# Radioactivity

Lecture 22

Radioactivity in Industry

# Industrial Products containing Radioactivity

- Ceramics and Glasses
- Radio luminescent paint
- Camera lenses
- Cosmetic materials
- Camping gas mantles
- Smoke detectors




# Ceramics – Fiesta Ware

Fiesta ware is ceramic glazed dinnerware, known for its particular style of concentric rings, it is a highly desired collectors item. The red Fiesta has a detectable amount of uranium oxide in its glaze, which produced the orange-red color. During World War II, the government took control of uranium for development of the atom bomb, and confiscated the company's stocks. Fiesta red was re-introduced in 1959 using depleted uranium ($^{238}U$).

Whole body $\gamma$ radiation exposure by Fiesta ware

| Distance | 10” Plate | 3.5” Cup |
|---|---|---|
| 1 foot | $6.5 \times 10^{-6}$ mSv/hr | $3.7 \times 10^{-6}$ mSv/hr |
| 3 feet | $7.7 \times 10^{-7}$ mrSv/hr | $4.1 \times 10^{-7}$ mSv/hr |
| 6 feet | $1.9 \times 10^{-7}$ mrSv/hr | $1.1 \times 10^{-7}$ mSv/hr |

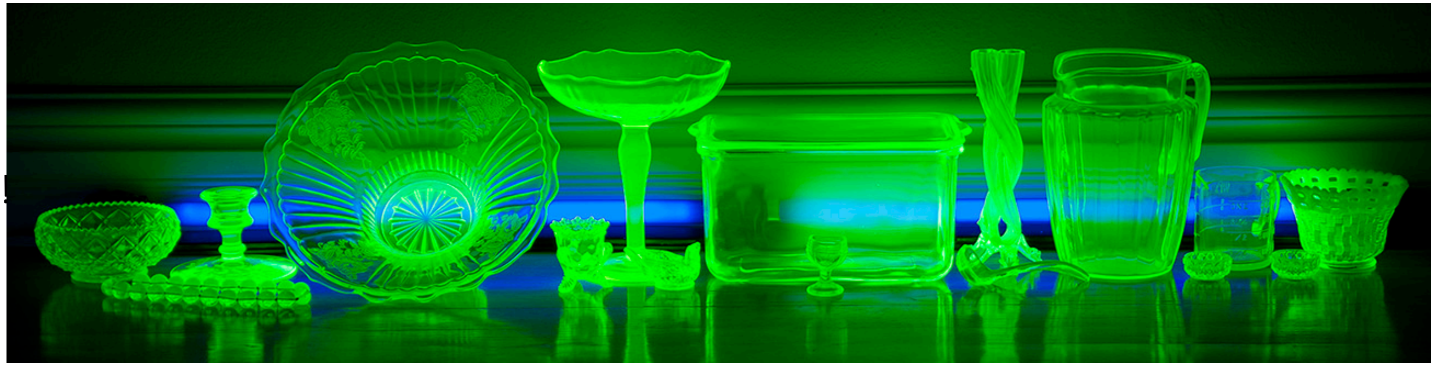
The $\beta$ dose rates at a depth of 7 mg/cm$^2$ as well as the estimated effective dose equivalent of a 10 inch diameter plate with a 20 % by weight uranium content.

| Distance | Dose Rate | Effective Dose Equivalent Rate |
|---|---|---|
| Contact | 0.240 mGy/hr | 0. 024 $\mu$Sv/hr |
| 1 foot | 0.0084 mGy/hr | 0.021 $\mu$Sv/hr |
| 3 feet | 0.0009 mGy/hr | $4.5 \times 10^{-3}$ $\mu$Sv/hr |

Average human dose: 0.06 $\mu$Sv/hr

# Vaseline Glasses

The glow is artificial, from external UV light, not internal radioactivity!

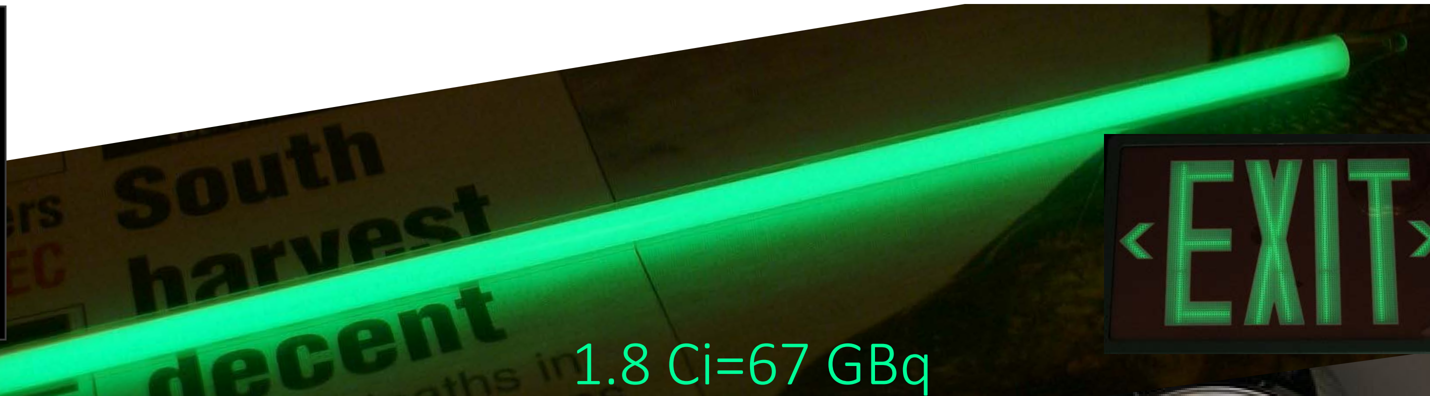


**Uranium glass** is glass which has had uranium, usually in oxide diuranate Na, Al …–$U_2O_7$ or form, added to a glass mix before melting for coloration. The glass glows greenish in UV light.

| Distance | Drinking Glass |
| --- | --- |
| 1 foot | 9.0 μSv/h |
| 3 feet | 1.0 μSv/h |
| 6 feet | 0.25 μSv/h |

# Luminescent Paint

Traditionally used of watches and signs, radium paint is replaced by radio-luminescent tritium paint, which in turn is replaced by photo-luminescent paint

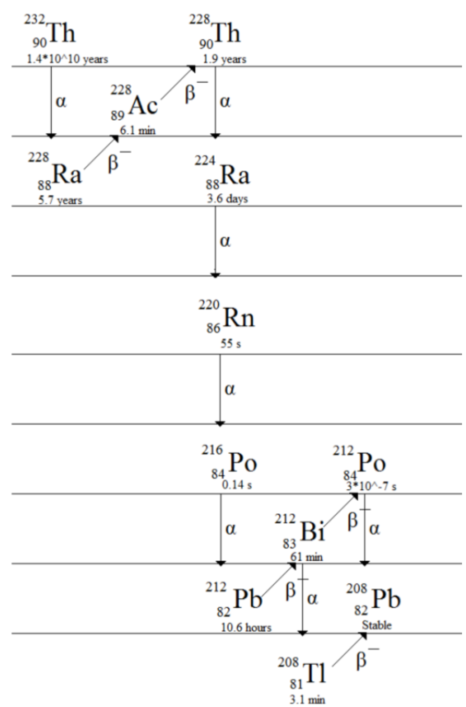





- Radium paint contains radium (25 to 300 μg) mixed together with a luminescent crystalline powder (ZnS) that causes the glow by scintillation
- Radio-luminescence lights or signs are glass tubes filled with tritium gas ($T_{1/2}$=12y) that are coated inside with phosphorus.
- Photo-luminescent material emits light under UV radiation

# Radioactive Camera Lenses


Aa significant number of lenses produced from the 1940s through the 1970s have measurable radioactivity due to the use of thorium oxide (up to 30% by weight) as a component of the lens glass. The optical properties of Thorium oxide generate high refractivity and low dispersion that minimizes chromatic aberration at a lower curvature, at lower costs.




Typical activity measured for several lens glasses range from 3 to 12Bq. The radiation level can vary between 100-2000 nSv/h as measured at the lens element's surface comparable to a typical chest x-ray exposure.


| |
|---|
| ≤210 |
| 220-500 |
| 510-1000 |
| 1100-1500 |
| 1510+ |

| | | | nSv/h | |
|---|---|---|---|---|
| | | | rear el. | front el. |
| background | | | 120 - 180 | |
| Asahi | Super Takumar V1 | 35/2 | 430 | 220 |
| Asahi | S-M-C Takumar | 35/2 | 890 | 490 |
| Asahi | Auto Takumar | 35/2.3 | 170 | 150 |
| Asahi | Auto Takumar | 35/3.5 | 160 | 180 |
| Asahi | S-M-C Takumar | 35/3.5 | 190 | 150 |
| Asahi | S-M-C Takumar | 50/1.4 | 1670 | 600 |
| Asahi | S-M-C Macro Tak. | 50/4 | 250 | 240 |
| Asahi | S-M-C Takumar | 85/1.8 | 250 | 820 |
| Asahi | S-M-C Takumar V2 | 135/2.5 | 180 | 170 |
| C.Zeiss Jena | MC Flektogon | 35/2.4 | 140 | 150 |
| C.Zeiss Jena | MC Pancolar | 50/1.8 | 160 | 160 |
| C.Zeiss Jena | Pancolar | 55/1.4 | 2360 | 1720 |
| C.Zeiss Jena | Prakticar Macro MC | 55/2.8 | 160 | 160 |
| C.Zeiss Jena | Biotar T (manual) | 58/2 | 180 | 170 |
| C.Zeiss Jena | Biotar T (pre-set) | 58/2 | 190 | 170 |
| C.Zeiss Jena | MC Pancolar | 80/1.8 | 180 | 140 |
| C.Zeiss Jena | Biometar (M42) | 80/2.8 | 120 | 160 |
| C.Zeiss Jena | Biometar (P6) | 80/2.8 | 320 | 380 |
| C.Zeiss Jena | MC Sonnar | 135/3.5 | 190 | 120 |
| C.Zeiss Jena | Triotar T | 135/4 | 170 | 200 |
| Cosina | Cosinon MC (M42) | 55/1.4 | 190 | 180 |
| Helios (KMZ) | 77M MC | 50/1.8 | 140 | 210 |
| Helios (KMZ) | 44-2 "00xxx" | 58/2 | 170 | 180 |
| Helios (MMZ) | 44-3 MC | 58/2 | 180 | 200 |
| Helios (KMZ) | 40-2 | 85/1.5 | 140 | 180 |
| Industar (KMZ) | 50-2 | 50/3.5 | 160 | 180 |
| Jupiter | 3 | 50/1.5 | 180 | 210 |
| Jupiter | 8 | 50/2 | 180 | 170 |
| Jupiter | 9 (M39 SLR) | 85/2 | 160 | 170 |
| Jupiter | 9 (M42) | 85/2 | 140 | 170 |
| Jupiter | 11 | 135/4 | 160 | 130 |
| Jupiter | 37AM MC | 135/3.5 | 140 | 190 |
| Laack Rath. | Anastigmat Pololyt | 135/4.5 | 130 | 140 |
| Leitz | Hektor (M39) | 135/4.5 | 170 | 140 |
| Meyer | Primagon V | 35/4.5 | 170 | 170 |
| Meyer | Helioplan V | 40/4.5 | 170 | 170 |
| Meyer | Trioplan | 50/2.9 | 190 | 160 |
| Meyer | Primoplan V (man.) | 58/1.9 | 150 | 140 |
| Meyer | Primoplan V (pre-set) | 58/1.9 | 150 | 160 |
| Meyer | Telefogar V | 90/3.5 | 170 | 190 |
| Meyer | Trioplan V | 100/2.8 | 150 | 160 |
| Pentacon | MC auto | 50/1.8 | 200 | 170 |
| Pentacon | Prakticar MC | 50/2.4 | 160 | 160 |
| Pentacon | | 135/2.8 | 170 | 170 |
| Porst (Cosina) | MC Color Reflex (K) | 55/1.2 | 170 | 190 |
| Schneider | Curtagon | 35/2.8 | 170 | 150 |
| Schneider | Xenar | 135/4.5 | 140 | 170 |
| Spiratone | | 135/1.8 | 190 | 160 |
| Tair (KMZ) | 11A | 135/2.8 | 170 | 130 |
| Tomioka | Yashinon | 55/1.2 | 1180 | 400 |
| Tomioka | Macro Yashinon | 60/2.8 | 150 | 200 |
| Vivitar (Tokina) | VMC Series 1 | 28/1.9 | 150 | 150 |
| Vivitar (Komine) | MC Close Focus | 28/2.8 | 190 | 160 |
| Vivitar (Komine) | Auto | 35/1.9 | 150 | 180 |
| Vivitar (Komine) | Makro | 55/2.8 | 130 | 180 |
| Vivitar | | 85/1.8 | 190 | 190 |
| Voigtlander | Color-Ultron | 50/1.8 | 150 | 160 |
| Voigtlander | Macro APO Lanthar | 125/2.5 | 190 | 150 |
| Volna (LZOS) | 9 Macro MC | 50/2.8 | 170 | 170 |
| Zeiss | Sonnar T* (C/Y) | 85/2.8 | 170 | 180 |
| Zenitar | M2s MC | 50/2 | 190 | 170 |

# Cosmetics and Personal Care

direct applications have been abandoned, but …



Saline solution that are used to clean and store contact lenses is sterilized by gamma radiation.

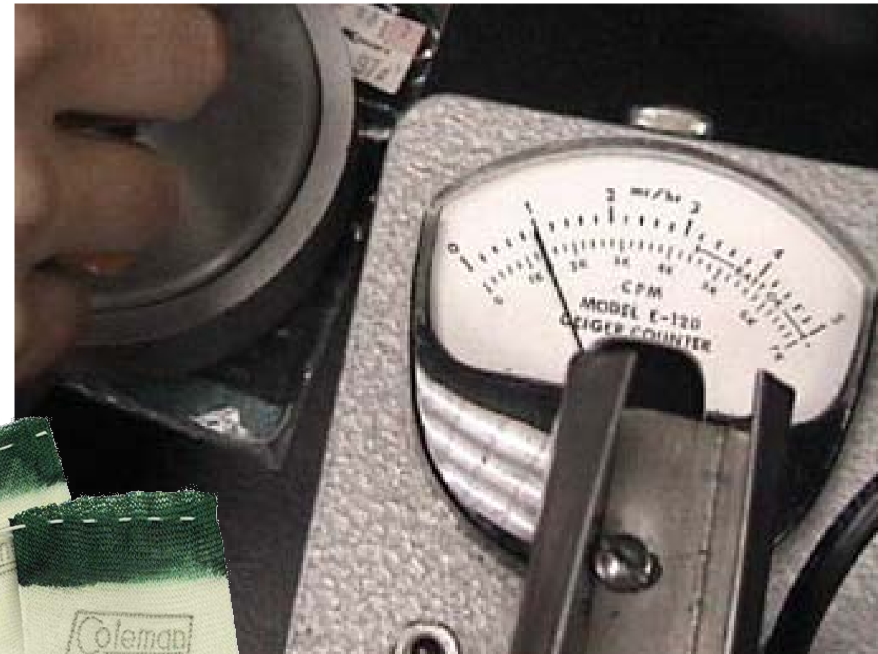
Neutron probes are used to ensure the proper moisture content during the making of the high-quality glass for eyeglasses.

