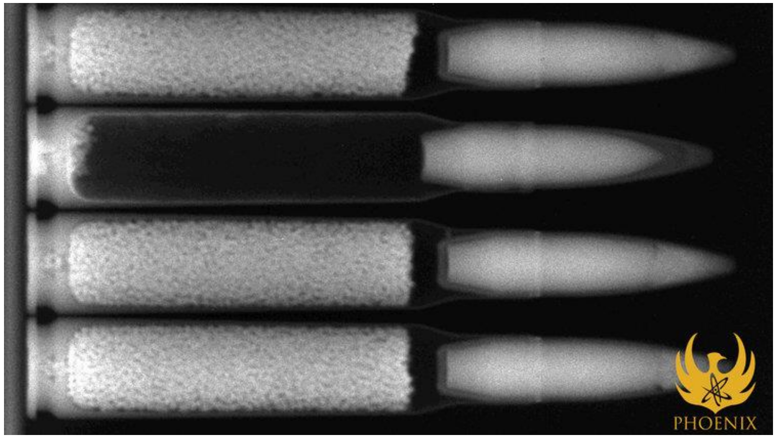
Neutron radiography

- Neutrons can penetrate metals better than x-rays and reveal internal structures.



Images of Metal-Alloy Turbine Blades From Nray Services Inc. (Canada)

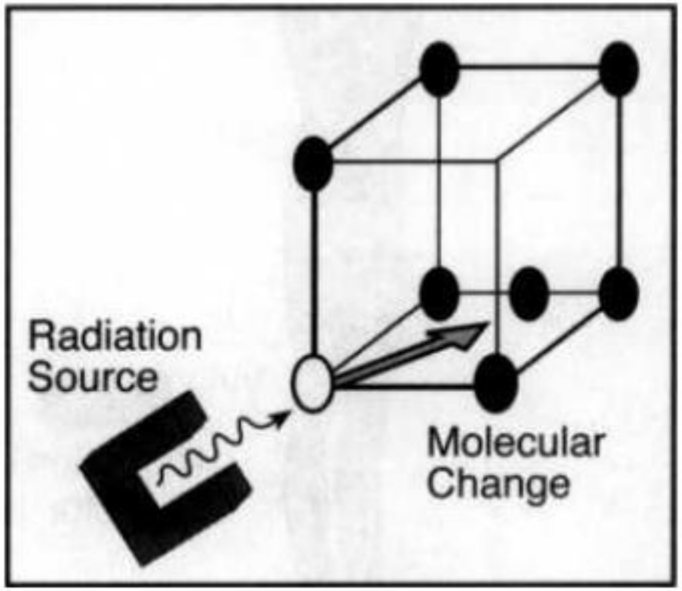


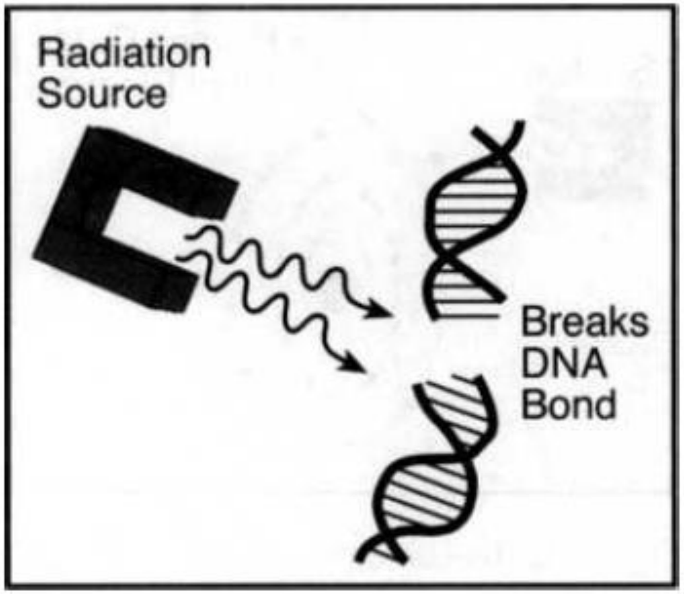


Phoenix Nuclear Lab (PNL, USA)

Change chemical structure or cell destruction

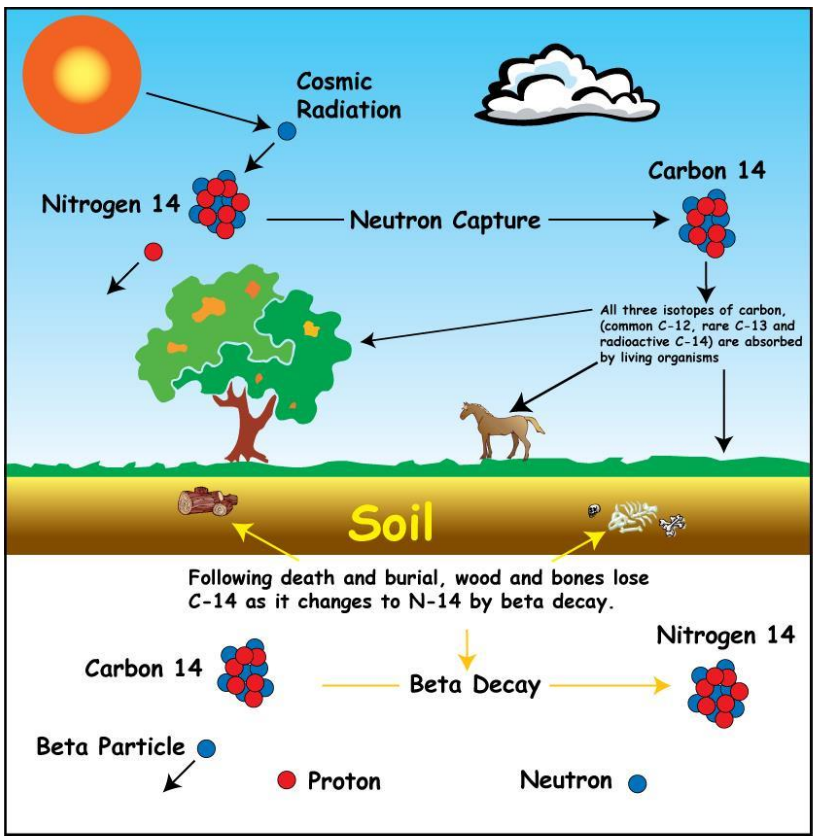
- Bombarding some materials with intense beams of gamma rays, electrons, or neutrons can break molecular bonds and evolve new types of materials (i.e., change the chemical or physical structure). Such treatment is used to produce stronger plastics or increase the rate of a chemical reaction. This approach is even used to enrich the color and brilliance of some types of gemstones by slightly modifying their structure.
- Controlled amounts of beta particles, x-rays, or gamma rays can be used to kill unwanted insects or microorganisms.

