GET1024 / GEC1036 Lecture 18

Applications of Radiation in Industries

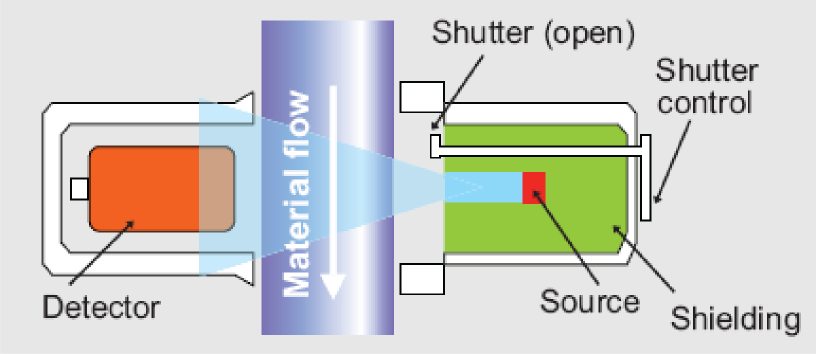
- Gauges:
  - Level, density & thickness
- Radiography
  - Industrial, Airport & Cargo Security, CT
- Sterilization
- Space Exploration
- Material Enhancement:
  - Gems, Semiconductor & Plastic
- Safety, Risks & Accidents

Applications of Radiation in Industries

- We have seen that the use of radiation in agriculture has very far-reaching effects, e.g., in improving crop production through induced mutation, sterile insect techniques and food irradiation.
- Radiation is also used very extensively in industries, though these applications may not be as well-known to the public
- Many characteristics of ionizing radiation are used in industries
  - Very low level of ionizing radiation can be detected (to be used as tracers)
  - Radiation is penetrating and its penetrating power is dependent on the absorbing medium
  - Radiation (using neutrons) can cause changes in nucleus
  - Radiation is energetic enough to break chemical bonds thus allowing new materials to be manufactured
- We will look at some of the applications in this lecture (which only represents a fraction of its actual use in the industries).

Nuclear Gauges I: Level Gauge

- **Quality control for modern manufacturing** – liquid levels, density of materials in vessels and pipelines, thickness of sheets and coatings, amounts and properties of materials on conveyor belts, etc.
- **Level gauges** – based on attenuation. Radiation source on one side of container to be filled and detector on the other side. Liquid rises to intersect the lines between the source and detector and finally block the beam. Electronic signal sent to the control station.
- Suitable for most liquids including extremely corrosive ones such as those in chemical plants.
- Because they can in effect "see" through solid tank walls, nuclear radiation gauges are perhaps the ultimate in non-contact sensing.

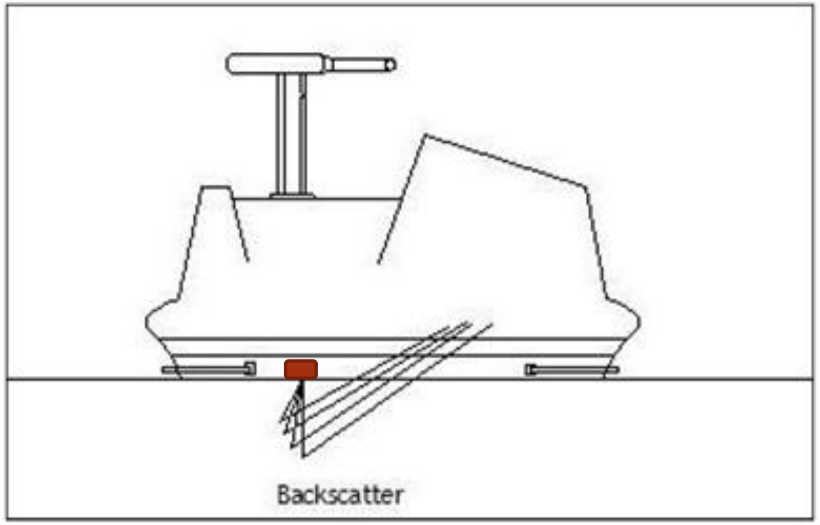


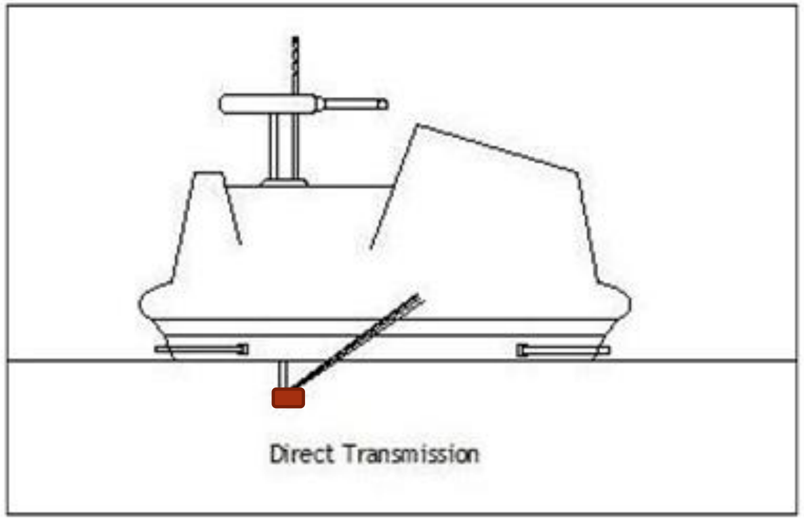
from https://www-ns.iaea.org/tech-areas/communication-networks/orpnet/documents/Nuclear-Gauges.pdf

from http://www.radsafe.com.au/index.php/industrial-radiation-production

Nuclear Gauges II: Density Guage

- **Density Gauges** - Measure the density of the inner structure or contents.
- May be based on direct transmission similar to level gauge. Reading is decreased with increasing density due to attenuation of gamma-rays.
- May also be based on radiation backscattered to the sensor.
- For soil or asphalt measurement, may also have a neutron source (Am-Be) and a thermal neutron detector to account for moisture.