Cosmetics often use gamma radiation to rid products of any microbes before the product is packaged for public consumption.

Radiation often changes the molecular structure of some materials to allow them to absorb huge amounts of liquid. Useful products that rely on this include air fresheners, disposable diapers, and tampons.

# Camping Gas Mantles

Until recently, camping lantern mantles had a considerable amount of radioactivity from the thorium illuminant used on the fabric of the mantle. Because the thorium could incandesce at extremely high temperatures without melting, they were far brighter than ordinary lamps.

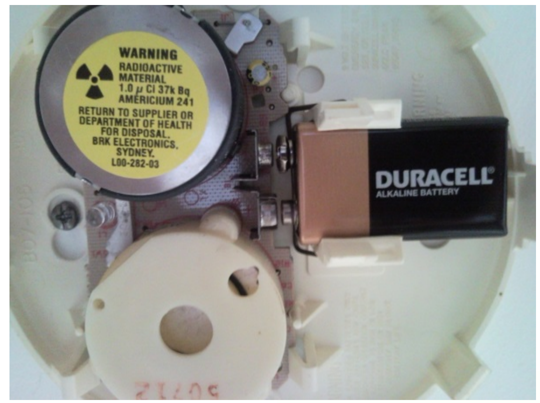




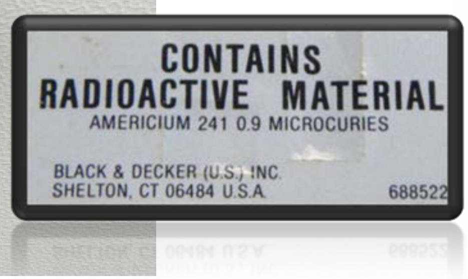
Packs of mantles like the one shown averaged 9 mr/hr. The one above is showing 10 mrad/h since it is on the 10x scale. This corresponds t 0.1 mGy/h. Recently obtained mantles showed no measurable radioactivity over background.

# Smoke Detectors

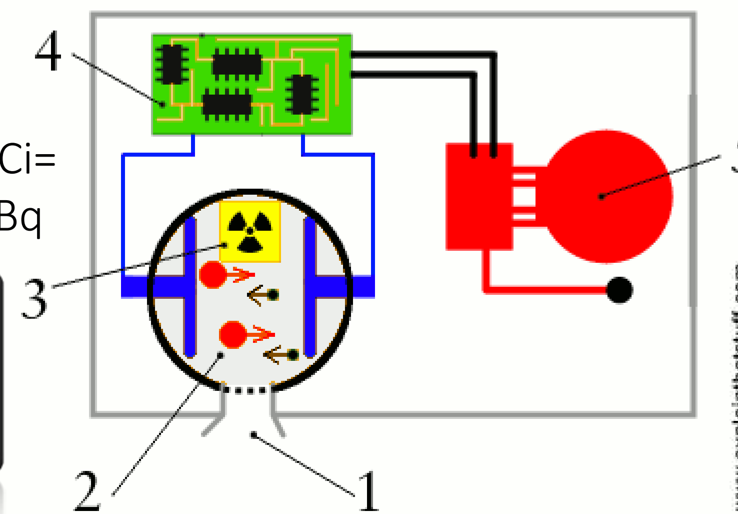
Smoke detectors operate on simple principle of absorption of $\alpha$ radiation. Smoke increases the stopping power of air and reduces the flux of $\alpha$ particles into a detector. The $\alpha$ particles are typically produced by a long-lived $^{241}$Am source ($T_{1/2}=5\cdot10^{10}$y).







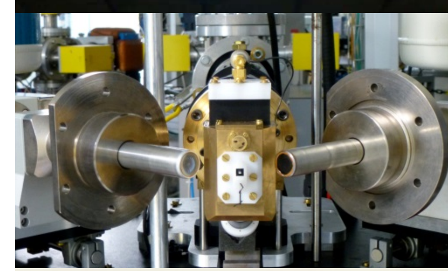

1.0 µCi -100 µCi=
37 kBq - 3.7MBq



# Industrial Processes using Radioactivity

- Ion implantation for material modification and quality test performance
- Radioisotope tracers for process tracking
- Radiography for project imaging
- Gauging for process control
- Irradiation for material modification
- Irradiation for sterilization and mutation
- Radiation processing (PIXE, XRF, NAA) for material composition analysis
- Nuclear batteries for long term power needs

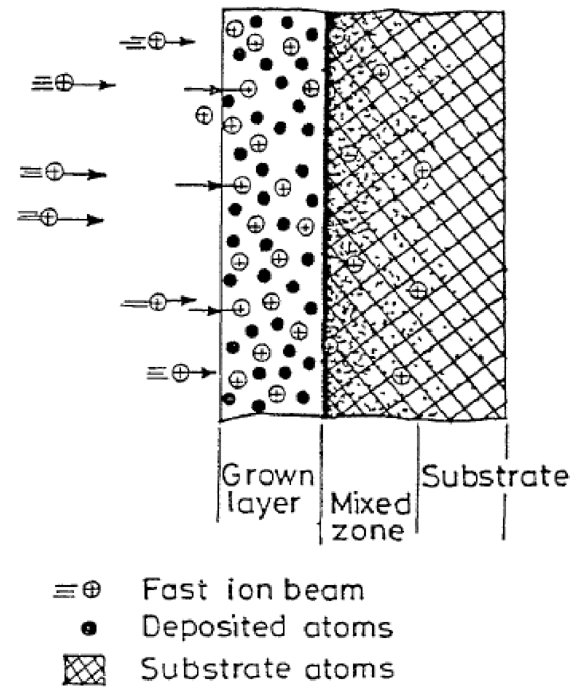


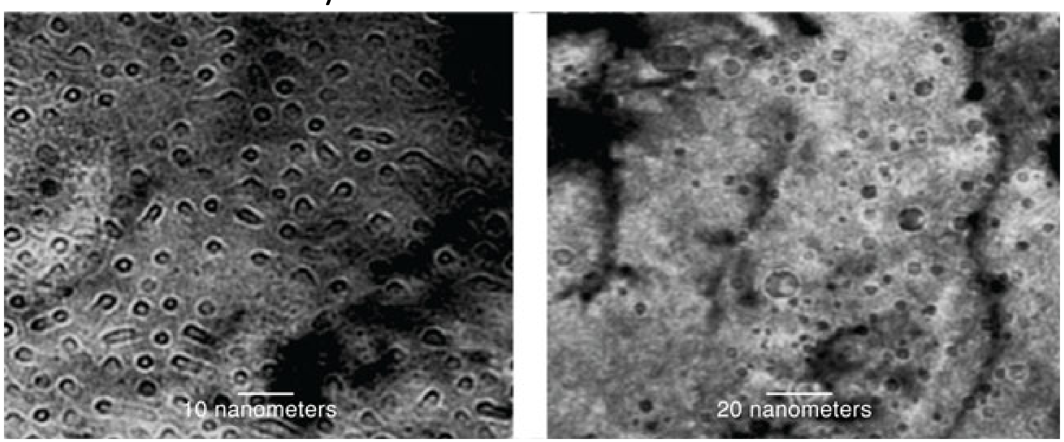




# Ion Implantation

Ion Implantation has a wide range of applications, in particular in the micro-electronics and chips industry. The implantation of radioactive ions is mainly used for wear and tear tests of new materials, for machines, tools, to artificial hip replacements and limbs.

Material is deposited onto the surface building a solid layer by forming a mixed zone with the to be tested material. The surface is tested and the wear is measured by the decline of the level of radioactivity .




Surface analysis with electron microscope after implantation of different ion-types

# Material hardness studies

ELSEVIER

Nuclear Physics A 701 (2002) 235c–239c

NUCLEAR PHYSICS A

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## Application of RNB for high sensitive wear diagnostics in medicine technique and industry

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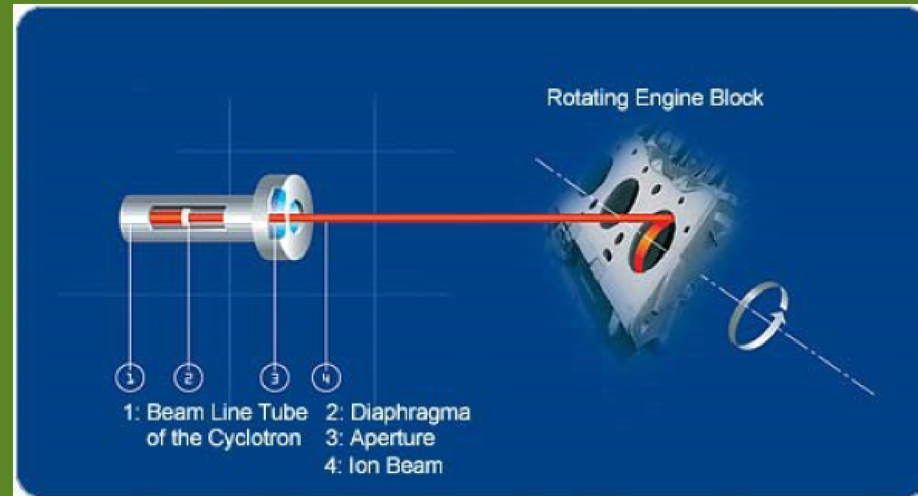


Traditional Thin Layer Activation with Light Ion Beams

*Journal of Radioanalytical and Nuclear Chemistry, Articles, Vol. 160, No. 1 (1992) 141–151*

## RADIONUCLIDE TECHNIQUE IN MECHANICAL ENGINEERING IN GERMANY

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*Kernforschungszentrum Karlsruhe GmbH, Zyklotron, D-7500 Karlsruhe, Postfach 3640 (Germany)*

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Available online at www.sciencedirect.com
ScienceDirect

Wear 261 (2006) 1397–1400

WEAR

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## Thin layer activation of large areas for wear study

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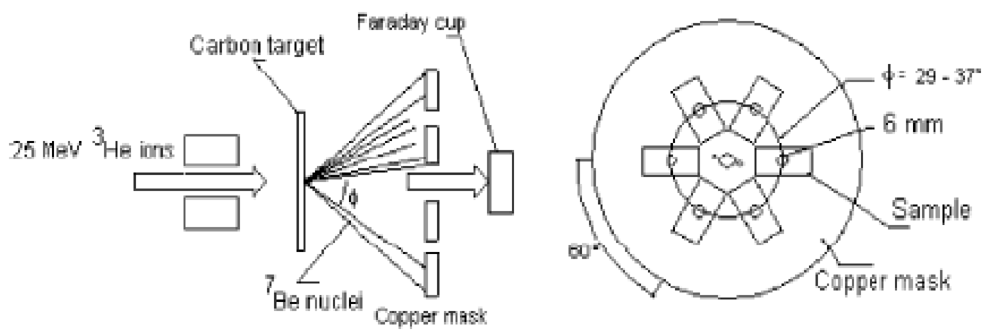
*Refractories and Industrial Ceramics* *Vol. 42, Nos. 3 – 4, 2001*

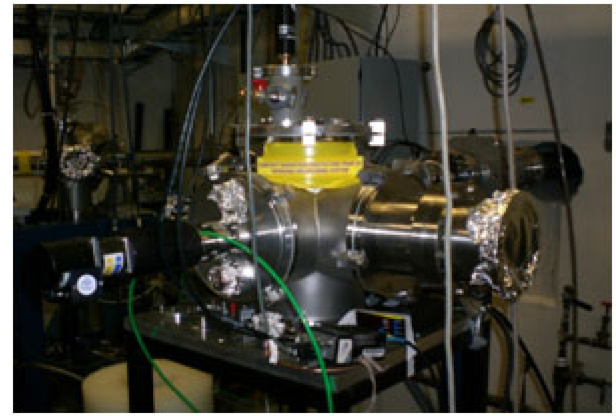
UDC 621.822:[666.762.93+666.762.5]:620.178.16

## A STUDY OF THE WEAR IN CERAMIC BEARINGS BY A THIN-LAYER ACTIVATION METHOD

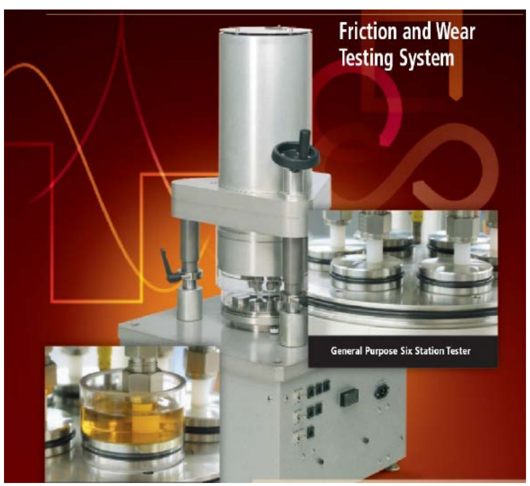
V. V. Sokovikov,[1] V. I. Konstantinov,[1] I. L. Shkarupa,[1] and V. P. Paranosenkov[1]

# Example: $^{7}Be$ implantation ($T_{1/2}$=53.3d)

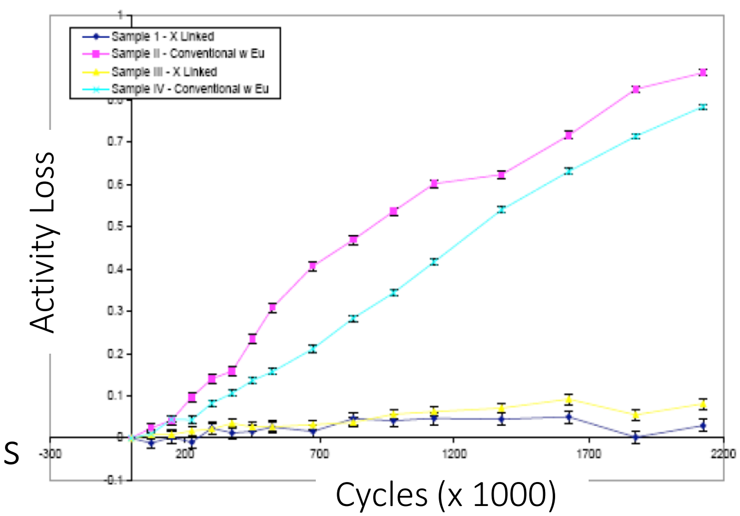


$^{12}C(^{3}He,2\alpha)^{7}Be$ or $^{10}B(p,\alpha)^{7}Be$; secondary radioactive $^{7}Be$ is implanted on material samples



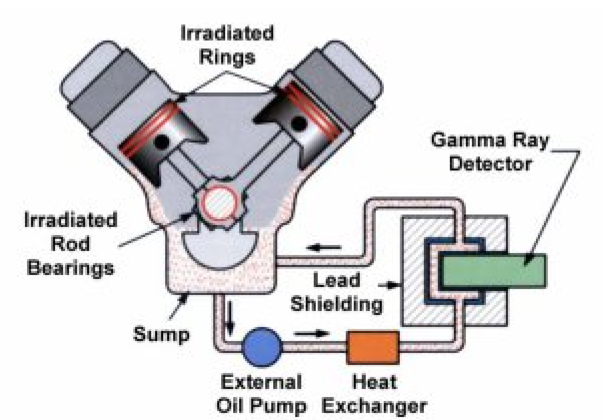

Wear test on different Polyethylen samples with implanted $^{7}Be$ ions



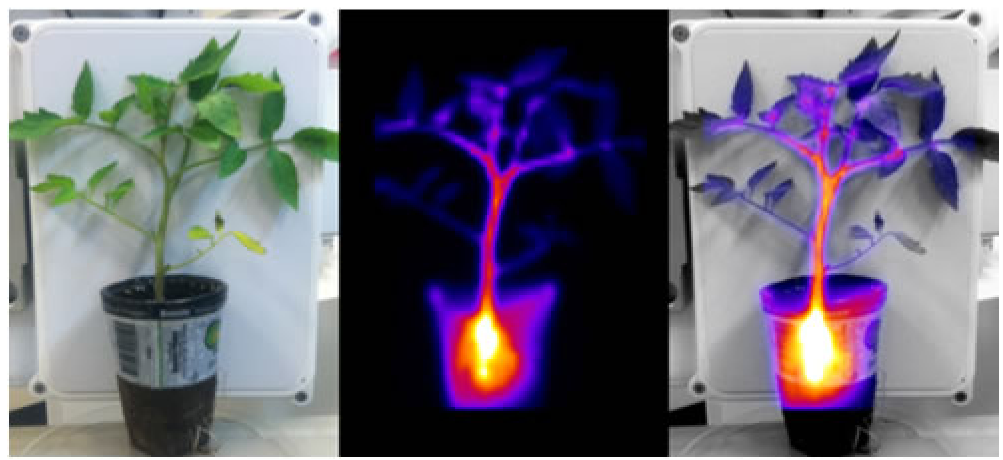
# Radioisotope Tracers in Industry

Radioisotopes can be detected with high sensitivity, spurious amounts attached to material allows tracing the material (George de Hevesy, lecture 3).