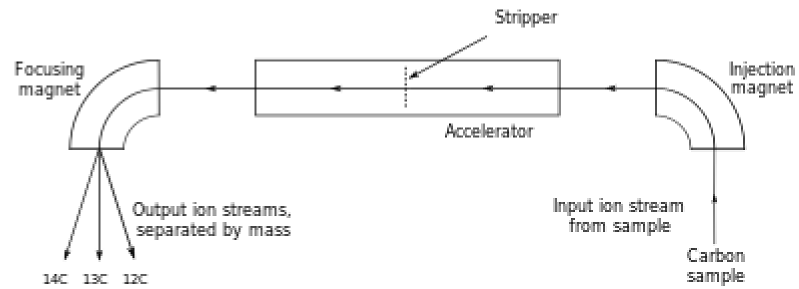


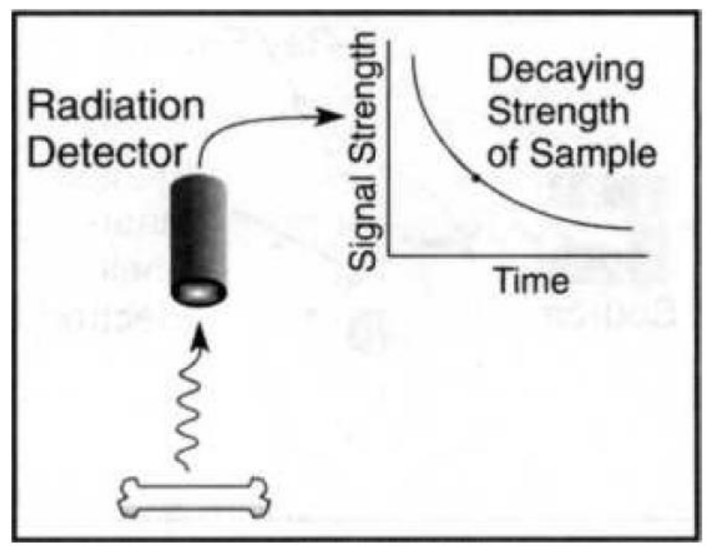


Decay time: aging analysis

- Knowing the "half-lives" of certain radioactive species, it is possible to perform aging analyses on a variety of archeological artifacts-including the age of Earth.
- This is the technique used to determine prehistorical climate changes, the role of the industrial age in contributing to greenhouse gases, and so on.