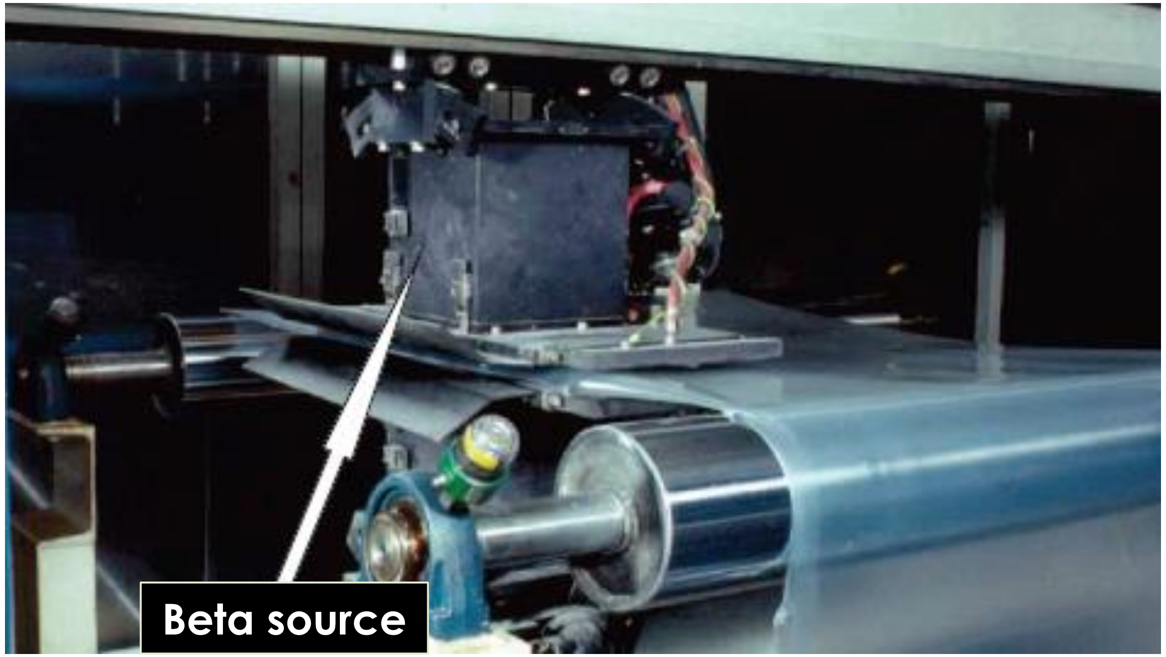


from http://article.sapub.org/10.5923.j.jce.20150501.01.html

Density gauge used to ensure proper compaction for the foundation for a school from https://en.wikipedia.org/wiki/Nuclear_density_gauge

Nuclear Gauges III: Thickness Gauge

- **Thickness Gauge** – Used extensively in almost any industry involved in producing sheet material.
- Most often uses beta source since it is less penetrating than gamma-rays.

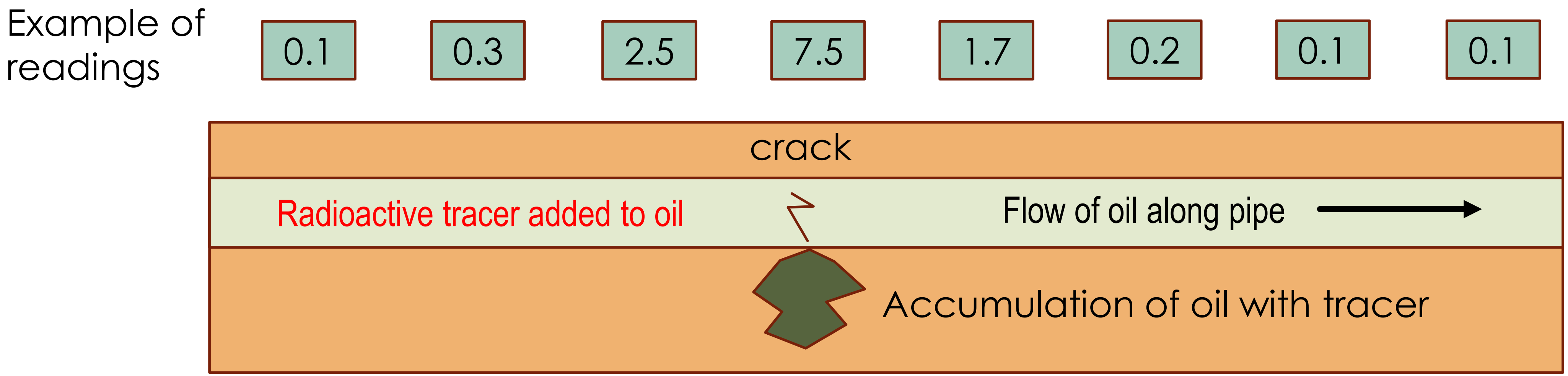


from https://www-ns.iaea.org/tech-areas/communication-networks/orpnet/documents/Nuclear-Gauges.pdf

- Signals from detector may be used to control the system for producing the sheet so that the thickness is uniform within certain tolerance limits.
- Examples of materials manufactured using thickness gauges include paper, plastic films, textile, fibreglass sheets, rubber plates, adhesive layers, plastic or electrolytic coatings, etc.
- Backscattering techniques may be used if transmission geometry is not possible.

Plant Diagnostics

- Signals from radiation monitors (as in previous slides) in industrial plants (factories) – at rate as rapidly as 1000 times / second – allow instantaneous plant diagnostics to be made – adjust quickly for any anomalous behaviours.
- Radioactive tracers are often used to investigate reasons of inefficiency, e.g., flow rate, mixing patterns, locate leaks in heat exchanges and pipelines as a function of time deep within a system.
- Example: Inspection of completed 140-km long crude oil pipeline in India. Chose radioisotope tracer method over hydrostatic pressurization and visual inspection, reduced the time needed to 6 weeks instead of 6 months and saved US$300,000.