Frequent application in medical industries and agricultural industries. Further applications are the tracing of chemical reactions with the radioisotope replacing a stable isotope. Other applications are the measurement of wear and tear of new materials, with radioisotopes introduced at the surface.



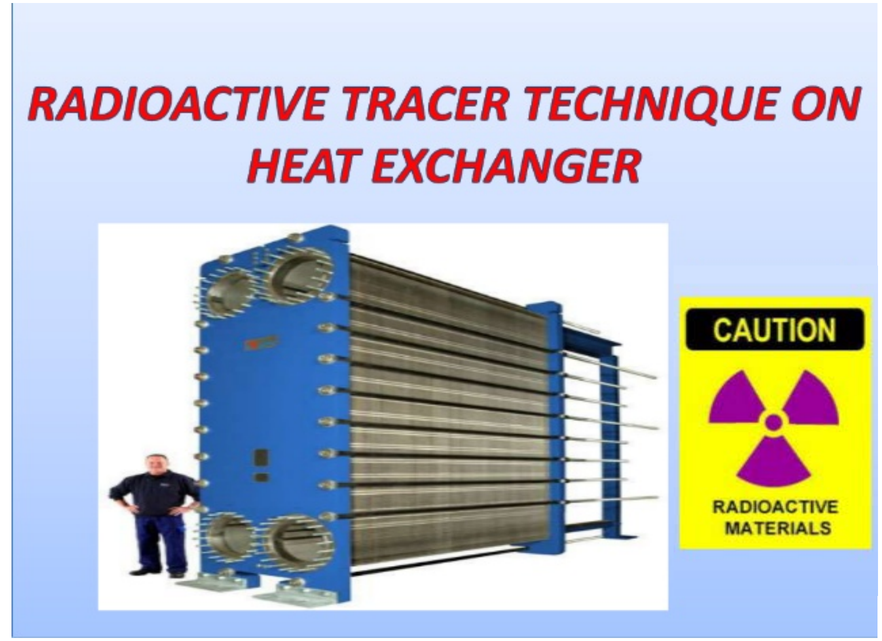

Wear and tear on engine parts by measuring the increase of radioactivity in the lubricant

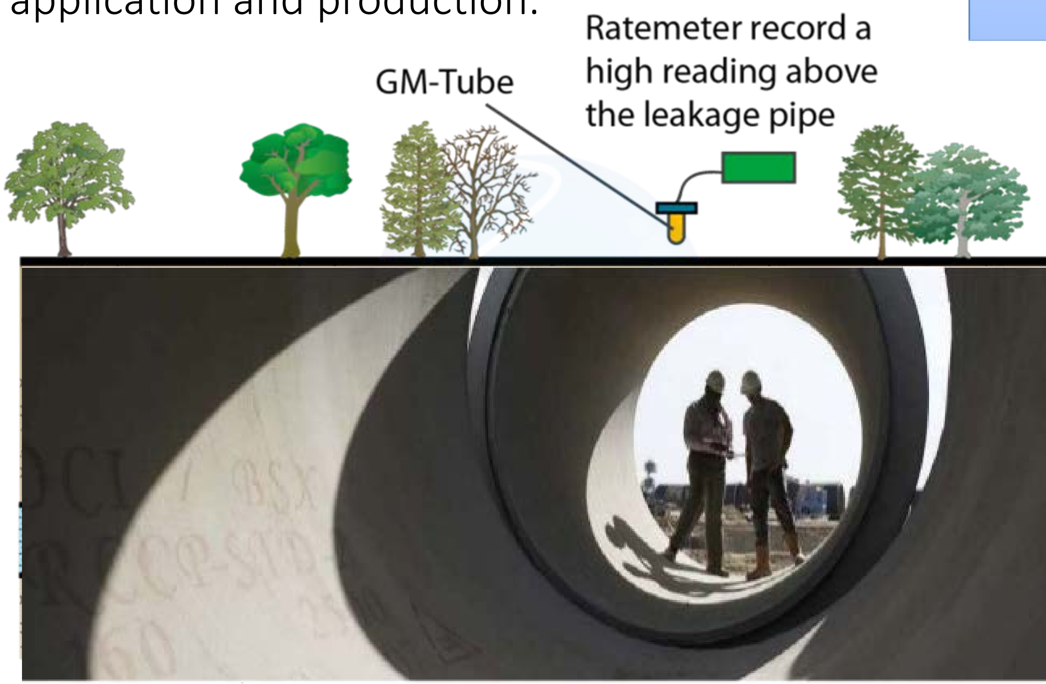


Up-take of nutrients doted with radioactive phosphorus ($^{32}P$ $T_{1/2}$=14.26 d) in plants.

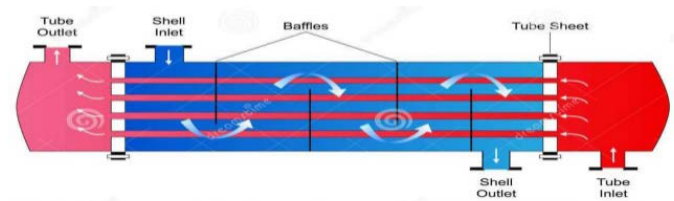
# Pipe line leaks

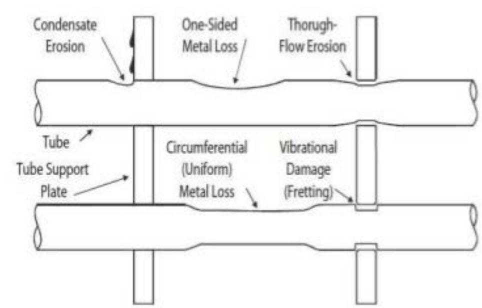
Leaky pipelines for liquids can be probed with radioactive $^{24}$Na solutions ($T_{1/2}$=15h) that decays to $^{24}$Mg. Leaky gas pipeline can be probed with radioactive noble gases $^{41}$Ar ($T_{1/2}$=1.83h) that decays to $^{41}$K or $^{133}$Xe ($T_{1/2}$=1.25d) that decays to $^{133}$Cs. The desired isotope half-life is dictated by application and production.




Water added with radioactive sodium-24

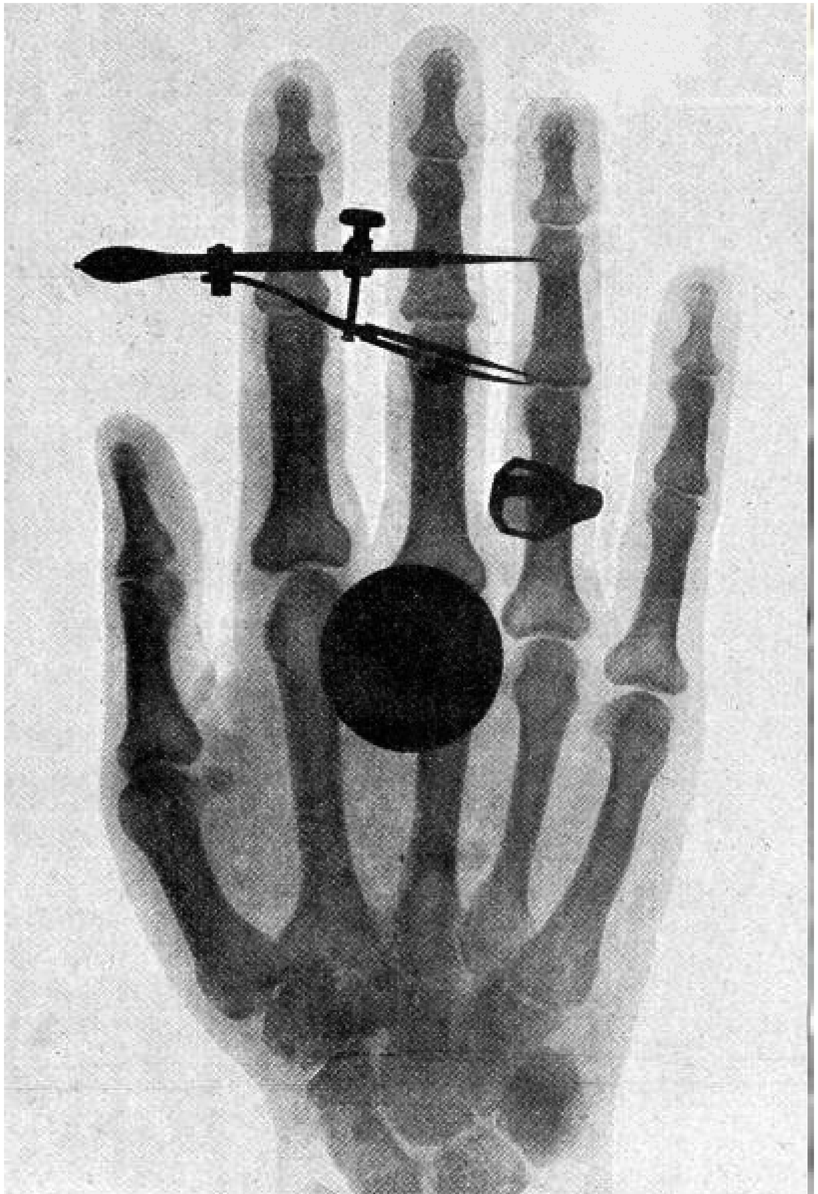


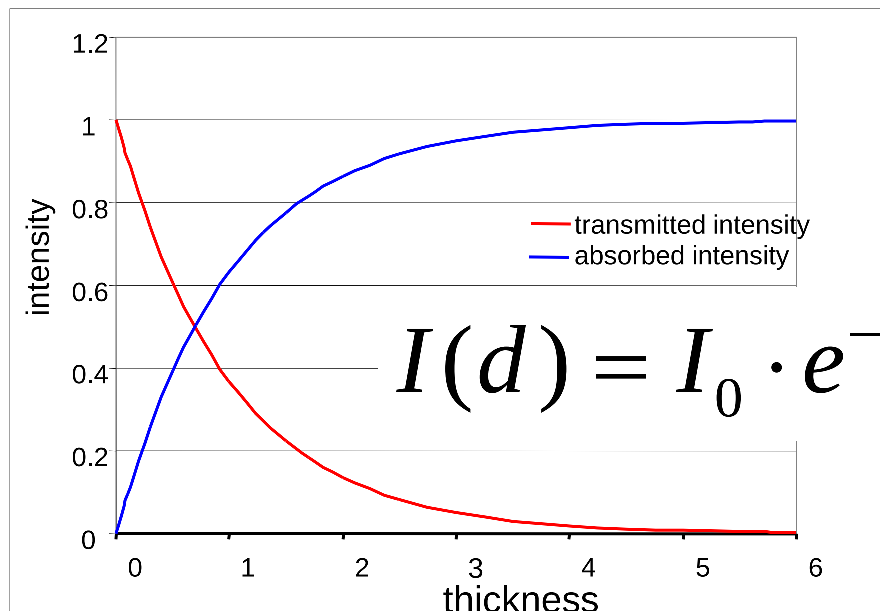



The lifetime of the radioisotope should be comparable to the time required for performing the leak tests.

# Radiography Principles

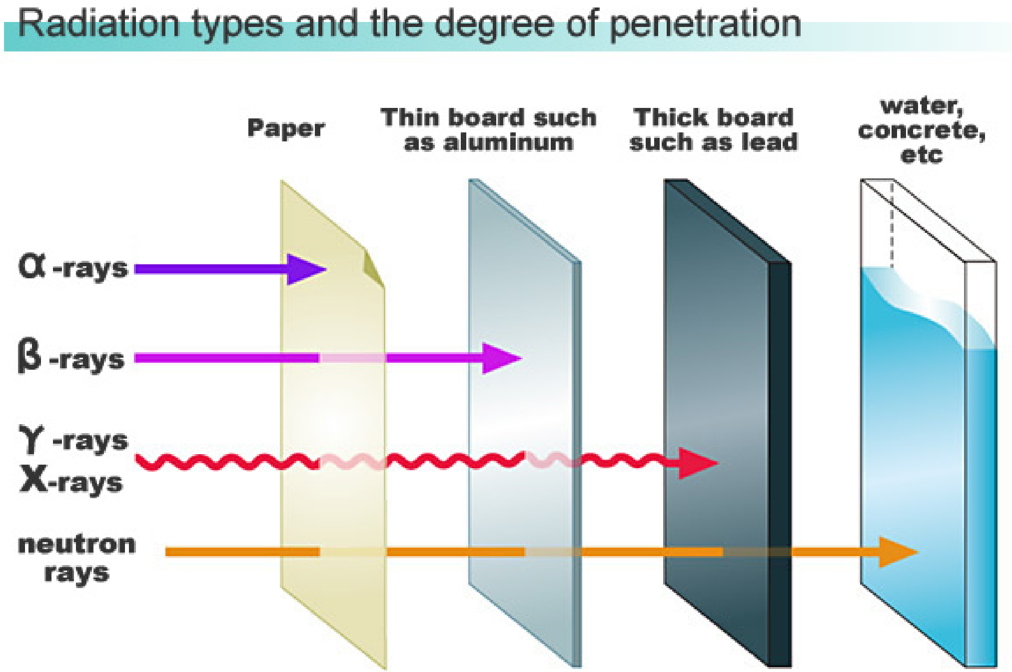


Radiography depends on the absorption (transmission) probability of X-rays or such as $\alpha$, $\beta$, $\gamma$ radiation through sample matter. On a photographic plate of CCD camera in the back material  and the photographic plate to generate an image is formed that  results from the difference in absorption probabilities, which is defined by the “absorption coefficient $\mu$ for a particular material! The coefficient $\mu$ is in units [1/cm], often tabulated as $\mu/\rho$ [$cm^2/g$] with $\rho$ being the density of the material [$g/cm^3$].