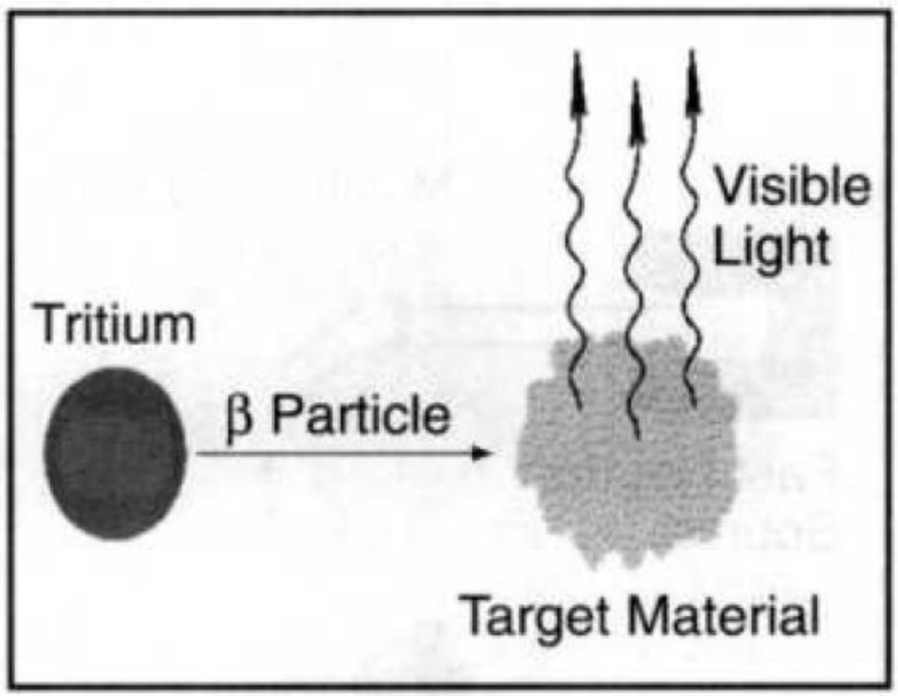






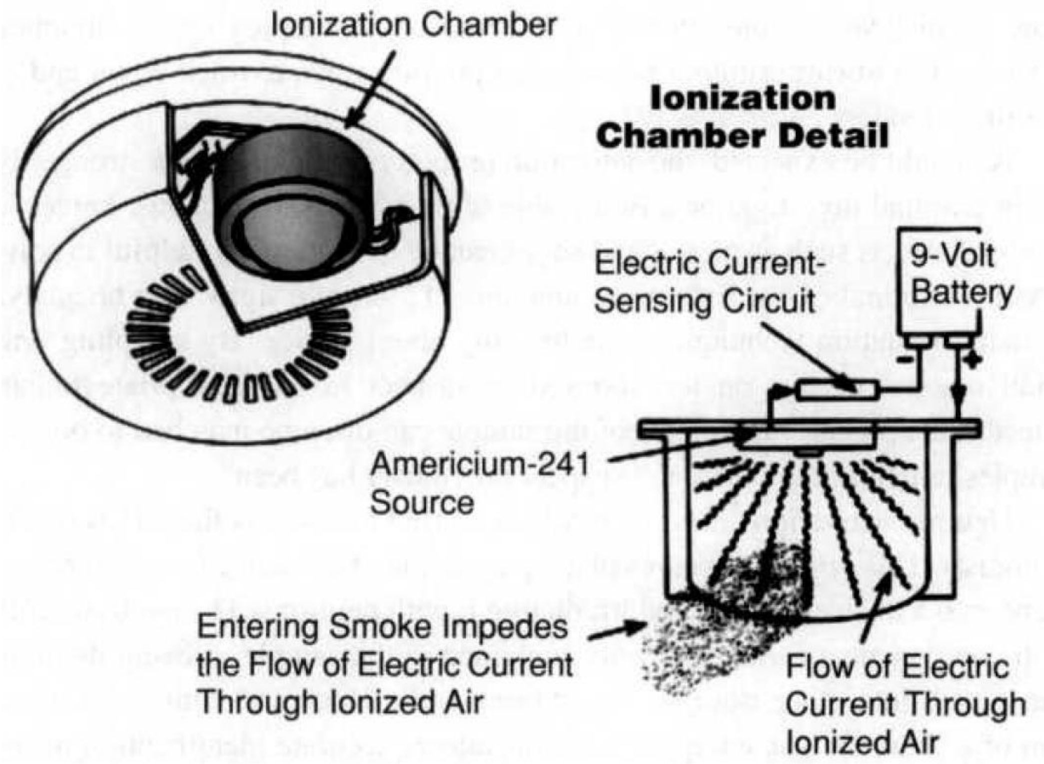
Self-powered lighting

- Tritium emits electrons through beta decay and, when they interact with a phosphor material, light is emitted through the process of phosphorescence.
- The overall process of using a radioactive material to excite a phosphor and ultimately generate light is called radioluminescence.



Smoke detector

- A household smoke detector contains a small amount of a special radioisotope (mostly Am-241) that constantly emits alpha particles into an ion chamber.
- During normal atmospheric conditions, a small but steady electric ion current is actively recorded. However, if a fire occurs, smoke particles enter the chamber and reduce the ion current. The change in current triggers the smoke alarm.

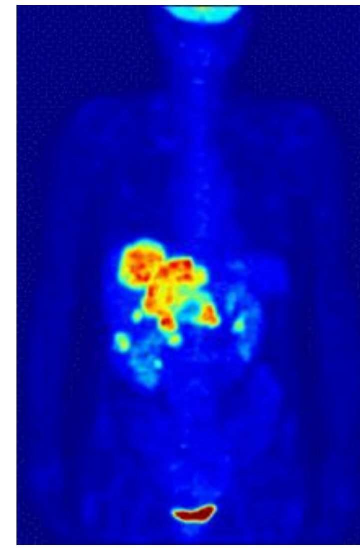


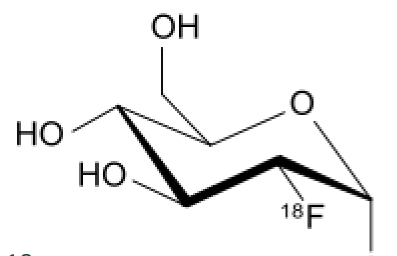
PET (positron emission tomography)

- The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide, most commonly fluorine-18. which is introduced into the body on a biologically active molecule called a radioactive tracer.

$$\text{O-18} \xrightarrow{p \text{ (Cyclotron)}} \text{F-18} \xrightarrow[110\text{ m}]{\beta^+} \text{O-18}$$

$$e^+ + e^- \rightarrow 2\gamma$$





^{18}F-FDG

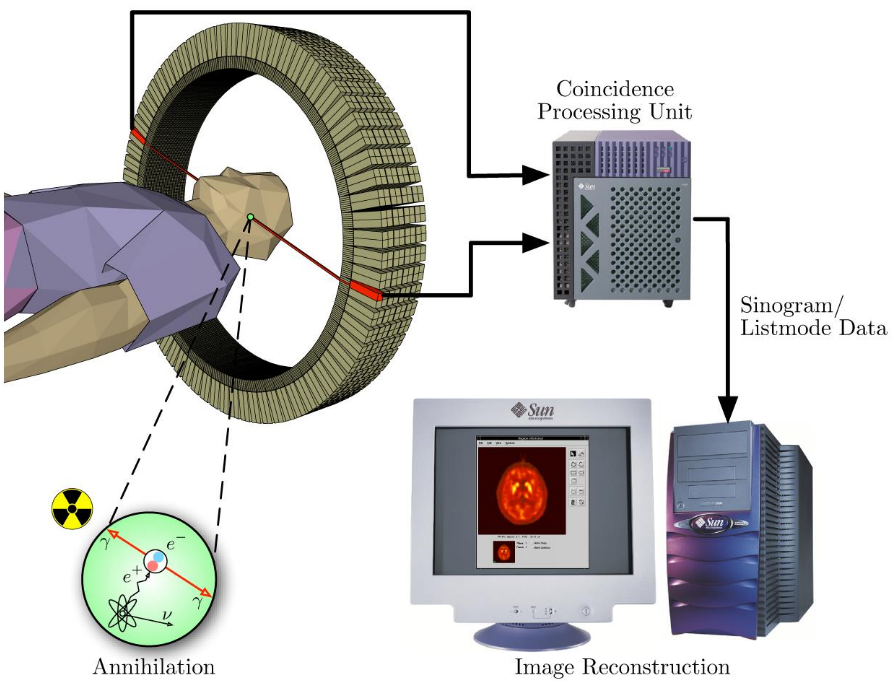


TABLE 2.1. THE MOST COMMONLY USED POSITRON EMITTERS AND TYPICAL REACTIONS FOR THEIR PRODUCTION

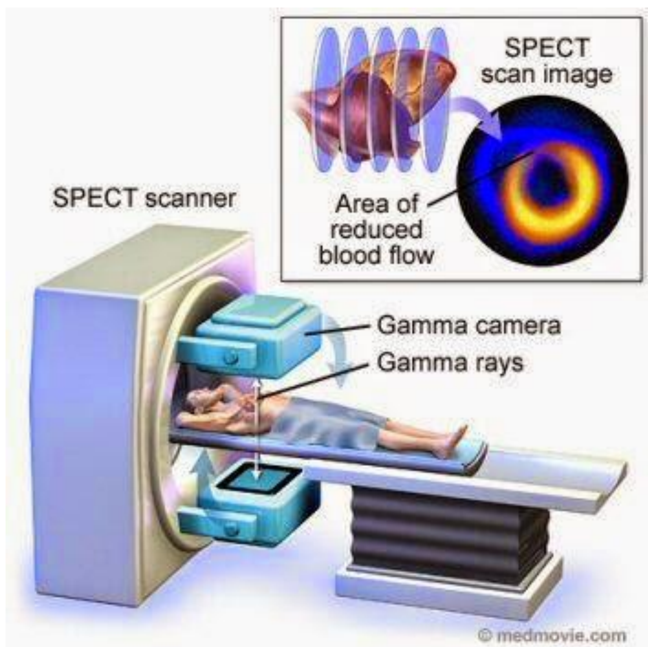
Radionuclide	$t_{1/2}$ (min)	Decay mode	Reaction	Energy (MeV)
C-11	20.3	β^+	^{14}N(p, α)	11–17
N-13	9.97	β^+	^{16}O(p, α) ^{13}C(p, n)	19 11
O-15	2.03	β^+	^{15}N(p, n) ^{14}N(d, 2n) ^{16}O(p, pn)	11 6 >26
F-18	110	β^+	^{18}O(p, n) ^{nat}Ne(d, α)	11–17 8–14