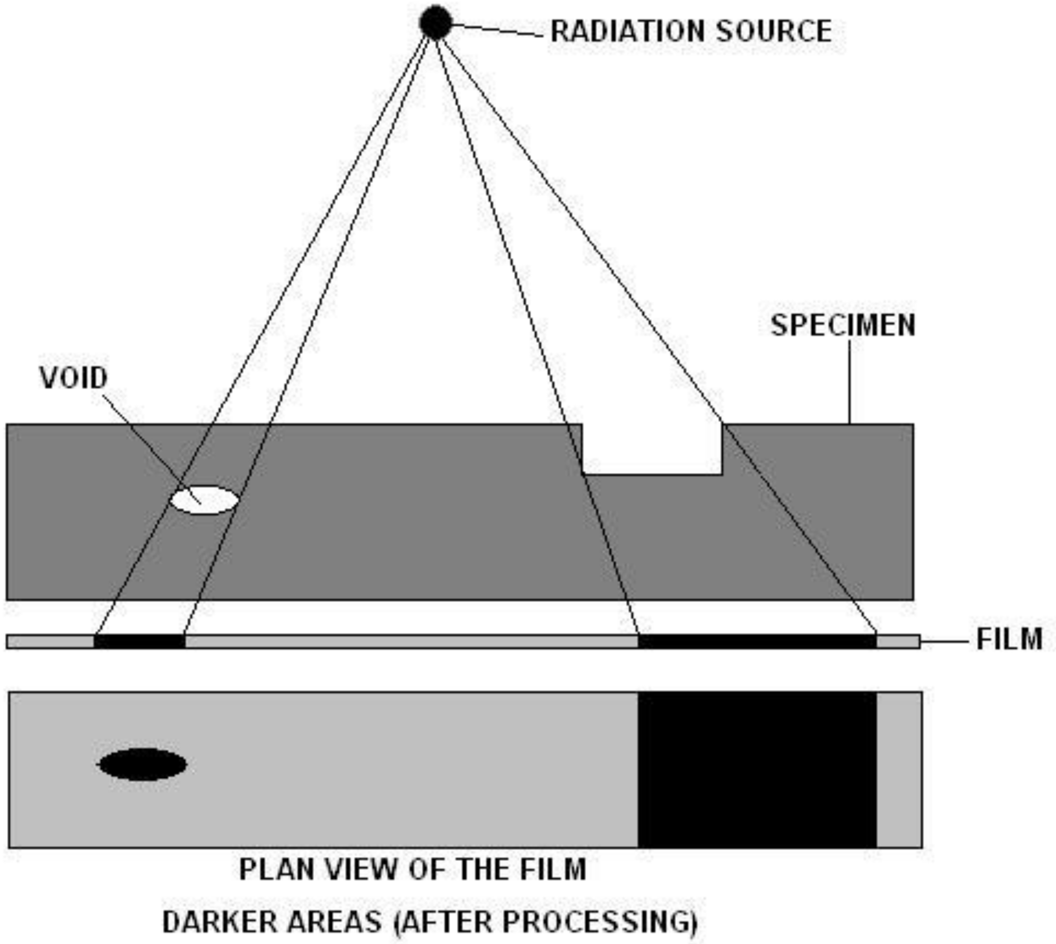


Industrial Radiography

- Industrial radiography is another method of non-destructive testing using either x-rays or gamma-rays where many types of manufactured components can be examined to verify the internal structure and integrity of the specimen.

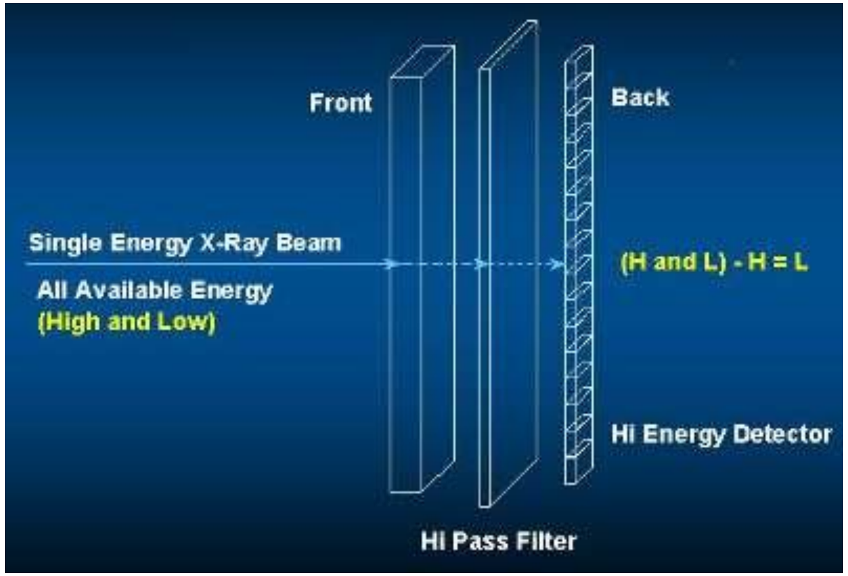
- Inspection of products – e.g., welds, concrete (such as locating reinforcement bar or conduits, machine parts, plate metals, pipelines or even ceramic in aircraft industries.

- Most often used gamma radiation sources, such as iridium-192 ($^{192}_{77}\mathrm{Ir}$, half-life of 73.8 days) and cobalt-60.



Airport X-ray Machine

- One of the most common radiography public encounter is the x-ray scanner in the airport or higher security locations.



The machine used in airports usually is based on a dual-energy X-ray system. This system has a single X-ray source sending out X-rays, typically in the range of 140 to 160 kilovolt peak.

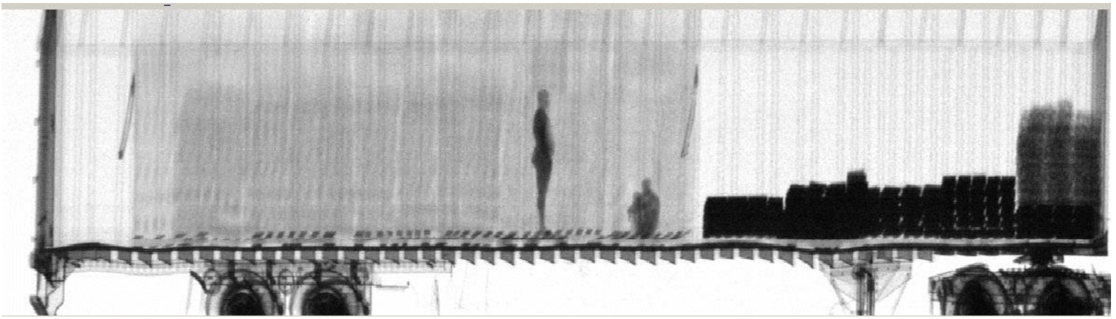
After the X-rays pass through the item, they are picked up by a detector. This detector then passes the X-rays on to a filter, which blocks out the lower-energy X-rays. The remaining high-energy X-rays hit a second detector. A computer circuit compares the pick-ups of the two detectors to better represent low-energy objects, such as most organic materials.

http://science.howstuffworks.com/transport/flight/modern/airport-security4.htm

Cargo Scanning

- Gamma-ray Radiography Systems capable of scanning trucks usually use Co-60 or Cs-137 as a radioactive source and a vertical tower of gamma detectors. This gamma camera is able to produce one column of an image. The horizontal dimension of the image is produced by moving either the truck or the scanning hardware. The Co-60 units use gamma photons with a mean energy 1.25 MeV, which can penetrate up to 15–18 cm of steel. The systems provide good quality images which can be used for identifying cargo and comparing it with the manifest, in an attempt to detect anomalies. It can also identify high-density regions too thick to penetrate, which would be the most likely to hide nuclear threats.