$$I(d) = I_0 \cdot e^{-\mu \cdot d}$$

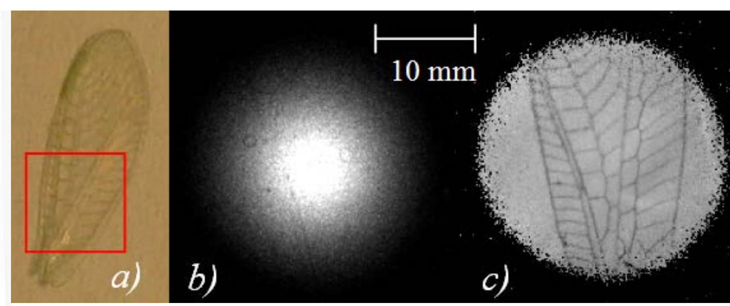
# Utilizing the range of radiation




The absorption coefficient also depends on the kind of radiation, which is due to the kind of interaction with the material. α radiation can only be used for thin layers (μm thickness) and gases (smoke detector), γ radiation and neutron radiation can be used for other metal etc. material. Neutron radiography can be used for light (plastic) material but can cause neutron activation because of neutron capture on material. This method requires higher energy neutrons that have lower capture cross sections.

x/γ radiograph

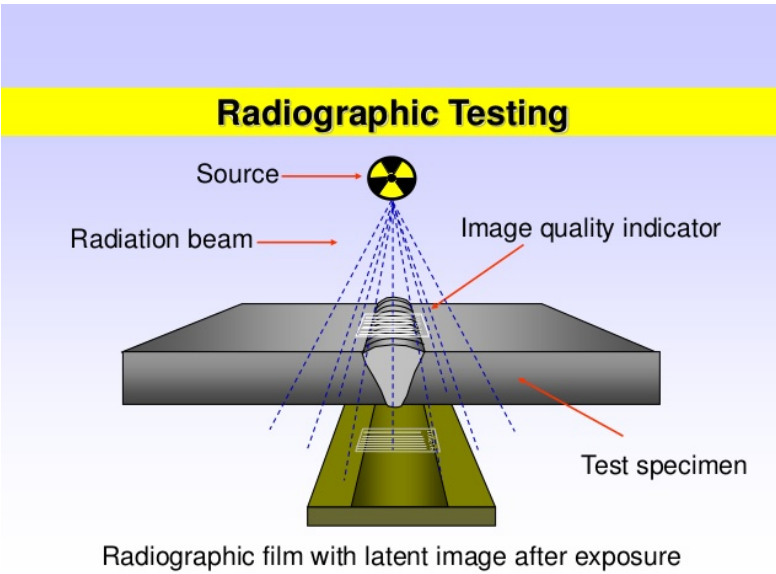
Neutron radiograph



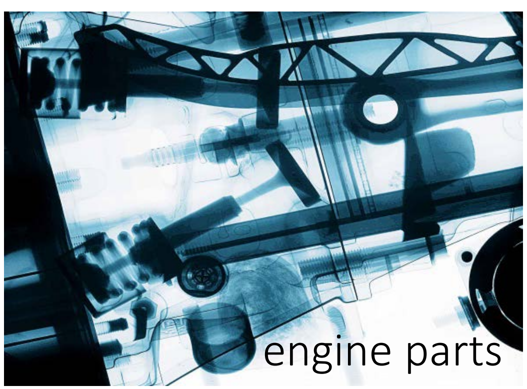

α Radiograph of fly wing

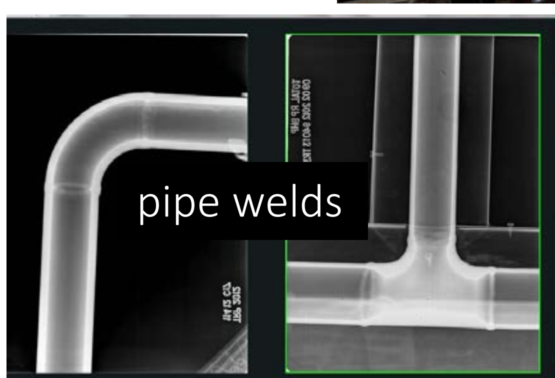
# Radiography in Industry

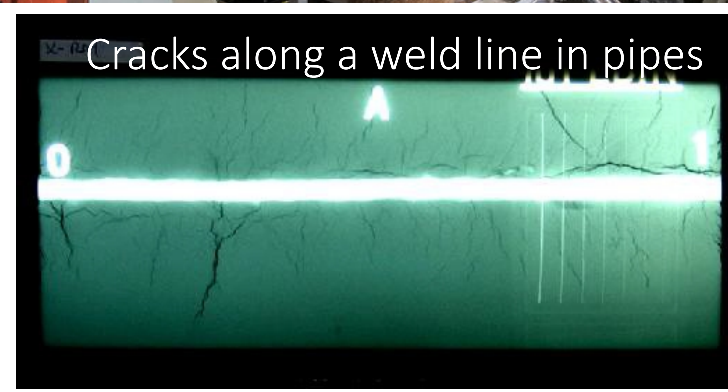
X-ray radiography is typically used in medical applications. The use if higher energy γ sources next to X-ray sources allows to expand the application to industrial parts  with higher absorption coefficient.



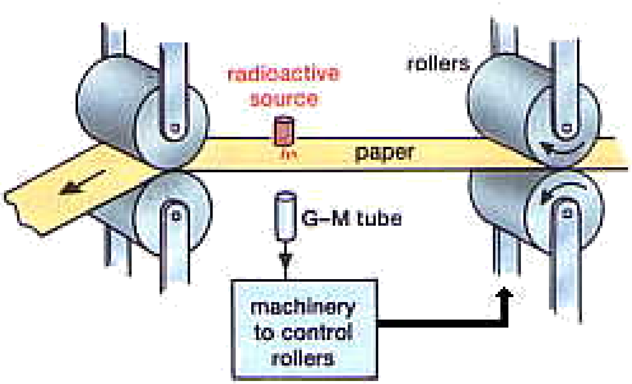

Film is today mostly replaced by CCD cameras.

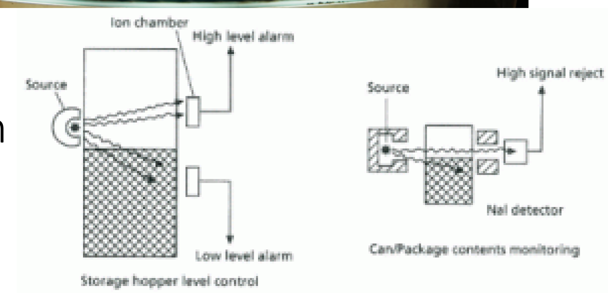



# Gauging with Radioactive Sources

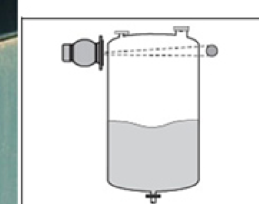




Paper industry
Thickness and
quality test!

Level gauging in
the beer to soft
drink industry



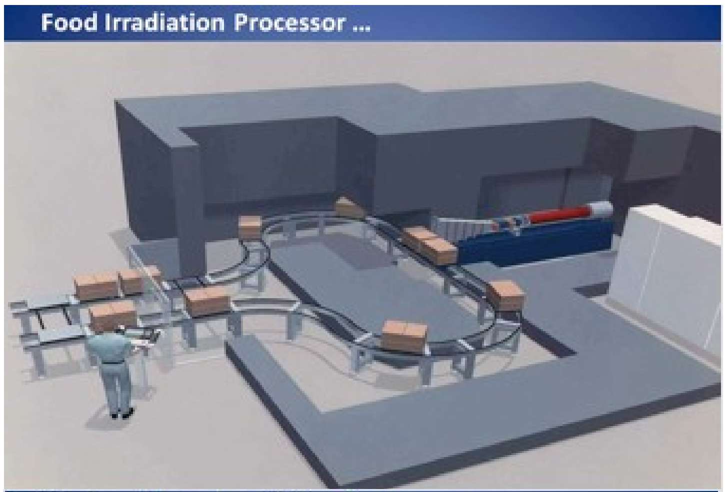

Tank filling level



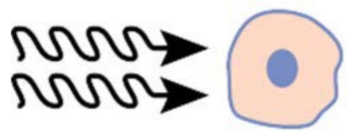
Long-lived radioactive $\alpha$ sources are
used for these kind of applications!

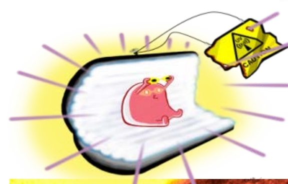
# Purification and Sterilization

Radiation sterilization of medical utensils and cosmetics utilizes Xray and gamma ray to control the growth of microorganism or even kill them. Radioactive sources commonly used are $^{60}Co$ and $^{137}Cs$.

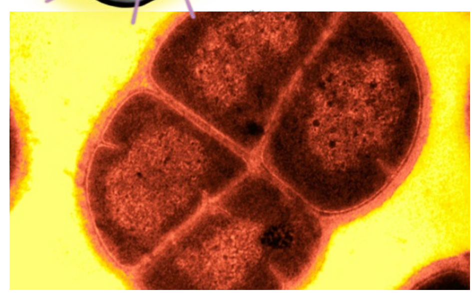






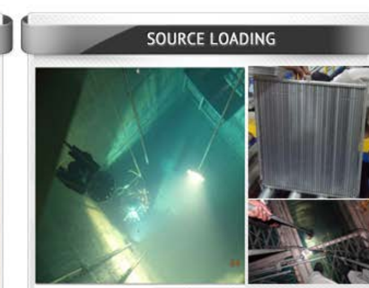


Kills bacteria and germs by damaging the DNA. Exception is: Conan the Bacterium



Deinococcus radiodurans





# Radiation induced Mutation

Mutation is widely used in developing new plant species by exposing plants to chemical mutagens, UV light and radiation. Radiation introduces random mutations – other than targeted mutations by chemicals. This generates a wide variety of mutant plants and species.

New Chrysanthemum “Ion-no-Seiko” | New Rose-Carnation Mutation | New color pigment in Cyclamen

New Chrysanthemum “Aladin” | New variety with enhanced $NO_2$ uptake | New rice sort with reduced fertilizer need

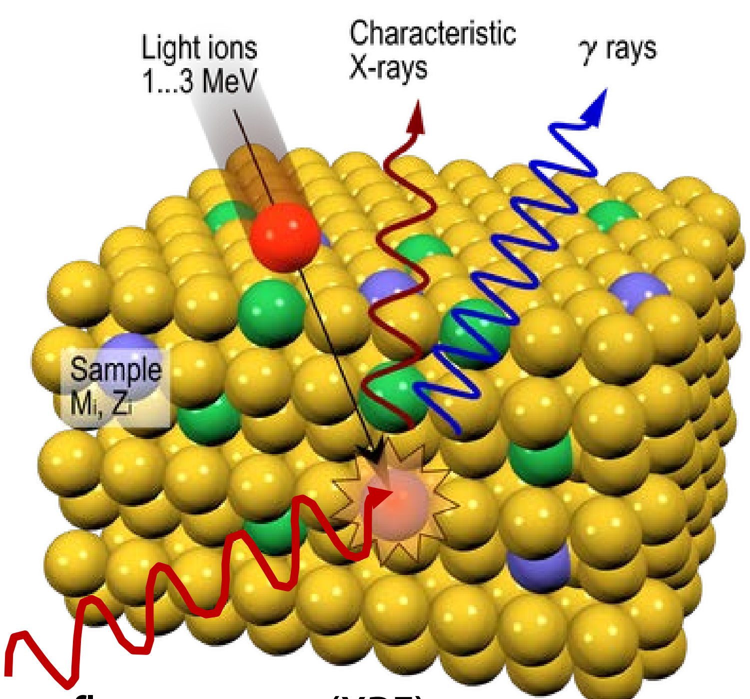

| Chrysanthemum: Original variety ‘Taihei’ with pink petals was used.[26] | | | | | | |
|---|---|---|---|---|---|---|
| Mutagen | Mutation frequency (%) | | | | | |
| | White | Light pink | Dark pink | Orange | Yellow | Complex/Stripe |
| Not irradiated | 0 | 0.3 | 0 | 0 | 0 | 0 |
| Gamma-rays | 0 | 27.7 | 2.1 | 0 | 0 | 0 |
| Carbon ions | 0.3 | 4.6 | 0.3 | 0.3 | 0.2 | 10.2 |

| Carnation: Original variety ‘Vital’ with cherry color and serrated petals was used.[27] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mutagen | Mutation frequency ($\times 10^{-1}$%) | | | | | | | | | |
| | Light pink | Pink | Dark pink | Red | Salmon | Cream | Yellow | Minute striped | Complex | Stripe |
| EMS | 0 | 5.2 | 0 | 1.0 | 0 | 0 | 0 | 0 | 0 | 3.1 |
| Soft X-rays | 1.7 | 8.4 | 0 | 3.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gamma-rays | 1.7 | 2.6 | 0 | 1.7 | 0 | 0 | 0 | 11.3 | 0 | 0 |
| Carbon ions | 2.4 | 4.7 | 2.4 | 3.5 | 2.4 | 1.2 | 2.4 | 0 | 2.4 | 3.5 |

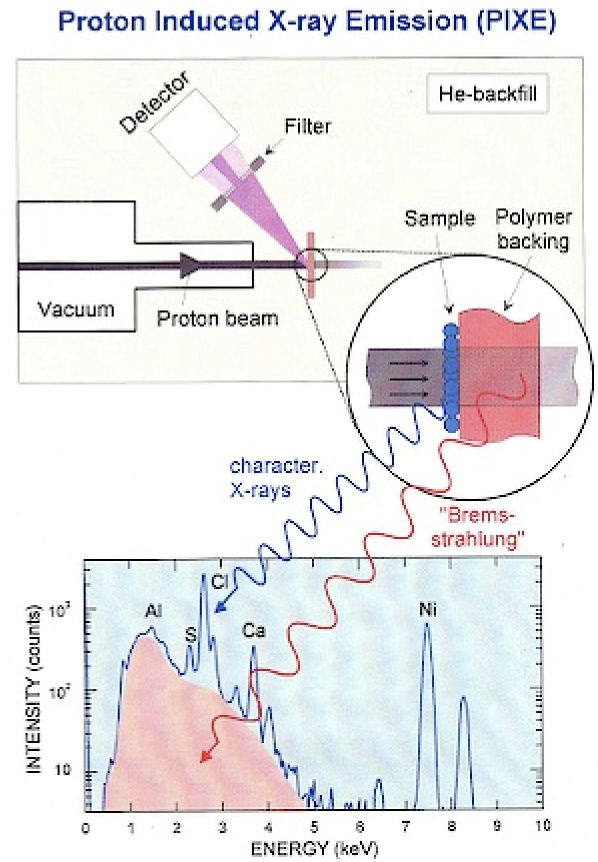
# Nuclear Processing

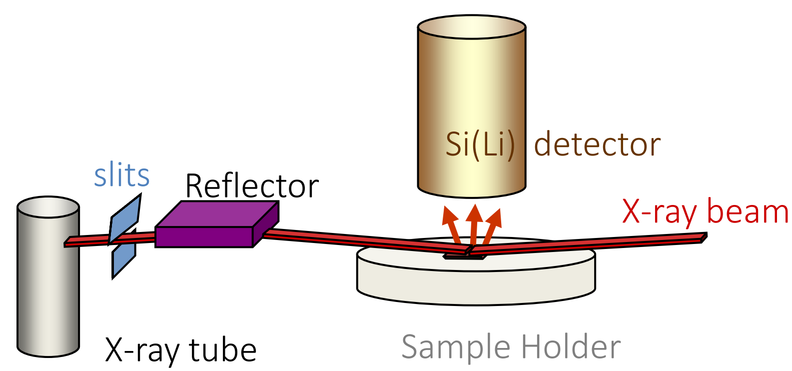
The analysis and imaging of material can be done by particle induced x-ray emission (PIXE) or x-ray fluorescence (XRF) or neutron activation techniques (NAA). These techniques allow punctual analysis or also the development of images for specific material components.