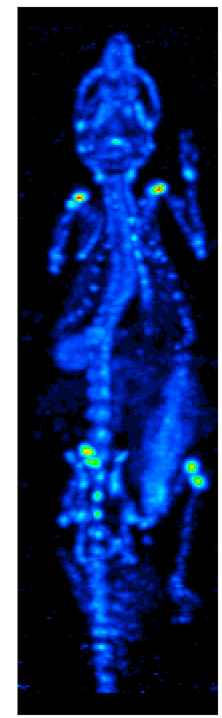
SPECT (single-photon emission computed tomography)

- SPECT is a nuclear medicine tomographic imaging technique using gamma rays. It is similar to PET in its use of radioactive tracer material and detection of gamma rays. In contrast with PET, however, the tracers used in SPECT emit gamma radiation that is measured directly.

$$\text{Mo-98} \xrightarrow{\text{n (Reactor)}} \text{Mo-99} \xrightarrow[66\text{ h}]{\beta^-} \text{Tc-99m}$$

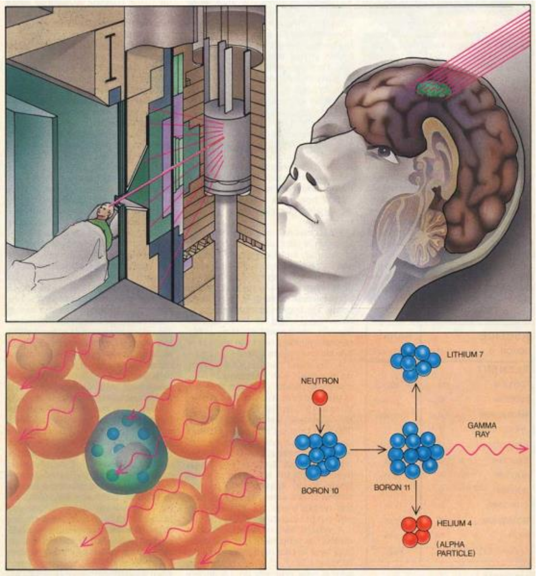
$$^{99m}_{43}\text{Tc} \xrightarrow[6\text{ h}]{\gamma\ 141\text{ keV}} {}^{99}_{43}\text{Tc} \xrightarrow[211{,}000\text{ y}]{\beta^-\ 249\text{ keV}} \overbrace{^{99}_{44}\text{Ru}}^{\text{ruthenium}-99}\ (\text{stable})$$





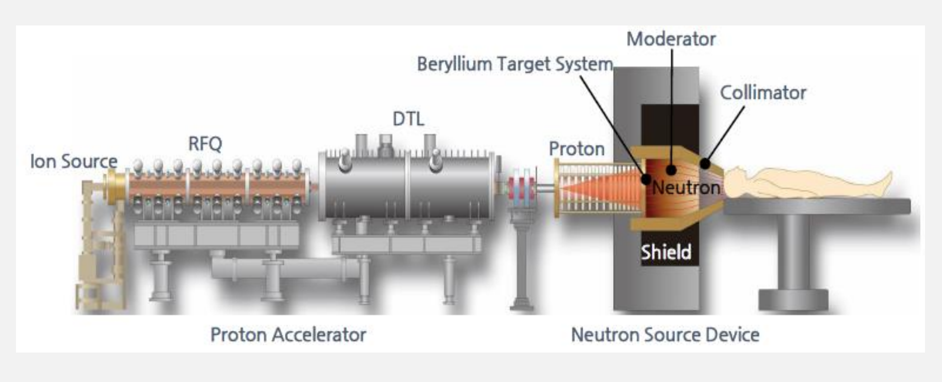
BNCT (boron neutron capture therapy)

- Neutron capture therapy (NCT) is a noninvasive therapeutic modality for treating locally invasive malignant tumors such as primary brain tumors and recurrent head and neck cancer.
- It is a two-step procedure:
  ① The patient is injected with a tumor-localizing drug containing the non-radioactive isotope boron-10 (^{10}B) that has a high cross section to capture slow neutrons.
  ② The patient is radiated with epithermal neutrons, the source of which is either a nuclear reactor or, more recently, an accelerator.



$$^{10}B + n_{th} \rightarrow [^{11}B]^{*} \rightarrow \alpha + {}^{7}Li + 2.31\ \text{MeV}$$