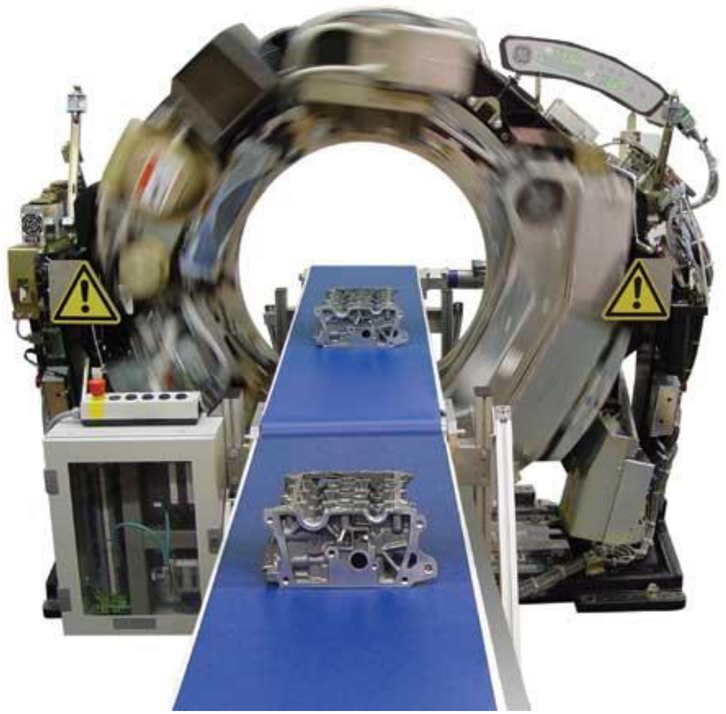
- X-Ray radiography uses a high-energy bremsstrahlung spectrum with energy in the 5-10 MeV range created by a linear particle accelerator (LINAC) instead. Such X-ray systems can penetrate up to 30–40 cm of steel in vehicles moving with velocities up to 13 km/h. They provide higher penetration but also cost more to buy and operate. They are more suitable for the detection of special nuclear materials than gamma-ray systems. They also deliver about 1000 times higher dose of radiation to potential stowaways.

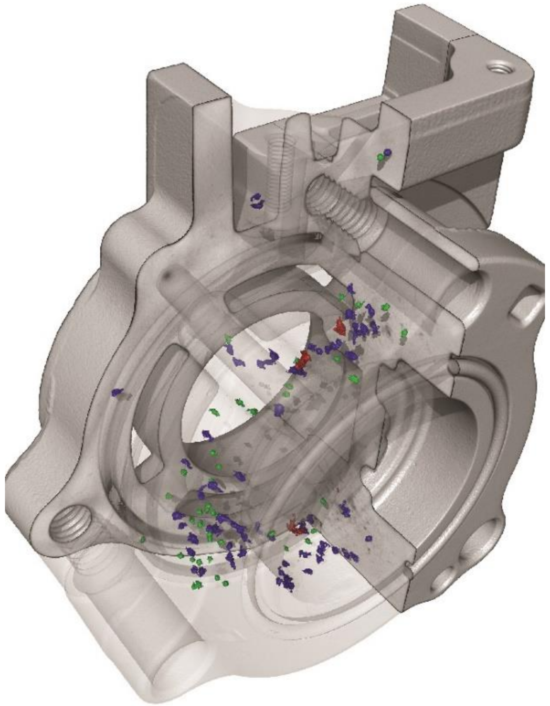


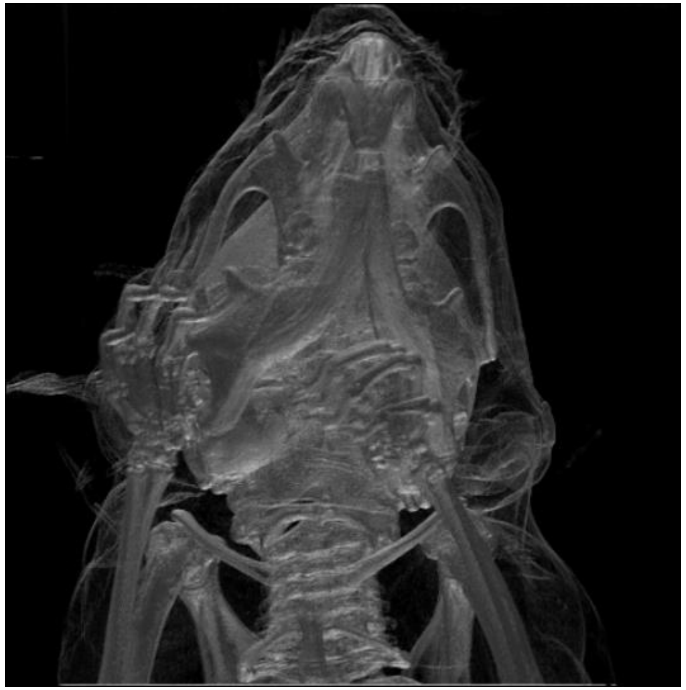
https://en.wikipedia.org/wiki/Cargo_scanning

Industrial Computed Tomography (CT)

- Similar to medical applications. Uses irradiation (usually with x-rays) to produce three-dimensional representations of the scanned object both externally and internally,.
- More than a million measurements to be taken over 180 degrees to develop a crisp CT image. Image formed in less than 1 minute.