Particle induced X-ray/$\gamma$ emission (PIXE/PIGE)

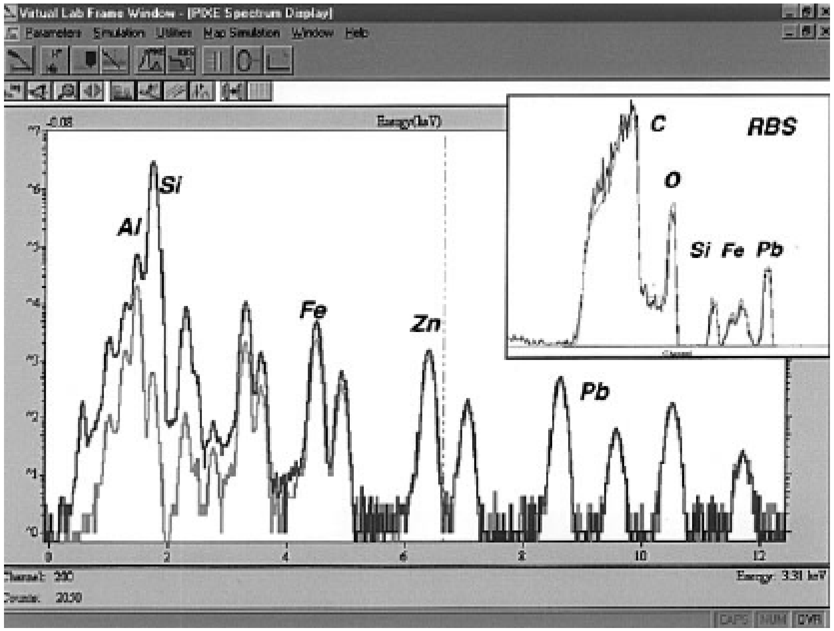


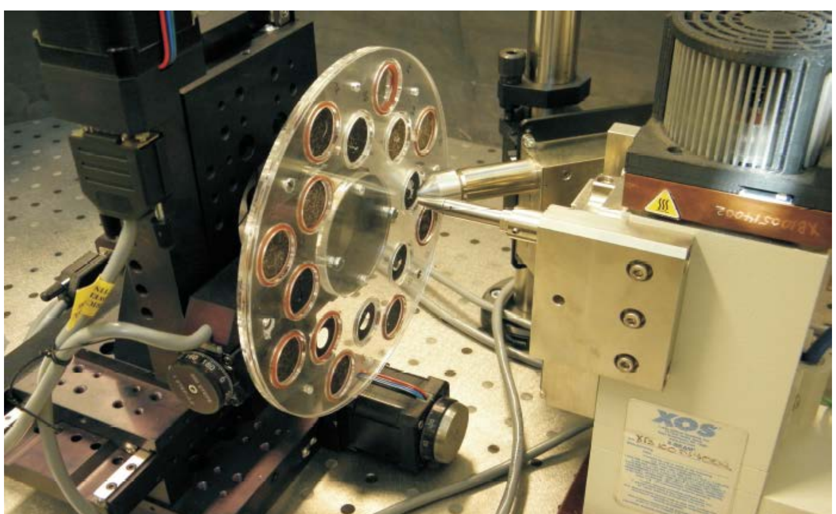

X-ray fluorescence (XRF)

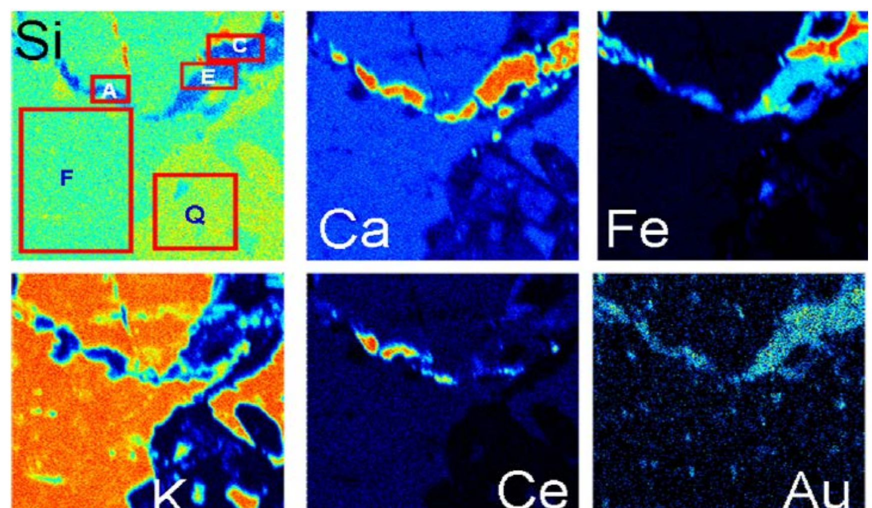


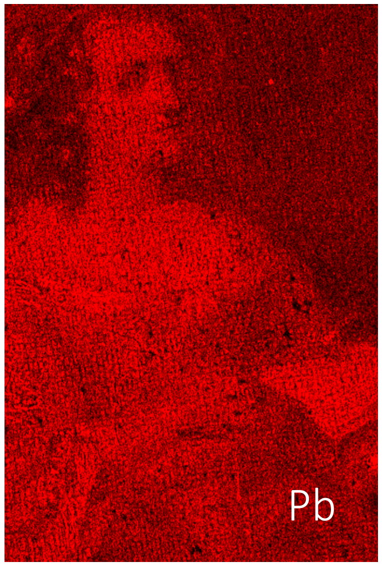
# PIXE and XRF


Virtual Lab Frame Window - [PIXE Spectrum Display]
Parameters Simulation Utilities Map Simulation Window Help
Energy(keV)
Al
Si
Fe
Zn
Pb
C
O
RBS
Si Fe Pb
Channel: 200
Counts: 2050
Energy: 3.31 keV

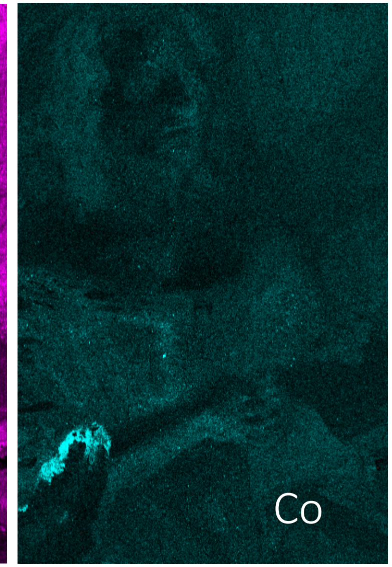

XOS

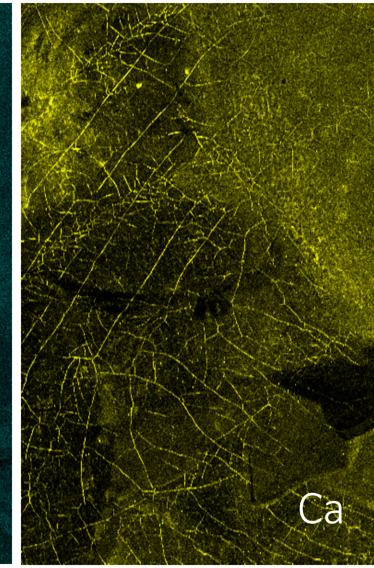

Si
A
C
E
F
Q
Ca
Fe
K
Ce
Au

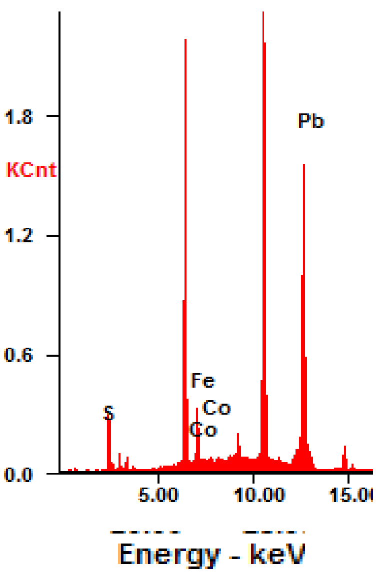
# Meet my Great-Great-Great-Great-Grandmother








$PbCO_3$ (lead-white) white pigment for preparing the backing (canvas, wood) and for highlighting bright areas, today TiO (titanium oxide)

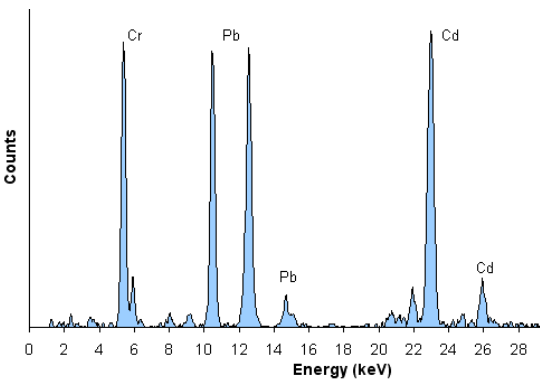
$C_xH_y$+ FeO + $CaC0_3$) (calcinated Van Dyke Brown) – a local product from the region near Cologne, which was used for the toning of darker brownish areas.

($Fe_4[Fe(CN)_6])_3$ (Prussian Blue, based on Fe)- was used for the blue tones of broche – no Cu (Azurite) was observed. $CoAlO_4$ (Cobalt Blue or Smalt ) was used for sleeve.

$C_xH_y$+ FeO + $CaC0_3$) (calcinated Van Dyke Brown) – a local product from the region near Cologne, which was used for the toning of darker brownish areas.

# XRF for consumer goods

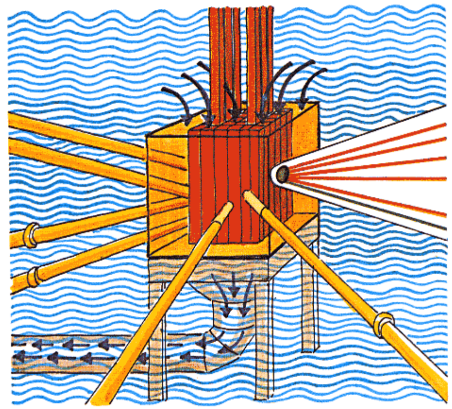
Easy approach for quick analysis of elemental composition of materials

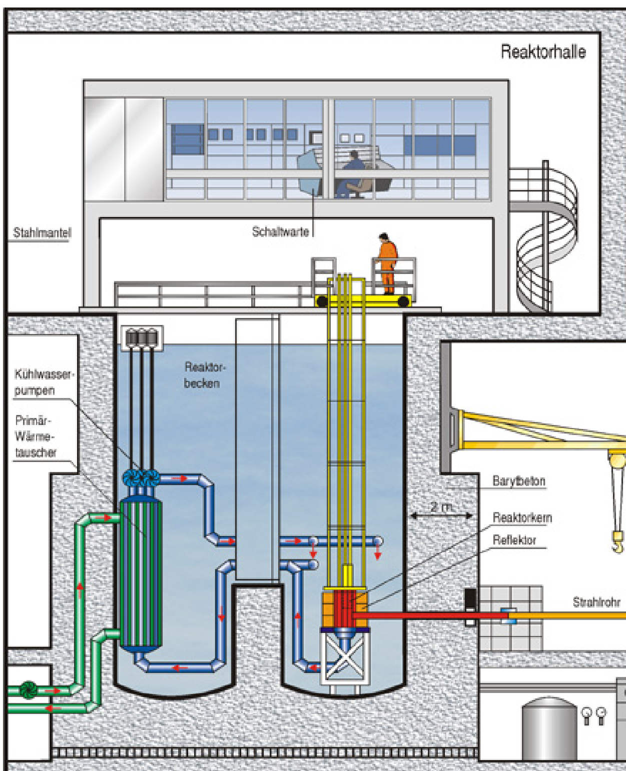
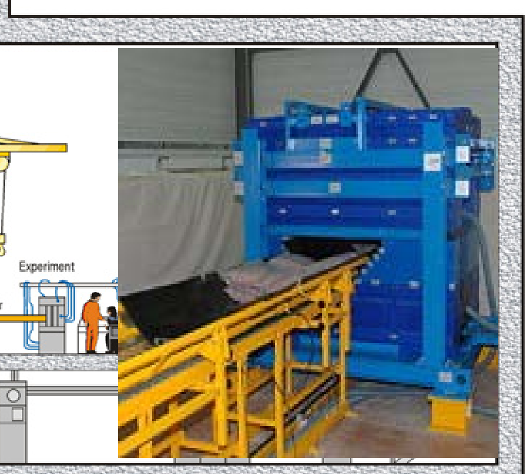



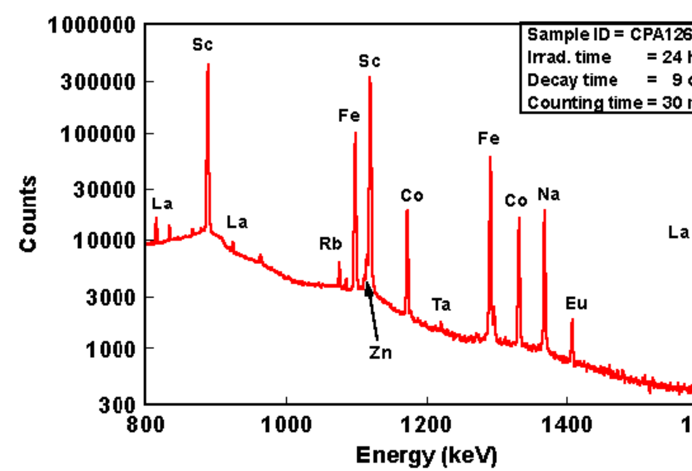

Multiple applications in analysis of merchandise (Chinese toys) to scrap metal, food, & environment

# Neutron Activation Analysis (NAA)

Expose material to high neutron flux and add neutrons to nuclei to produce an radioactive isotope with subsequent analysis of elemental components for its characteristic radioactive decay pattern.