Heavy charged particles: short range (< 10 um), localized dose



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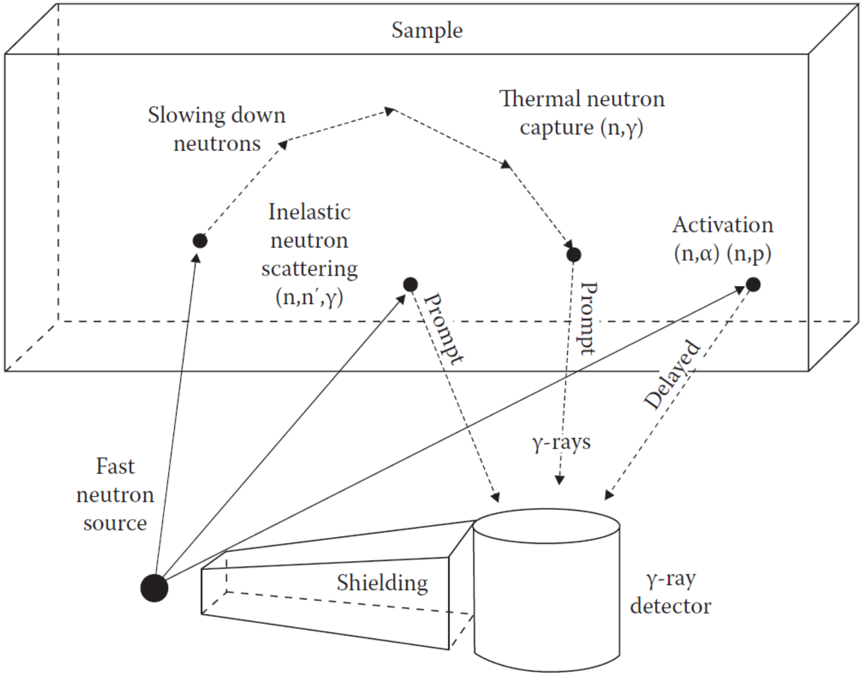
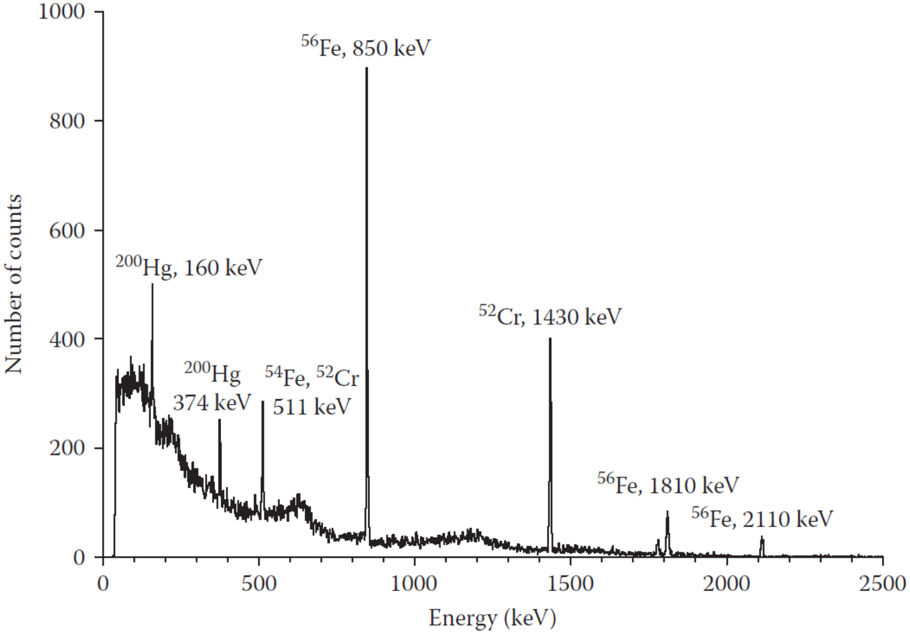
Neutron activation analysis

- With NAA (neutron activation analysis), samples are irradiated with highly thermalized neutrons inside the reactor and then taken to a low background counting area where the induced radioactive decay products are analyzed.
- The intensities of the obtained specific gamma rays provide information about the number of atoms in the sample. Hence, the information on its chemical composition can be extracted from the measured gamma ray spectrum.





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Neutron activation analysis

- There are several distinguished methodologies of using neutrons as an analytical tool.

Basic facts on neutron based techniques relevant for non-intrusive inspection [1,2]

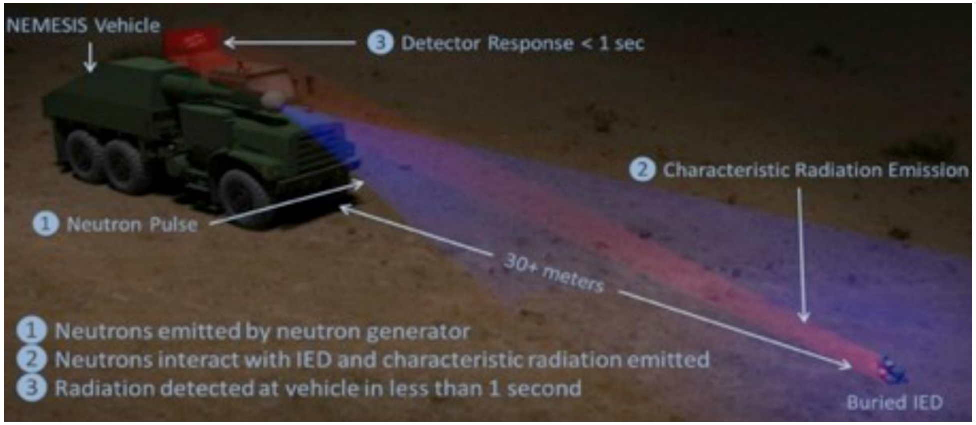
#	Technique name	Probing radiation	Main nucl. reaction	Detected radiation	Sources	Primary/secondary detected elements
1	TNA	Thermalized neutrons	(n, γ)	Neutron capture γ-rays (prompt & delayed neutrons for SNM)	^{252}Cf, also accelerator based sources (ENG[a])	Cl, N, SNM[b] H, Metals, P, S
2	FNA	Fast (high energy, usually 14 MeV) neutrons	$(n, n'\gamma)$	γ-rays produced from inelastically scattered neutrons	ENG based on (d,T)	O, C (N) (H) Cl, P
3	FNA/ TNA	Pulsed neutron source; fast neutrons during the pulse, thermal neutrons between pulses	$(n, n'\gamma) + (n, \gamma)$	During pulse #2 + after pulse – #1	μs pulsed ENG based on (d,T)	N, Cl, SNM H, C, O, P, S
4	PFNA	Nanosecond (ns) pulses of fast neutrons	$(n, n'\gamma)$	Like FNA (#2) (prompt & delayed neutrons for SNM)	ns pulsed (d,D) accelerator with $E_d \sim 6$ MeV	O, C, N, Cl, Others, SNM H, Metals, Si, P, S, Others
5	API	14 MeV neutrons in coincidence with the associated α-particles	$(n, n'\gamma)$	Like FNA in delayed coincidence with α	(d,T)	O, C, N Metals
6	NRA	ns pulsed fast neutrons (0.5–4 MeV), broad energy spectrum	(n, n)	Elastically and resonantly scattered neutrons	ns pulsed (d,Be) accelerator, with $E_d \leqslant 4$ MeV	H, O, C, N (Others)

[a] Electronic neutron generator – can be based on neutron production processes such as (d,D), (d,T), (d,Be), (P,Li), (P,Be).
[b] Special nuclear materials – ^{235}U and ^{239}Pu.