High speed Industrial CT system (Image from http://www.qmtmag.com/display_eds.cfm?edno=2546207)

Sterilization by Irradiation

- Sterilization (process that eliminates, removes, kills, or deactivates all forms of life and other biological agents) can be achieved by heat, chemicals, irradiation, high pressure, and filtration.
- Irradiation is preferred in many situation, e.g.,
  - Closed packaged products – ranging from medical devices to raw materials and consumer products such as peat moss, poly-lined drums, teething rings, and hermetically sealed products.
  - Dense materials – limiting permeation of steam or gases into the container. Further, steam and gas may cause clumping, change particle size, and have other physical effects that render the product useless. Spices, talc, raw materials, water soluble materials, powders, and other like materials are processed only with gamma radiation for this reason.
  - When unwanted chemical residuals are undesirable – Certain products have a propensity to absorb/adsorb chemical sterilants. Gamma radiation is considered a “clean” process – no chemicals are involved, only pure energy.

https://en.wikipedia.org/wiki/Sterilization_(microbiology)#Ionizing_radiation_sterilization

Sterilization by Irradiation

- Three types of radiation are commonly used:
  - Gamma radiation is very penetrating, and is commonly used for sterilization of disposable medical equipment. It is emitted by a radioisotope, usually Cobalt-60 (^{60}Co) or cesium-137 (^{137}Cs). Note that the gamma ray from Co-60 is twice more energetic than that from Cs-137 and thus is more penetrating.
  - High-energy X-rays (produced by bremsstrahlung when energetic electrons bombard a dense target) does not required radioactive materials. Can be more penetrating depending on energy of X-ray photons.
  - Electron beam - much higher dosing rate than gamma or x-rays. Less exposure time is needed and thereby any potential degradation to polymers is reduced. Not as penetrating.
- **Irradiation with X-rays or gamma rays does not make materials radioactive.** Low energy particles also cannot make materials radioactive but cannot penetrate too deeply. Neutrons and very high-energy particles have good penetration power but can make materials radioactive (but are **not used**.

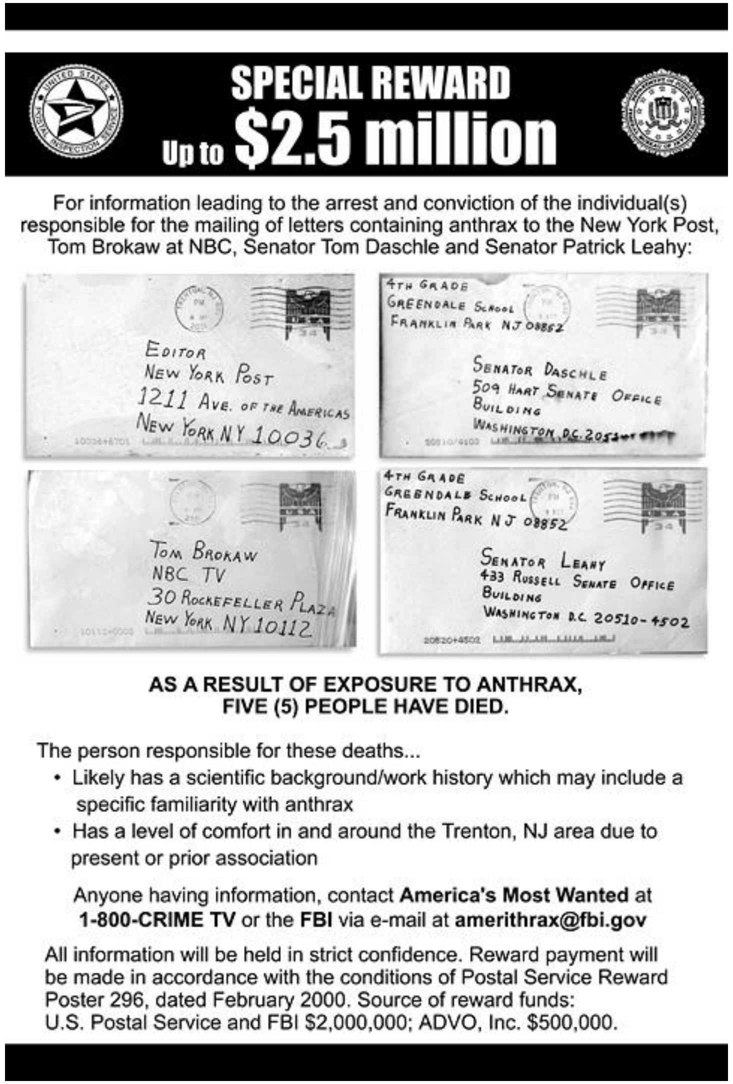
https://en.wikipedia.org/wiki/Sterilization_(microbiology)#Ionizing_radiation_sterilization

Examples of Irradiated Products

- Surgical products such as implants (hips, knees, fingers, etc.), shunts, instruments, syringes, bone saw, OR towels, gloves, etc.
- Medical / Pharmaceutical products, e.g., Body bags, blood lancets, dental anchors, thermometers / covers, specimen containers, etc.
- Sterilized saline solutions (for cleaning contact lenses), some cosmetic, etc.

Another Example: 2001 Anthrax Attacks in US

- From September 18, 2001 (1 week after Sep 11 attacks) to October 9, 2001, mails containing anthrax spores were sent to some US politicians and media.
- In total, the attacks killed 5 persons and injured 17 others.
- Mails to Federal Offices in Washington DC region piled up as the fear mounted.
- Solution: irradiate the mail with sufficient energy to kill the anthrax spores.
- The irradiation process passes mail through a high-energy beam of electrons or x-rays. It delivers a radiation dose that is approximately 2 million times stronger than a chest x-ray. The beam penetrates deep into the mail to destroy bacteria and viruses. It can even penetrate letter trays and packages.



https://en.wikipedia.org/wiki/2001_anthrax_attacks

Space Exploration: Radioactive Heater Unit (RHU)

- The decay energy of radioactive materials may be used to provide energy (heat).

- One common radioisotope used is Pu-238 ($t_{1/2}$ = 87.7 years).
- Decay is via alpha-particle with energy of

$$^{238}_{94}\mathrm{Pu} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{4}_{2}\alpha$$

$t_{1/2}$ = 246,000 yrs   5.593 MeV

- Pu-238 is produced mainly by neutron radiation on Np-237 (extracted from NPPs).
- I gram of pure Pu-238 has activity of **634 GBq** (17.1 Ci) and produces **0.568 W** of power. [Verify figures yourself.]
- RHUs are used to heat up instruments in deep space missions.