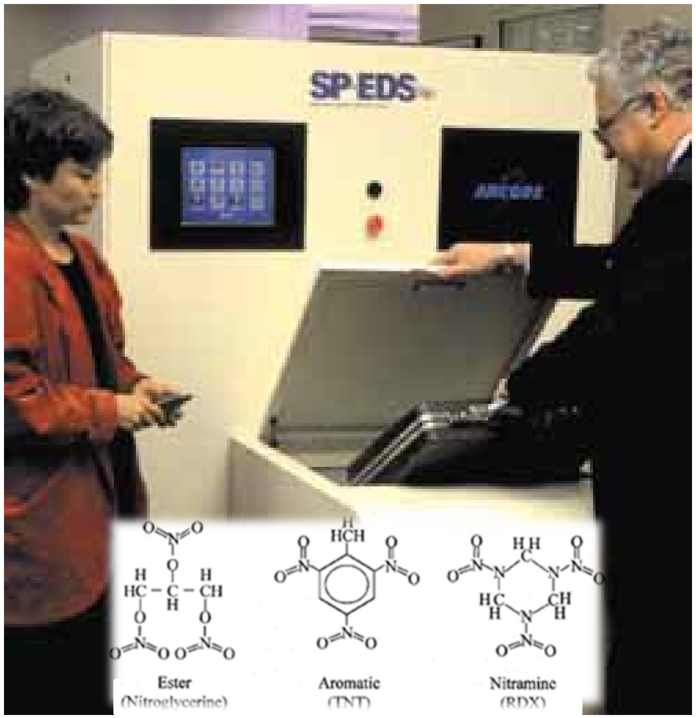



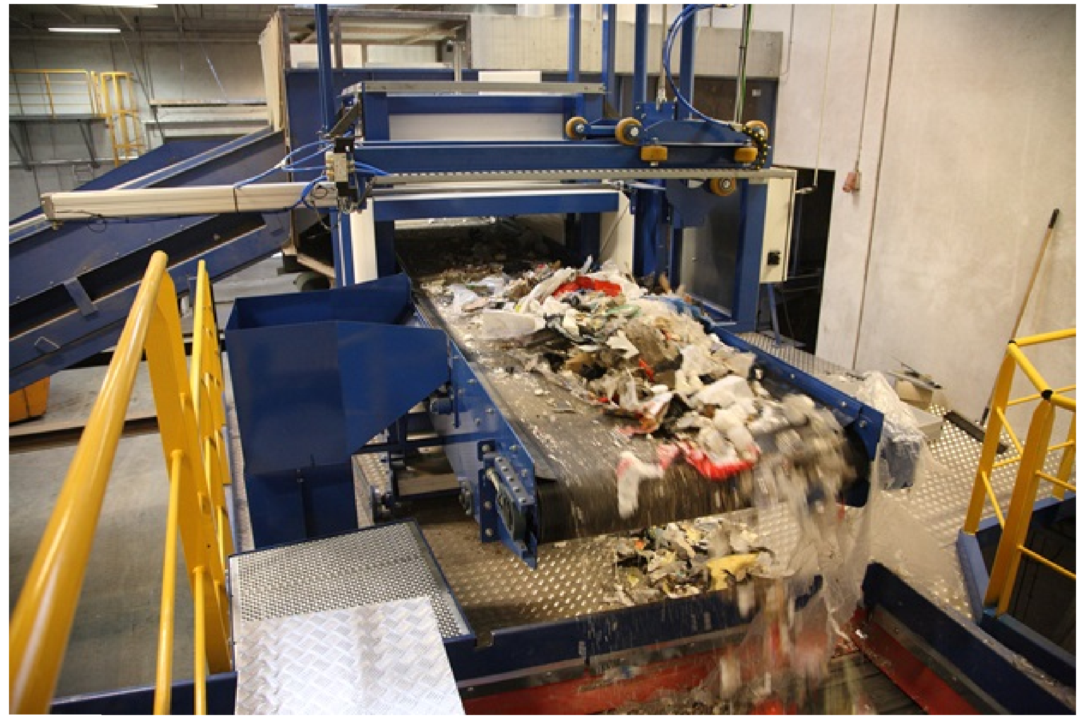
# Prompt Neutron Activation Analysis

## with Am-Be neutron sources

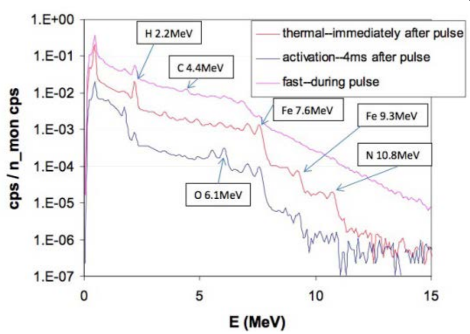
Sorting of security issues at airports



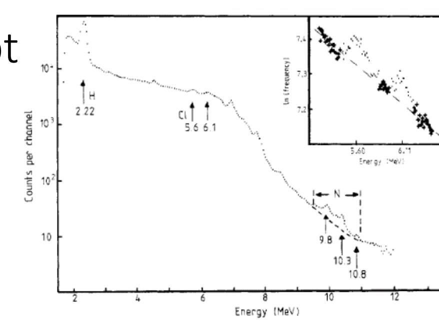

Sorting of waste components by activity analysis



$^{14}N(n,\gamma)^{15}N$ ejecting prompt 10.8 MeV $\gamma$-rays




$^{37}Cl(n,\gamma)^{38}Cl$ ejecting prompt 5.6 and 6.11 MeV $\gamma$-rays.



# Nuclear Batteries

Nuclear batteries get their energy from the decay of radioactive material. The lifetime of a battery is associated with the lifetime **τ** or the half life $T_{1/2}$ of it's radioactive fuel:

$$\tau = \frac{1}{\lambda} = \frac{T_{1/2}}{\ln 2} = 1.44 \cdot T_{1/2}$$

Example: radioactive fuel $^{3}H$: $\tau$ = 17.8 y, $^{63}Ni$: $\tau$ = 144 y, $^{210}Po$: $\tau$ = 200d.

The power $P$ (Watt=Joule/s) generated by the battery depends on the decay energy $Q$ and the activity $A$ of the radioactive fuel at any given time $t$:

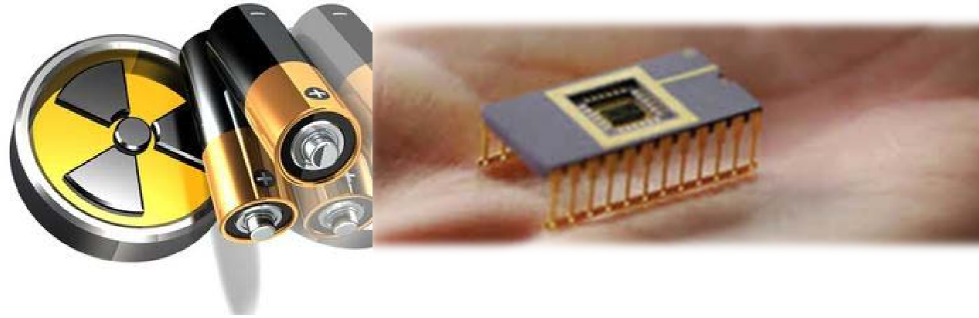
$$P = Q \cdot A = Q \cdot \lambda \cdot N(t) = Q \cdot \frac{N(t)}{\tau} = Q \cdot \frac{N_0 \cdot e^{-\lambda \cdot t}}{\tau}$$

Example: energy release $^{3}H$: $Q$=5.7 keV, $^{63}Ni$: $Q$ = 66.9 keV, $^{210}Po$: $Q$ = 5304 keV.

$$A = \frac{P}{Q} \qquad 1eV = 1.6022 \cdot 10^{-19}\,J$$

Example: activity of a 12W battery $^{3}H$: $A$=$1.3 \cdot 10^{16}$Bq, $^{63}Ni$: $A$=$1.1 \cdot 10^{15}$Bq, $^{210}Po$: $A$=$1.4 \cdot 10^{13}$Bq. The use is pretty much restricted to micro-batteries with nano-Watt or micro-Watt power output with Giga- to Mega-Becquerel activities (Micro-electronic-mechanical systems MEMS)

# Betavoltaics

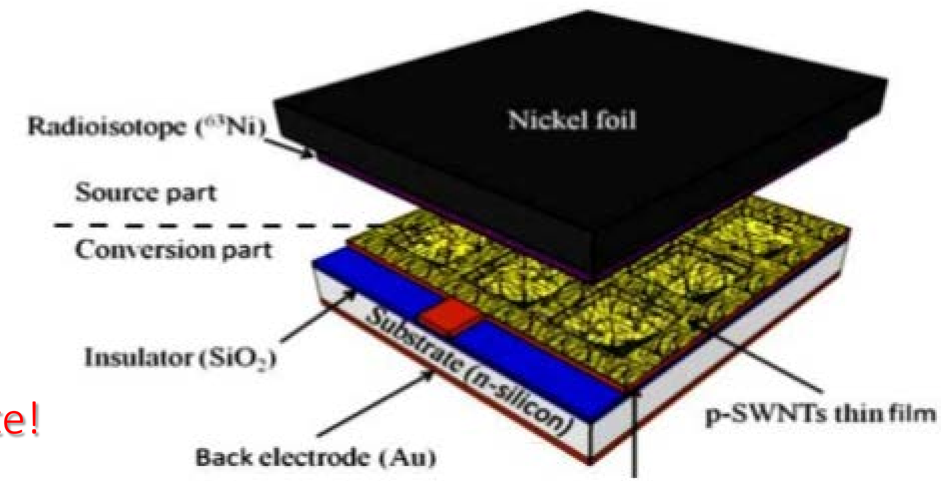


Micro-batteries use electric diode techniques to convert the nuclear decay energy into electrical energies for micro-electronic devices. Small scale nuclear batteries expand the longevity compared to micro-batteries based on electro-chemical processes. Batteries powered by nuclear decay  have a lifespan of decades and are up to 200 times more efficient

$\beta$ articles (electrons) from decay of a radioactive sample generate electron-hole pair in semi-conductor material generating voltage between the electrodes.

Radioactive samples should be free from $\gamma$ radiation to avoid external activity.

Used up-batteries are considered nuclear waste!



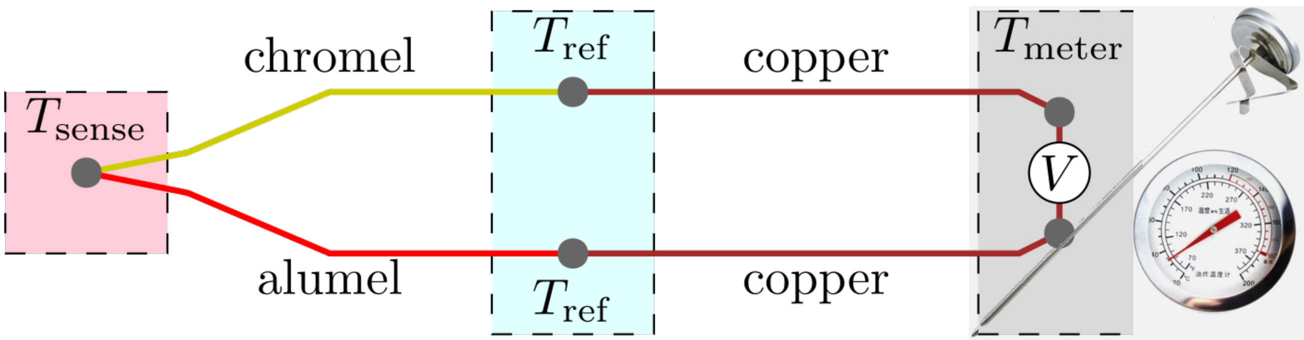

Applications for electronic units in long-term space missions, nuclear powered pacemakers. The nuclear powered laptop battery Xcell-N has a 150 day life-time!

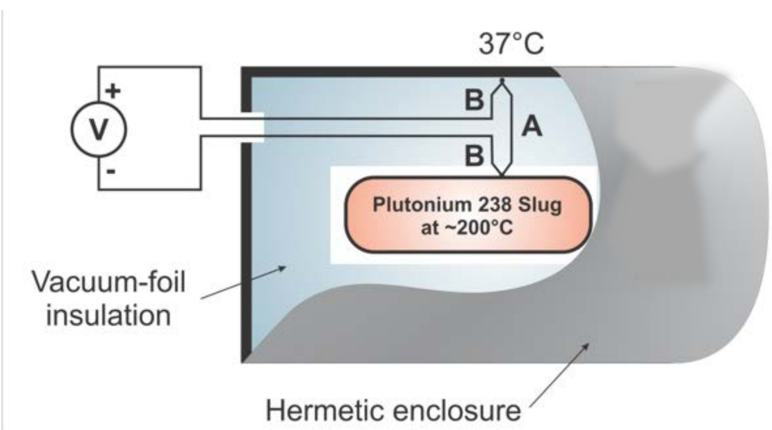
Future Applications: car batteries, deep-sea water probes, and long-term sensors

# Radioisotope Thermoelectric Generator (RTG)

A RTG is an instrument that uses an array of thermocouples to convert the heat released by the decay of a suitable radioactive material into electrical voltage.

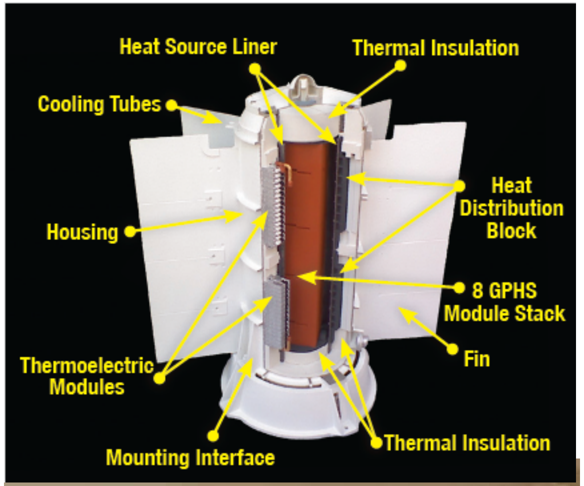
Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature is measured. When the junction experiences a change in temperature, a voltage is created that generates an electrical current.

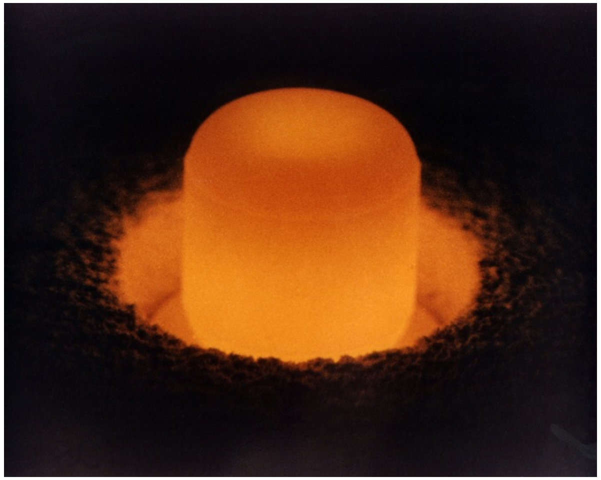



# Space craft applications

The Multi-Mission RTG (MMRTG) contains a total of **10.6 pounds (4.8 kilograms) of plutonium dioxide** (including Pu-238) that initially provides approximately 2,000 watts of thermal power and 110 watts of electrical power when exposed to deep space environments. The thermoelectric materials (PbSnTe, TAGS, and PbTe) have extended lifetime and performance capabilities. The MMRTG generator is about 25 inches (64 centimeters) in diameter (fin-tip to fin-tip) by 26 inches (66 centimeters) tall and weighs about 94 pounds (45 kilograms).