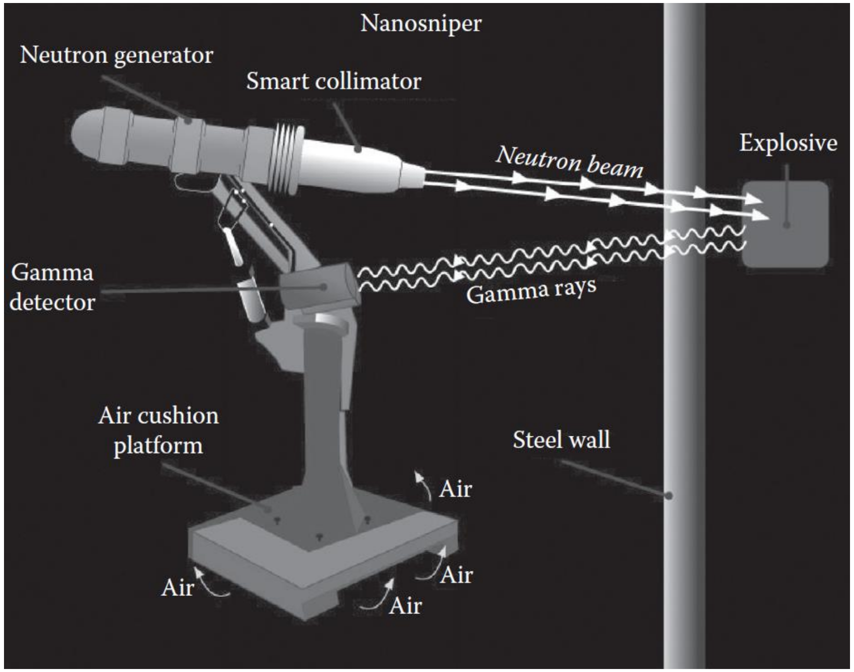
TNA: Thermal neutron analysis
FNA: Fast neutron analysis
PFNA: Pulsed fast (nanosecond) neutron analysis
PFNTS: Pulsed fast neutron transmission spectroscopy
API: Associated particle imaging
PFTNA: Pulsed fast and thermal neutron analysis
FNSA: Fast neutron scattering analysis

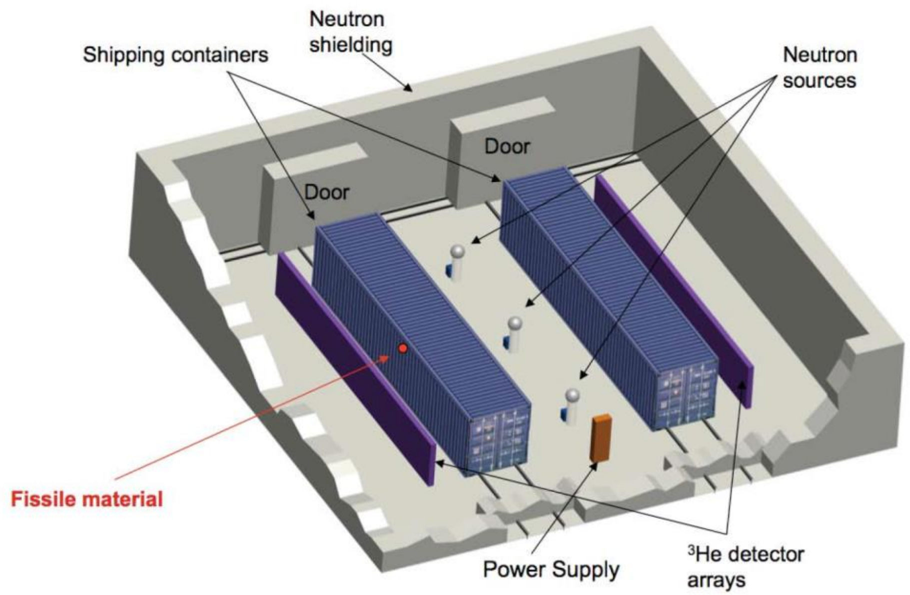
Neutron activation analysis

- Landmine detection
- Explosive detection
- Detection of special nuclear material