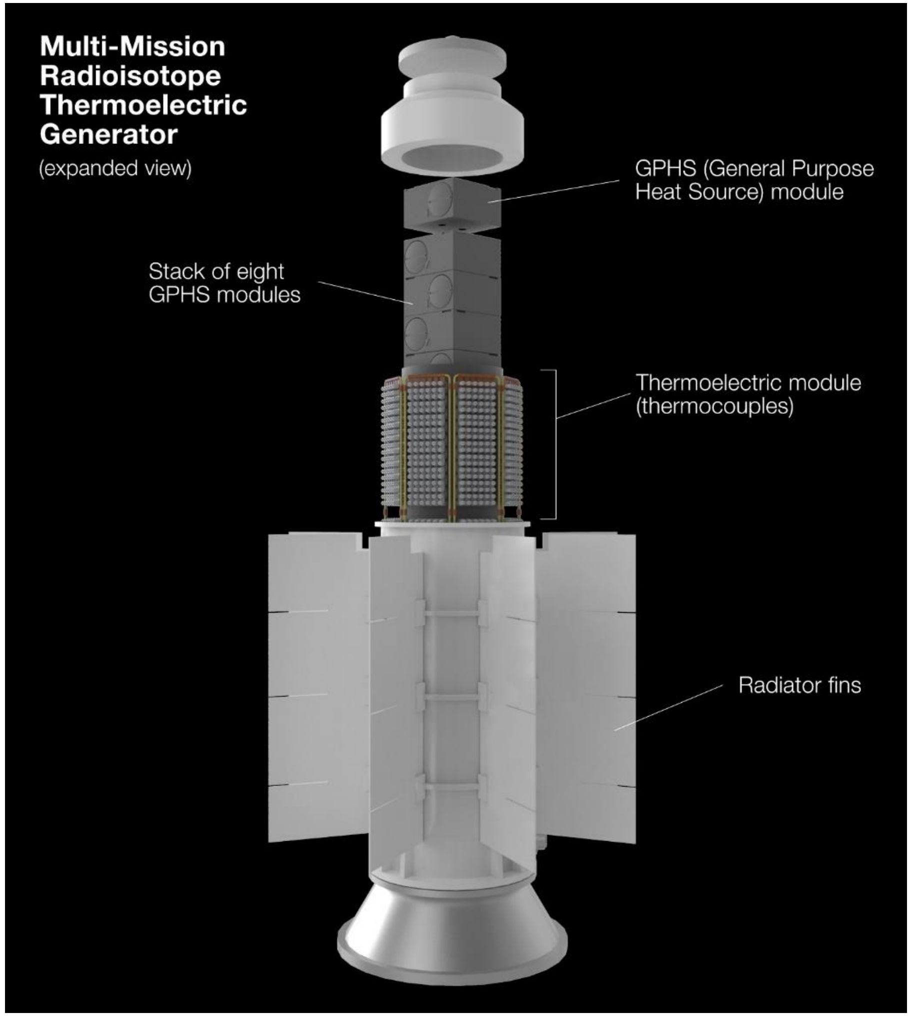
https://en.wikipedia.org/wiki/Uranium-234

Choice of Radioisotope for Space Missions

- Criteria for choosing radioisotopes for space missions
  - Its half-life must be long enough so that it will release energy at a relatively constant rate for a reasonable amount of time (say decades but may be shorter if specific missions can be completed in less time). Half-life cannot be too long or activity will be too low.
  - For spaceflight use, the fuel must produce a large amount of power per mass and volume (density). Alpha decays in general release about 10 times as much energy as the beta decay of strontium-90 or caesium-137.
  - Radiation must be of a type easily absorbed and transformed into thermal radiation, preferably alpha radiation. Beta radiation can emit considerable gamma/X-ray radiation through bremsstrahlung secondary radiation production and therefore requires heavy shielding.
- Pu-238 satisfies the three criteria above as it has very little beta and gamma radiation.
- Some radioisotopes that have been used or being considered are
  - Sr-90 (half-life of 28.8 years, beta decays only, slightly lower power density of 0.46 W/g)
  - Am-241 (half-life of 432 years but contains gamma radiation, power density ¼ that of Pu-238)
  - Po-210 (half-life of 138 days, almost pure alpha radiations, power density of 140 W/g)

Radioisotope Thermoelectric Generator (RTG)

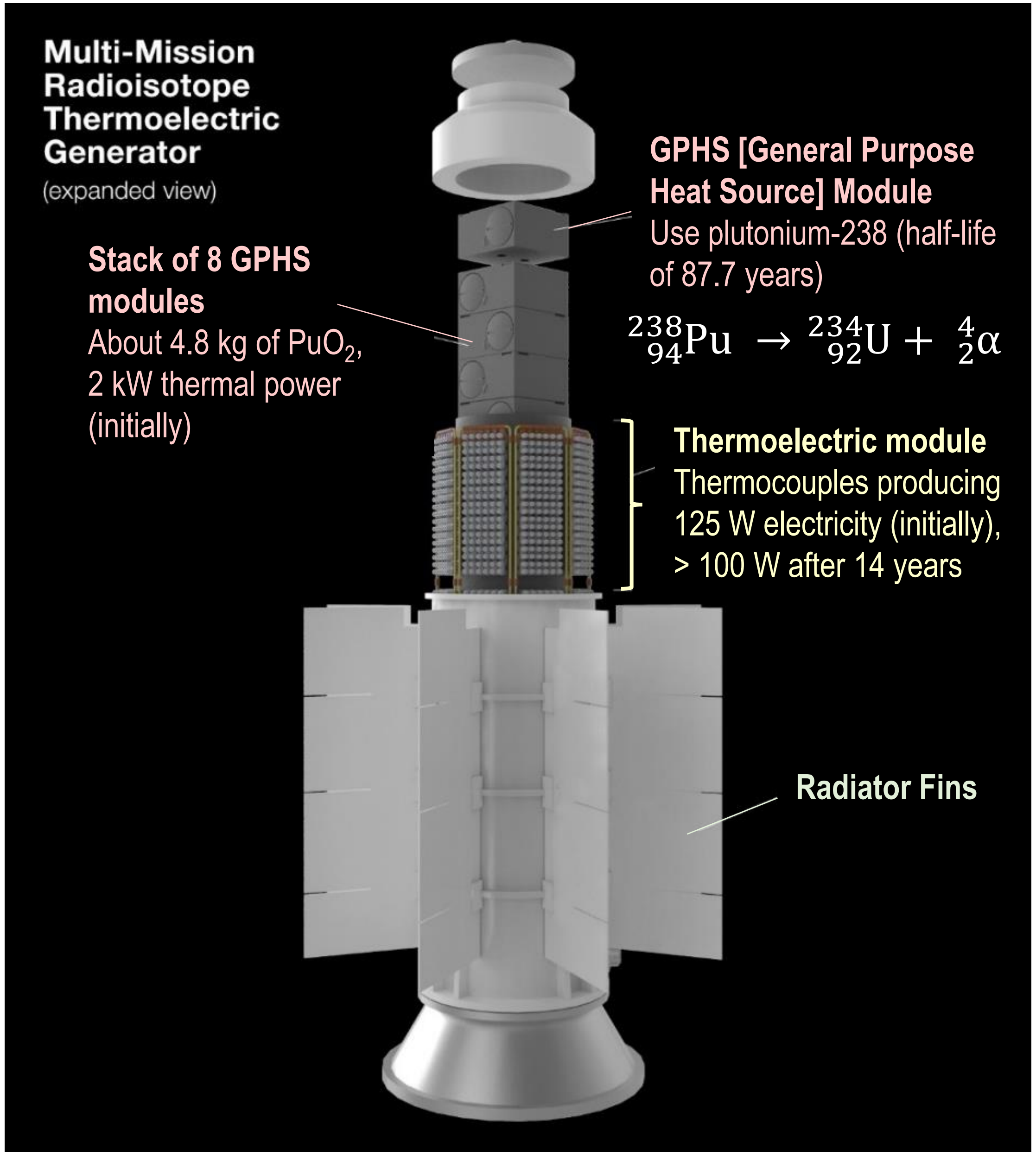
- Beside using the radioisotopes for simple heating, they can also be used to provide electricity.
- Again, Pu-238 is often used due to reasons given earlier.
- If two wires (of different materials) are joined at two ends and these two ends are at different temperatures, there will be a potential difference between the two junctions and can be used to produce an electric current (Seebeck Effect).
- The Radioisotope Thermoelectric Generators (RTGs) used this principle – converting the heat from radioisotope to produce electricity needed to run the instruments and other essential functions.
- Used in more than 20 space missions such as Voyage 1 & 2, Galileo, Pioneer 10 & 11 and even in Moon mission such as Apollo 12-17 as well as for Mars Rover.
- Greater amount of fuel is used to produce up to a few kW of heat and 300 W of electricity.