A plutonium oxide pellet ($^{238}Pu^{16}O_2$), glowing from its own heat, generated by the energy release of 5.6 MeV in the $\alpha$ decay. One gram $^{238}Pu$ generates thermal power of approximately 0.5 W.

# Calculation of Activity and Power

$$^{238}Pu^{16}O_2: \quad Mass\,number\,is\,270. \quad 270g \equiv 6.022 \cdot 10^{23}\ molecules$$

$$4.8\,kg\ of\ ^{238}Pu\,contains\ N = \frac{4800g \cdot 6.022 \cdot 10^{23}}{270g} = 1.07 \cdot 10^{25}\ ^{238}Pu\ particles$$

$$T_{1/2} = 87.74y = 2.76 \cdot 10^{9}\,s$$

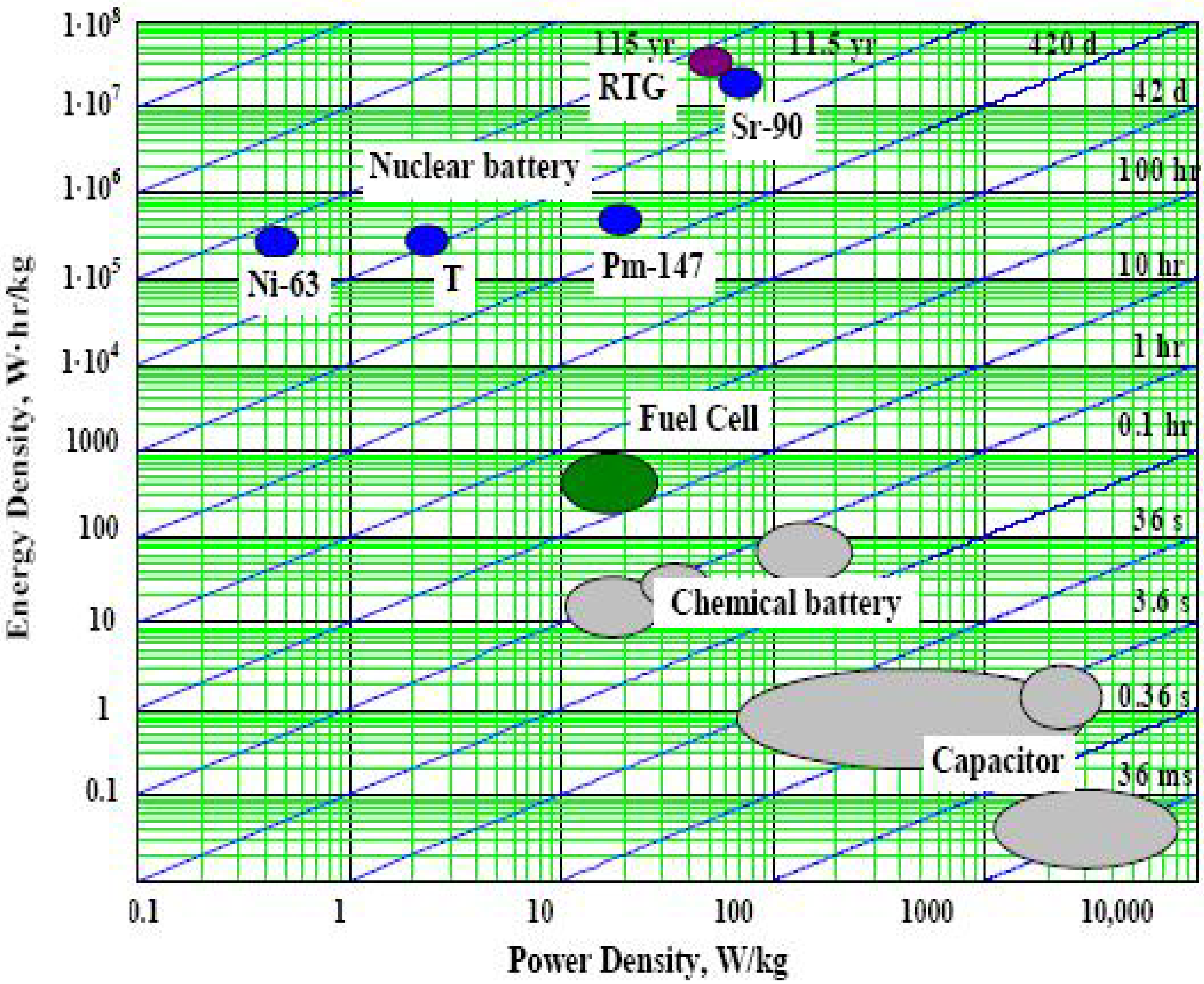
$$A = \frac{\ln 2}{T_{1/2}} \cdot N = \frac{\ln 2}{2.76 \cdot 10^{9}\,s} \cdot 1.07 \cdot 10^{25} = 2.69 \cdot 10^{15}\,Bq$$

The Plutonium based RTG battery on the Mars mission contains 2.69 PBq activity; it needs to be shielded because of associated γ-decay radiation that cannot easily be absorbed.

$$P = Q \cdot A = 5.593 \cdot 10^{6}\,eV \cdot 2.69 \cdot 10^{15}\,Bq = 8.96 \cdot 10^{-13}\,J \cdot 2.69 \cdot 10^{15}\,\frac{1}{s} = 2411W$$

This provides an overall power of about 2400 W with a lifetime of 127 years, after 87 years  the power output is reduced to 1200 W.

# Nuclear battery efficiencies



# Radiation and Micro-Electronics

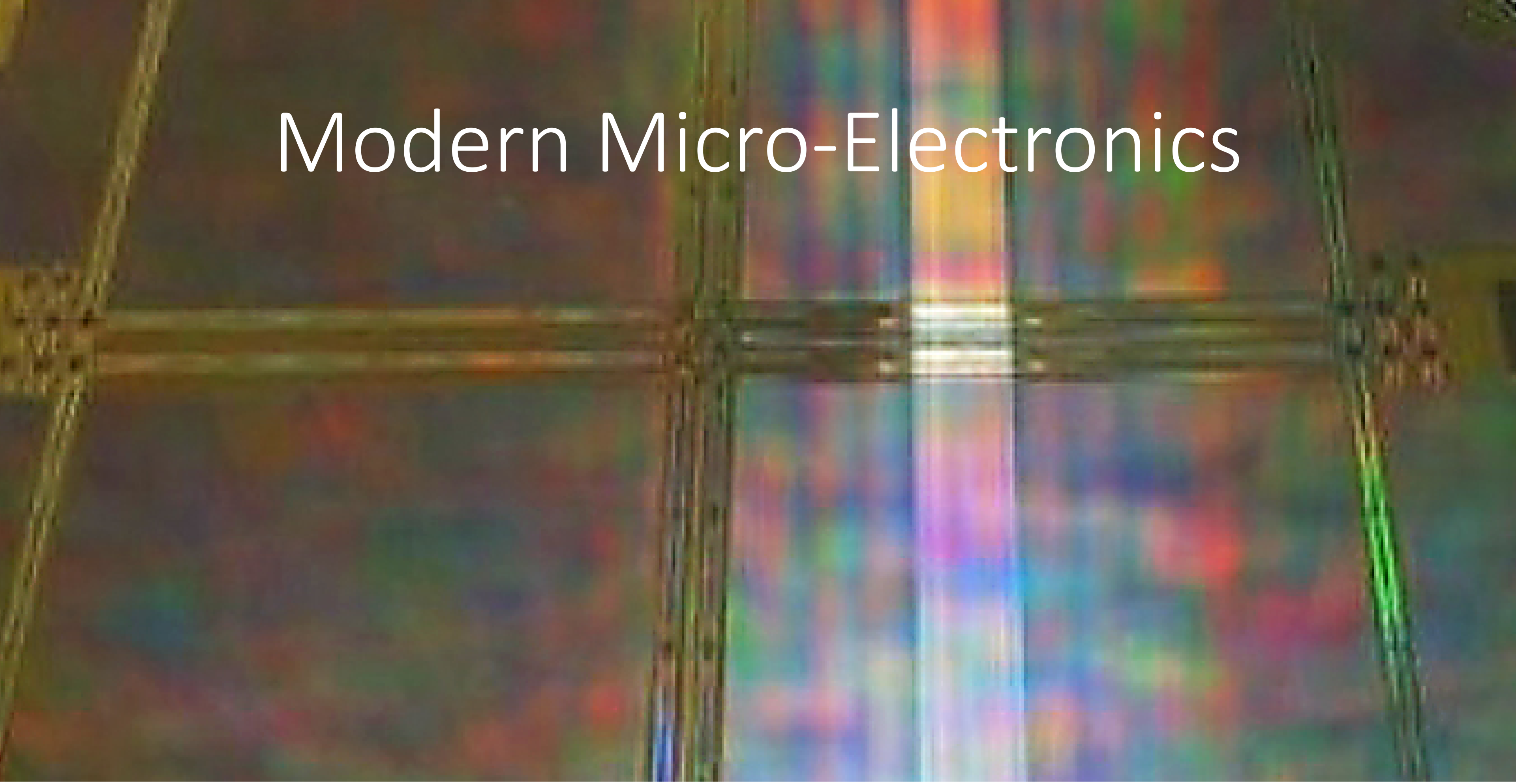
- Radiation damage on chips and/or micro-electronics in integrated circuits
- Affects as Single Event Effect SEE
- Satellite and airplane control
- Computer and cell phone operation
- Remote and computer controlled car and other traffic units

Everything is computer controlled through the miniaturization of electronics, everything is vulnerable!

# Cosmic Ray Flux

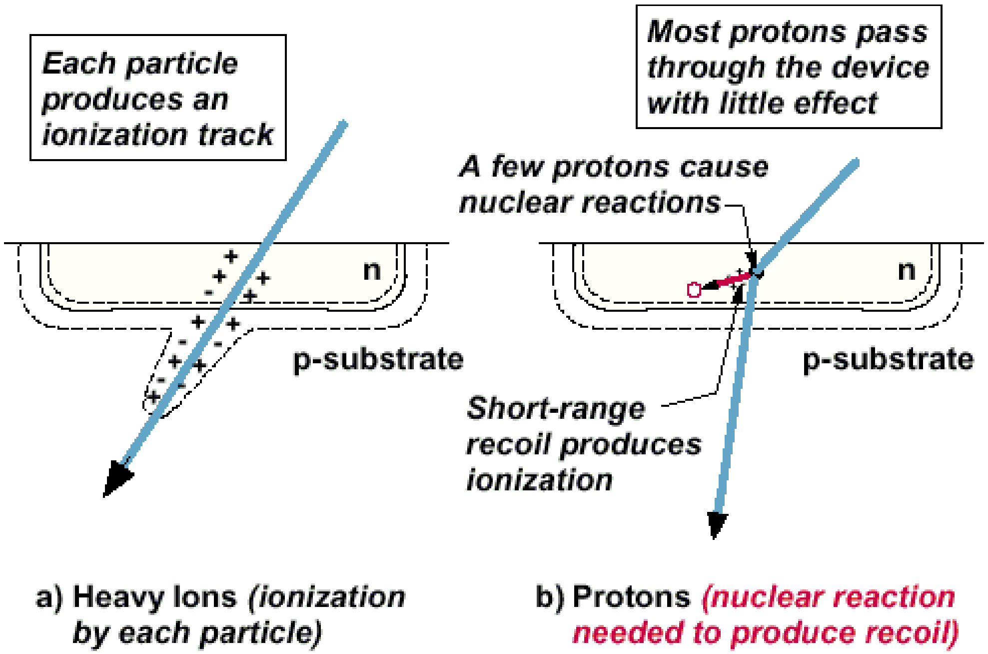
Magnetic fields are of concern, but a larger concern is the flux of high energetic radioactivity.

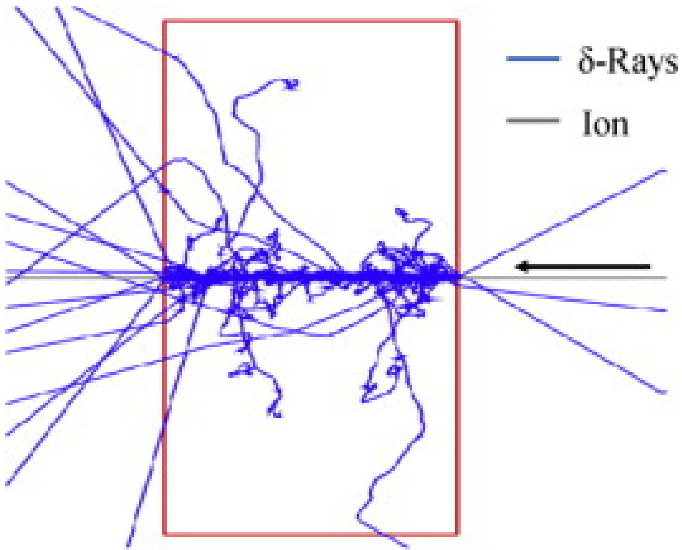
# Modern Micro-Electronics



Increasing amounts of damage that radiation damage in electronic materials due to damage in crystal structure, deformation in lattice structure, and electron ion dislocations . The number of possible defects in electronic materials rapidly increases with the shrinking size of microelectronic devices. A traditional transistor containing millions of atoms can absorb quite a bit of damage before it fails. But a micro-electronic transistor containing only a few thousand of atoms, a single defect can cause it to stop working. Damage is random, due to radiation exposure and hit pattern.

# Single Event Effect, SEE




SEE effects are statistical, damage and reaction of electronic unit is difficult to predict, because of the complexity of damage. But as higher radiation level, as higher the likelihood of electronic failure; space exploration units and airplane control electronic are particularly susceptible to damage due to the combination of high radiation environment and microelectronic complexity. But a single hit can also do substantial damage to ground-based electronic units, doing local damage in chip structure and performance, flipping bits, damaging memory and control.