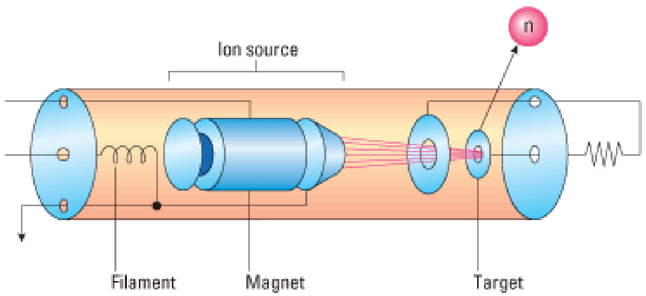
IED: improvised explosive device

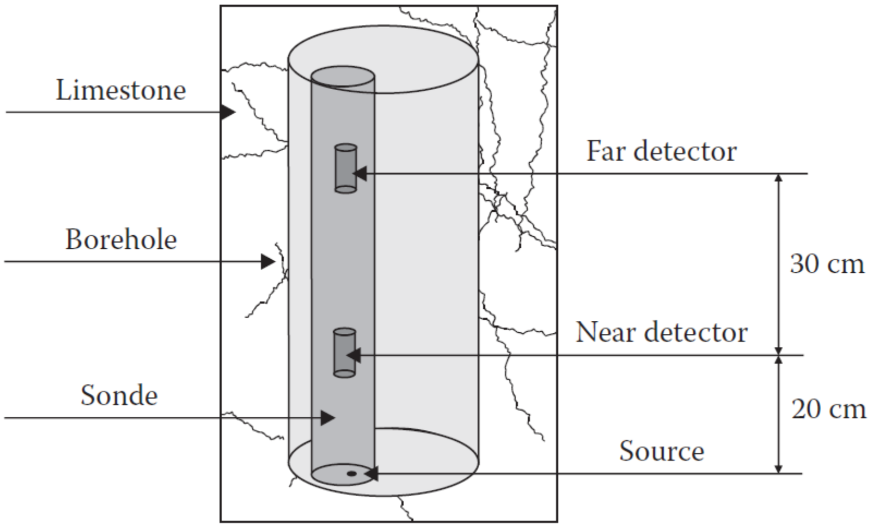


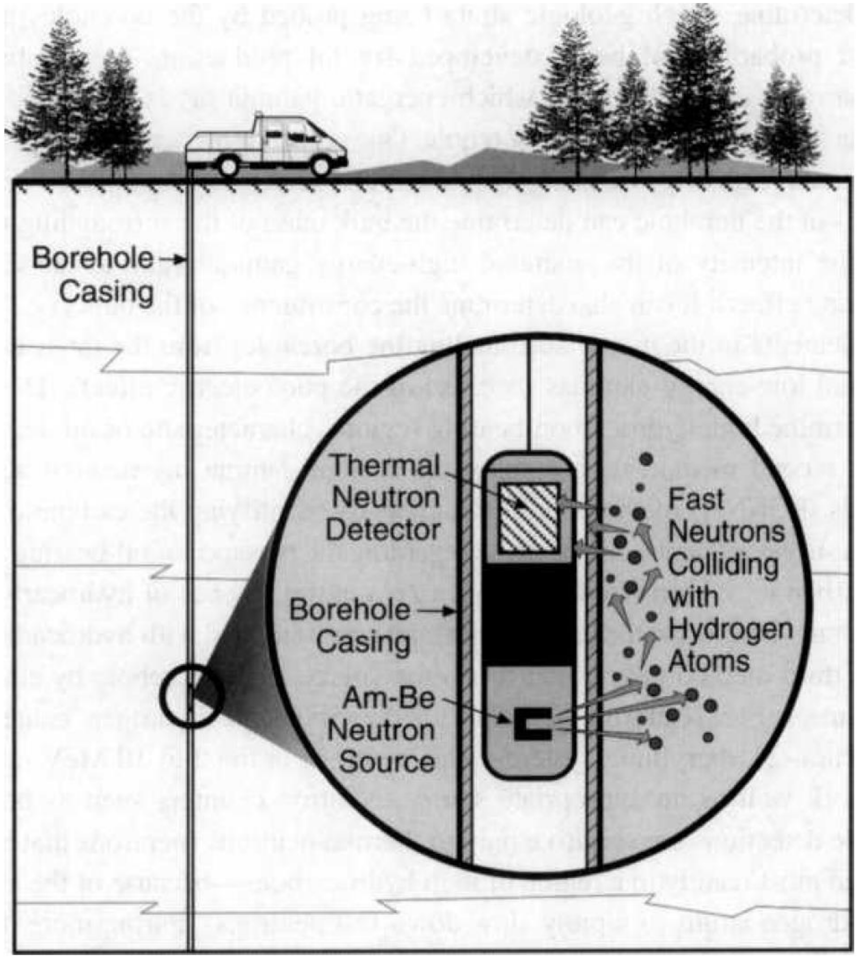


Nuclear well logging

- Nuclear well logging is a method of studying the materials surrounding exploratory boreholes. A tool consisting of a neutron or gamma-ray source and one or more detectors is lowered into the borehole.







Neutron applications

GENERAL ATOMICS

OAK RIDGE National Laboratory

Limited Availability

> $100M

Reactors
Accelerators

Neutron yield (n/s)

10^{17}

Neutron Diffraction/Tomography

Research Reactor Applications

Boron Neutron Capture Therapy

10^{13}

$1M - $10M

Medium-scale
Intense Sources

Isotope Production

Radiography

Non Destructive Assay

Landmine/Explosive Detection

Air Luggage Security Inspection

PHOENIX NUCLEAR LABS
PROVIDING NUCLEAR TECHNOLOGY FOR THE BETTERMENT OF HUMANITY

adelphi TECHNOLOGY, INC.

Limited Strength

10^{10}

< $1M

Neutron Tubes
Radioisotopes

Research for New Applications

SNU

Oil Well Logging

Dosimeter Calibration

Teaching Experiments

10^{6}

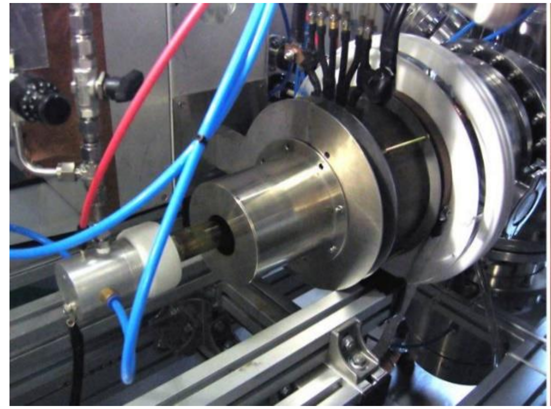
SODERN

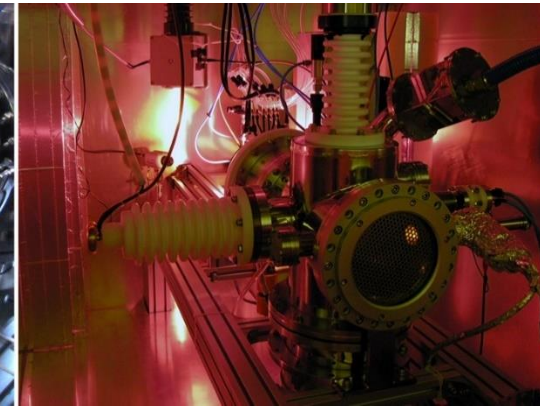
Thermo SCIENTIFIC

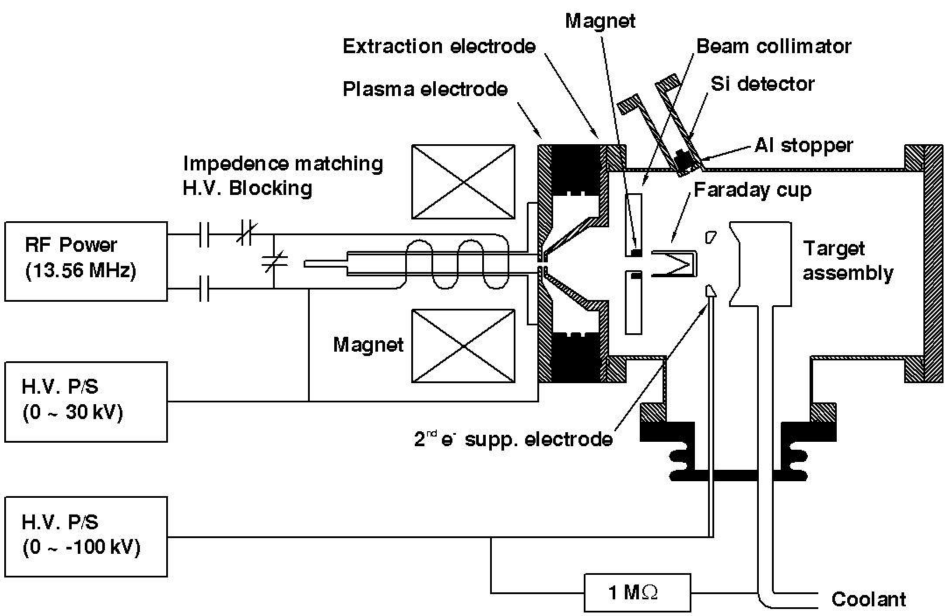
Neutron sources at SNU (2007)