https://rps.nasa.gov/power-and-thermal-systems/power-systems/current/

Radioisotope TE Generator (RTG)

The Mars Science Laboratory rover, Curiosity

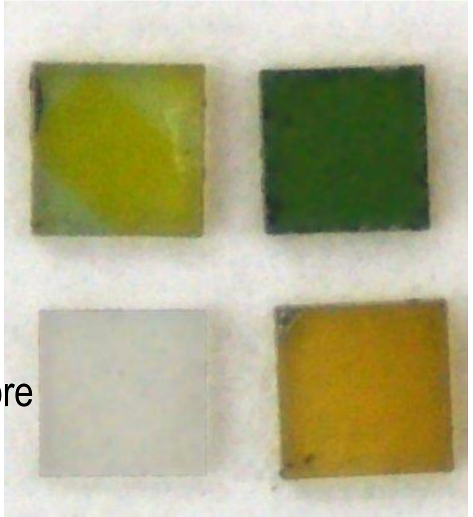


- No moving parts that can fail or wear out, highly reliable
- No thermocouple used in RTGs has ever ceased producing power in total combined time over 300 years of operation
- Used also in as Voyage 1 & 2, Galileo, Pioneer 10 & 11, Moon missions such as Apollo 12-17, etc.

Enhancing Gemstone Appearance with Radiation

- The gemstone irradiation is a process in which a gemstone is artificially irradiated in order to enhance its optical properties. High levels of ionizing radiation can change the atomic structure of the gemstone's crystal lattice, which in turn alters the optical properties within it.
- As a result, the gemstone's color may be significantly altered or the visibility of its inclusions may be lessened. Irradiation has enabled the creation of gemstone colors that do not exist or are extremely rare in nature.
- This process can take place in a nuclear reactor (neutron bombardment), an accelerator (electron bombardment), or by exposure to gamma rays in an irradiator.

Before



Diamonds (2 x 2 mm): before and after irradiation by different doses of 2 MeV electrons and annealing

https://en.wikipedia.org/wiki/Gemstone_irradiation

Diamonds: colorless → variety of colors. Some of the irradiated colors are then heated as a second step, resulting in additional colors

https://www.gia.edu/gem-treatment

Enhancing Gemstone Appearance with Radiation

- Besides diamond, other gemstones that are irradiated include pearl, topaz, quartz, tourmaline and zircon.
- The most commonly irradiated gemstone is topaz as blue topaz is very rare in nature. About 30 million carats (6,000 kg) of topaz are irradiated every year.
- Gemstones irradiated with neutrons may remain radioactive for a short time and will be required to be kept by suppliers until its radiation level is low enough as stated in the country's regulations.

Topaz: colorless → deep blue after irradiation

Quartz: colorless → Green

https://www.iaea.org/sites/default/files/calvo.pdf

Doping in Semiconductor

- Doping (intentional adding impurities) in pure semiconductors is an important and standard method to modulate its electrical properties.
- Phosphorus is one of the dopants used for silicon. Instead of using diffusion of phosphorus into the silicon crystal, nuclear transmutation is often used.
- The silicon crystal is irradiated with neutrons (usually in a reactor). Natural silicon contains 3 stables isotopes: 92.2% of ^{28}Si, 4.7% of ^{29}Si and 3.1% of ^{30}Si. Note that there are traces of ^{31}Si ($t_{1/2}$ = 2.62 hrs) and ^{32}Si ($t_{1/2}$ = 153 yrs).
- When irradiated, some silicon nuclides will absorb one neutron and change to the next higher mass. In particular for ^{30}Si:

$$ {}^{30}_{14}\mathrm{Si} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{31}_{14}\mathrm{Si} \rightarrow {}^{31}_{15}\mathrm{P} + {}^{0}_{-1}\mathrm{e}^{-} $$

- ^{31}P is stable and will thus become the impurities needed as any newly formed ^{29}Si or ^{30}Si are stable and the very few ^{32}Si nuclides produced in the process has long half-life.
- Note that some points defects will result from the irradiation and the crystal has to be annealed at high temperature after irradiation.

http://www.topsil.com/media/56052/ntd_application_note_long_version_october2013.pdf

Doping in Semiconductor

- This method is the most precise and uniform way of introducing phosphorus into the crystal. By varying the neutron dose through the neutron flux rate or time of exposure, one can precisely control dopant concentration and thus the resistivity of the crystal as seen in the table below.