# Single Event Effects (SEEs)

- An SEE is caused by a *single charged particle* as it passes through a semiconductor material
  - Heavy ions
    - Direct ionization
  - Protons for sensitive devices
    - Nuclear reactions for standard devices
      - This is similar to the soft error rate (SER) in many respects

**In field-programmable gate arrays (FPGA)**

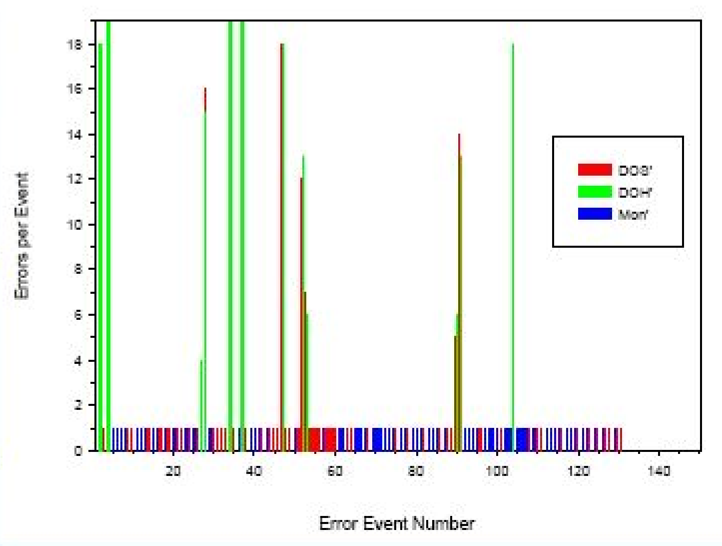
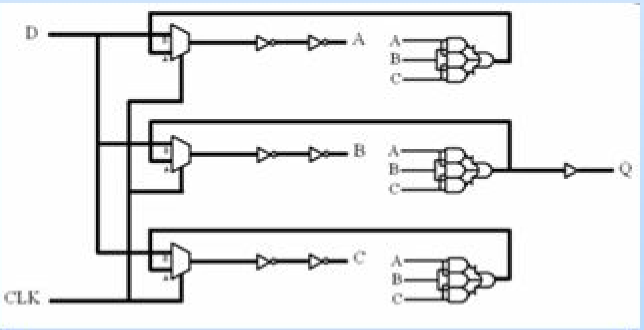



*Chart shows the number of bit errors per event in a shift error from a single SET, in this case a "clock upset." FPGA design was subsequently modified.*

- Effects on electronics
  - If the **LET** of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Complete loss of control of the device, or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- Severity of effect is dependent on
  - Type of effect
  - System criticality




*NASA designed SEU hard latch for FPGAs*

# Endangered Electronic Systems

Malfunctions in integrated circuits (IC) due to radiation effects from high energy neutrons or alpha particles at ground level are now becoming a major concern; especially for life-critical and safety-critical applications such as aviation, industrial automation, medical devices, automotive electronics and for high-availability, revenue-critical applications such as communication infrastructure.

# Radiation Risk Analysis

Sources of Errors

• **Neutrons, muons, protons:** High energy neutrons present in the atmosphere arise from interaction with atmospheric gases and high energy subatomic particles from the sun and deep space. When a neutron strikes a silicon atom, heavy ions are ejected which cause momentary current pulses, causing data to change in memory cells or flip flops.

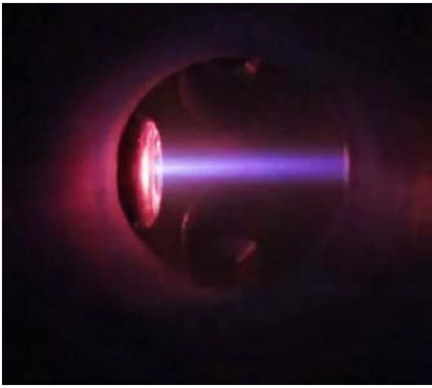
• **Alpha particles:** These are emitted by naturally occurring radioactive isotopes present in IC package molding compounds. Even today's low-alpha compounds in package materials generate sufficient alpha particles to cause a significant rate of upset in integrated circuit units.

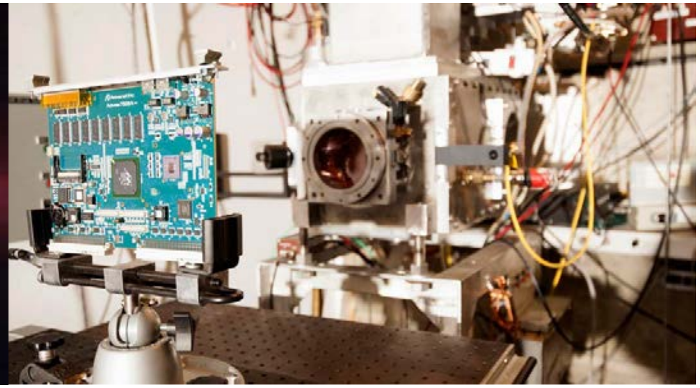
Types of Errors

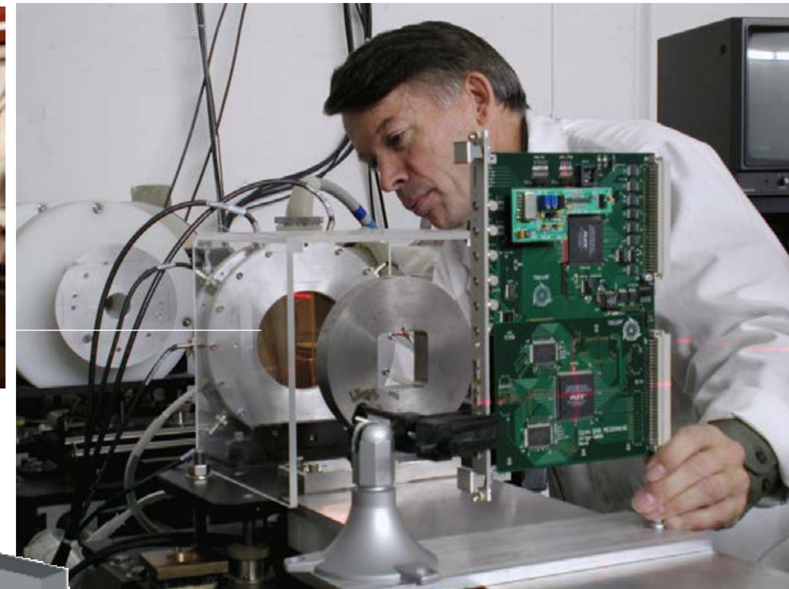
• **Configuration Memory Errors:** When the interconnecting elements used for routing and configuration of logic elements are corrupted due to high energy particles, they can lead to functional change in a logic module or misconnected or misrouted signals, resulting eventually in system failure.

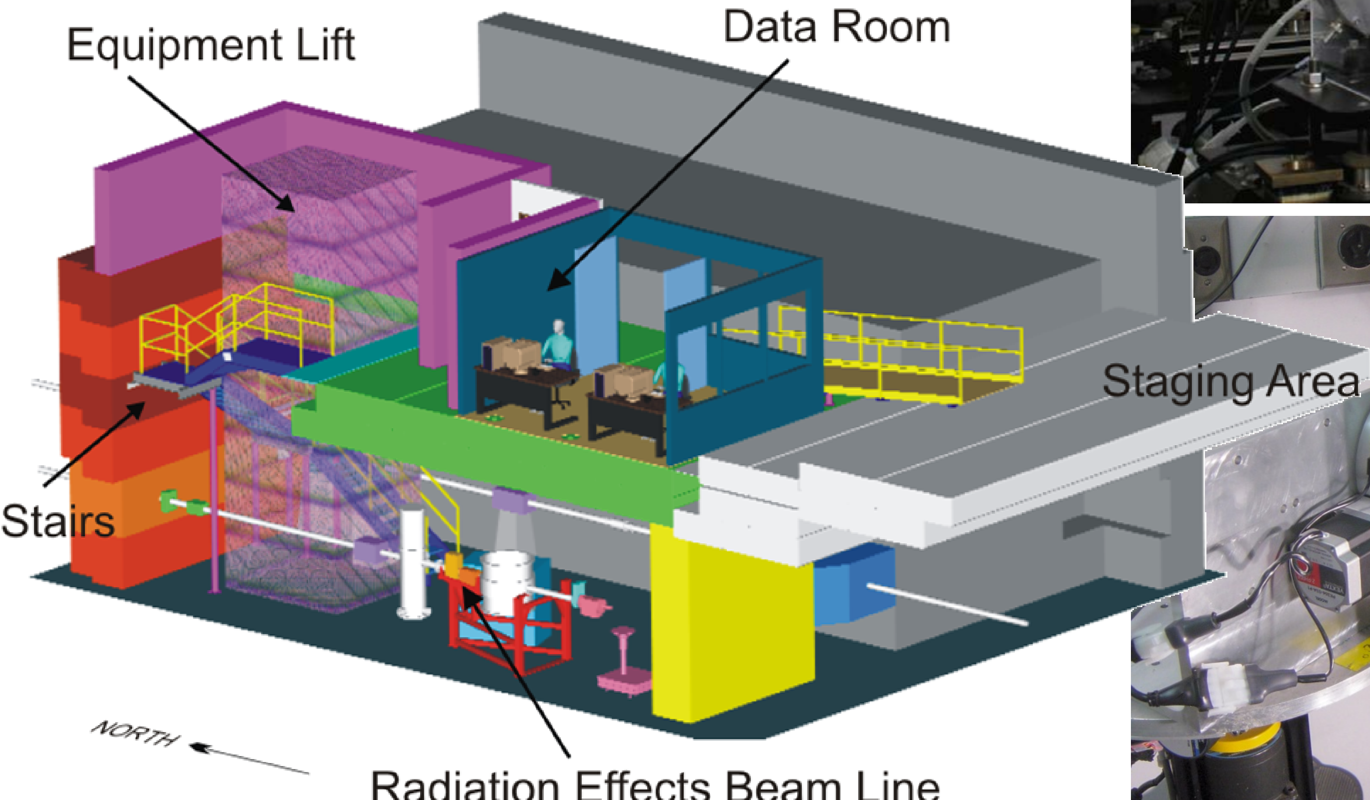
• **Soft Errors:** When flip-flops or memory cells change state due to neutron- or muon-induced radiation effects, the resulting errors are commonly referred to as soft or data errors. These types of errors can be mitigated using techniques such as local or global triple module redundancy (TMR) or error correcting codes (ECC).

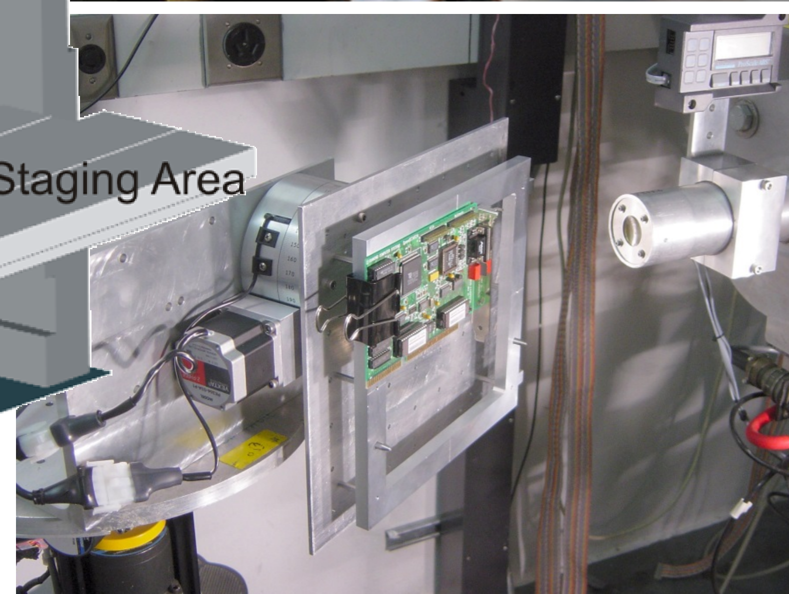
# Radiation testing at accelerator laboratories





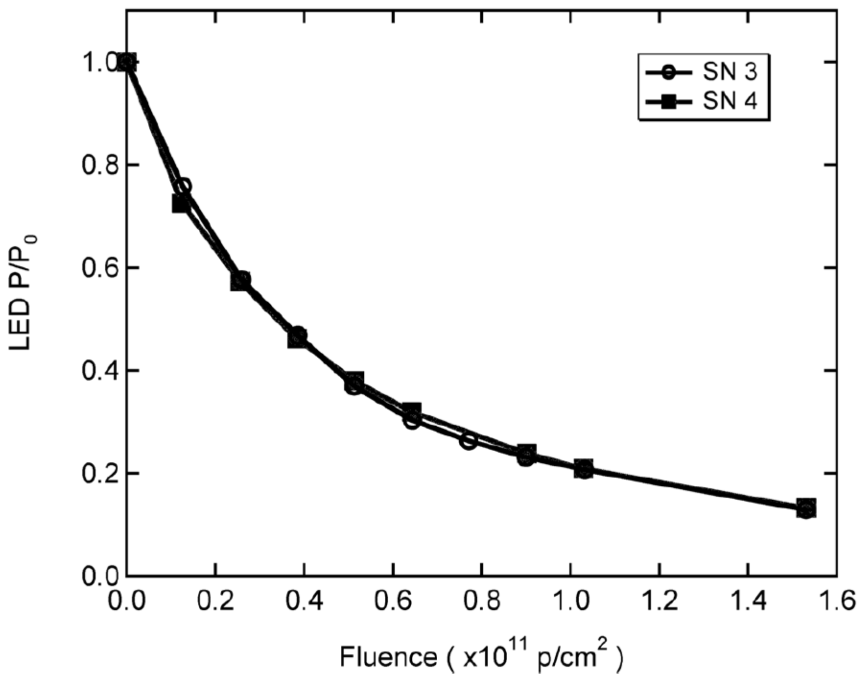




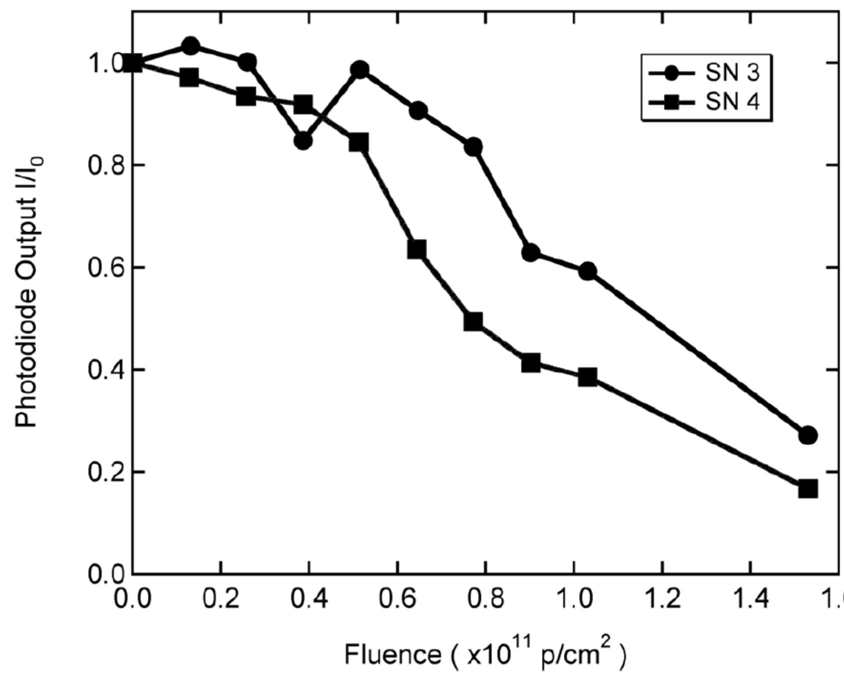



# Radiation Tests of Electronic Units

Radiation tests with accelerator beams simulating the energy range of cosmic radiation to assess damage and risk of failure as well as effects and consequences of failure. Which components fail first, which parts need to replaced regularly can only be determined on a statistical analysis basis. This was of primary interest to space and aeronautics industries, today damage and risk assessment  expanded to the car and computer industries.




Proton induced degradation of LED power devices




Proton induced degradation of transistor units

Combination of radiation testing and simulation of radiation impact for identifying safe units, and removing vulnerable units leads to radiation hardness technologies that are increasingly necessary but doesn't provide absolute safety against radiation damage at high radiation levels.