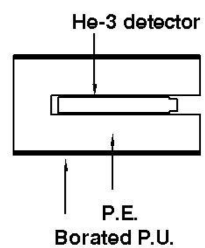
- D-D fusion neutron source

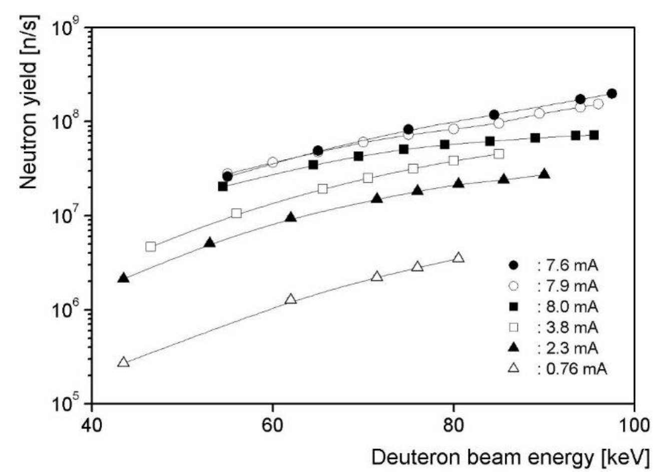
Max. beam energy	**: 95.5 keV**
Beam current	**: 8 mA**
Neutron yield	**: 2×10⁸ n/s**



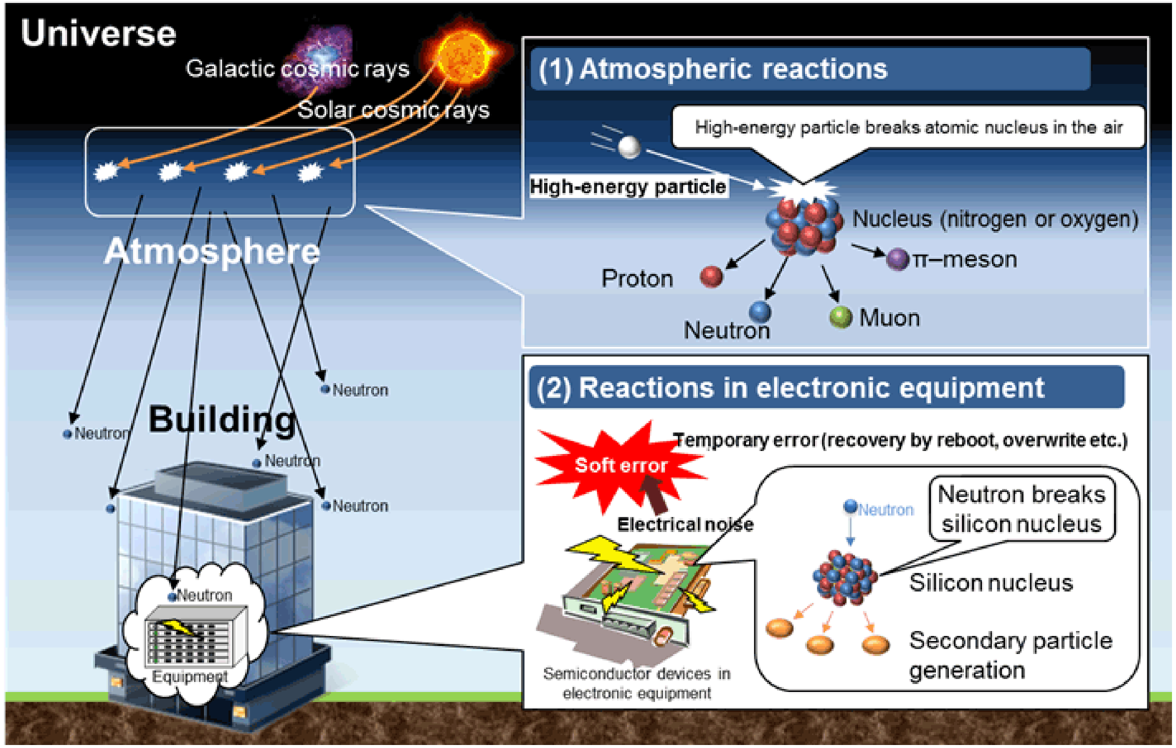


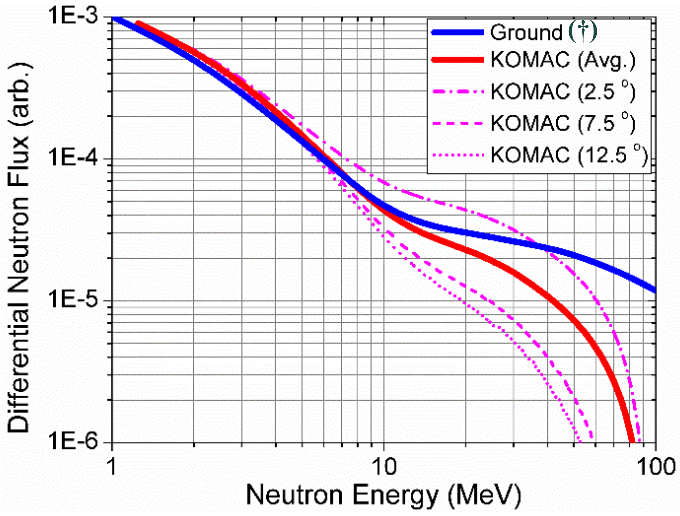






Soft error by background radiations





† M. S. Gordon et al.,
IEEE Trans. nucl. sci. **51**, 3427-3434 (2004)