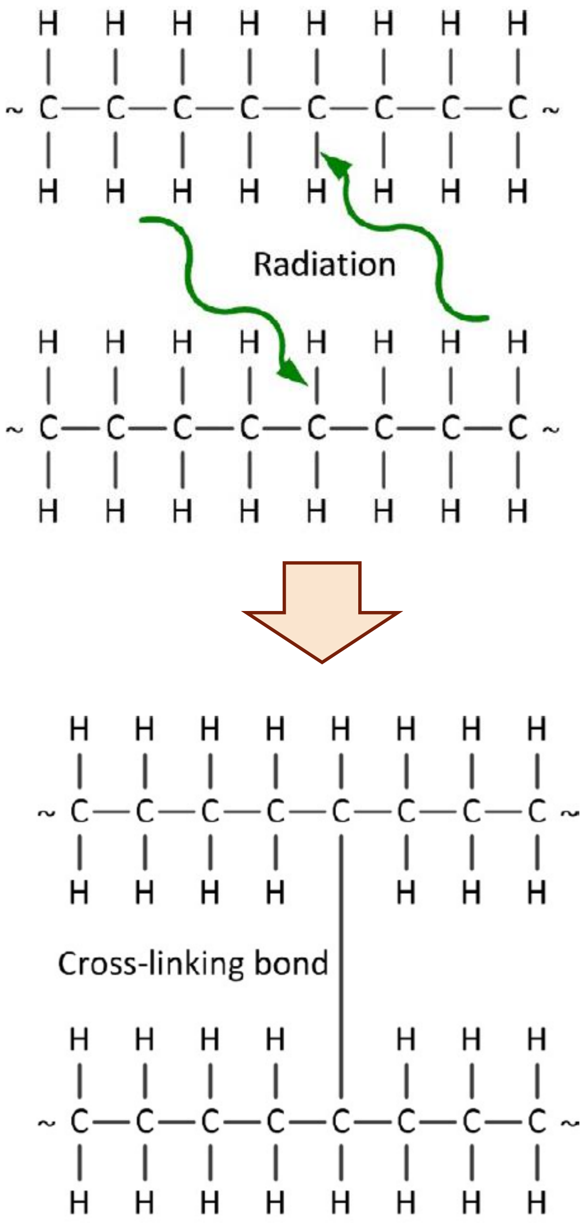
Resistivity (Ωcm)	Dopant conc. (10^{13} atoms/cm^3)	Ppba Phosphorus	Neutron dose (10^{16} cm^{-2})
30	14.5	2.9	86
100	4.3	0.85	24
200	2.1	0.42	10
300	1.4	0.28	7
500	0.85	0.17	4
1000	0.45	0.086	2

- This is used in the manufacture of power thyristors, which are high-voltage, high-current semiconductor rectifiers with an annual yields of the product material are more than 50 tons. The virtue of neutron transmutation doping (NTD) compared with other methods is that it provides a uniform resistivity over the large area of the device.

http://www.topsil.com/media/56052/ntd_application_note_long_version_october2013.pdf

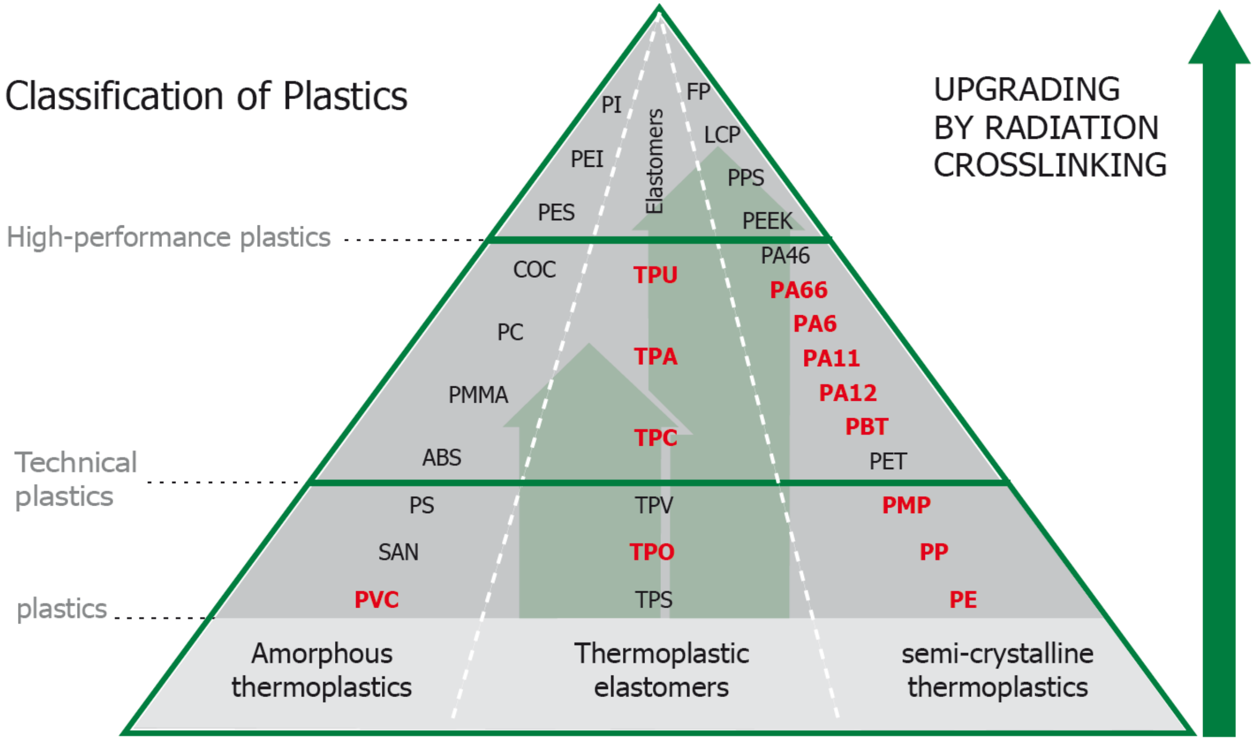
Radiation Induced Crosslinks in Plastic

- Plastic is made up of long polymers.
- When plastic is irradiated, chemical bonds are broken and free radicals are formed which, in the next step, react to new chemical bonds (crosslinks between the chains of molecules.) This is an extremely resistant 'network'.
- Many properties of the plastic can be enhanced through the formation of crosslinks.
- Furthermore, since it is the finished plastic product which is modified in this way, it is even possible to vary the degree of crosslinking within one component by shielding parts of the product during irradiation.
- Radiation crosslinking is basically suitable for all types of plastics which can be chemically crosslinked by the use of radical initiators.



Advantages of Crosslinks in Plastic

- Crosslinks allows some of the commonly available plastics such as polyvinyl chloride (PVC), polyethylene (PE), polyamide (PA), polypropylene (PP), polybutylene terephthalate (PBT), etc. to have some of the properties of the expansive high-performance plastics – savings in raw materials.
- New properties which may lead to new applications for certain raw materials
- Exactly reproducible processes
- Fast process
- Unlike chemical crosslinking methods, radiation crosslinking takes place at low temperatures.

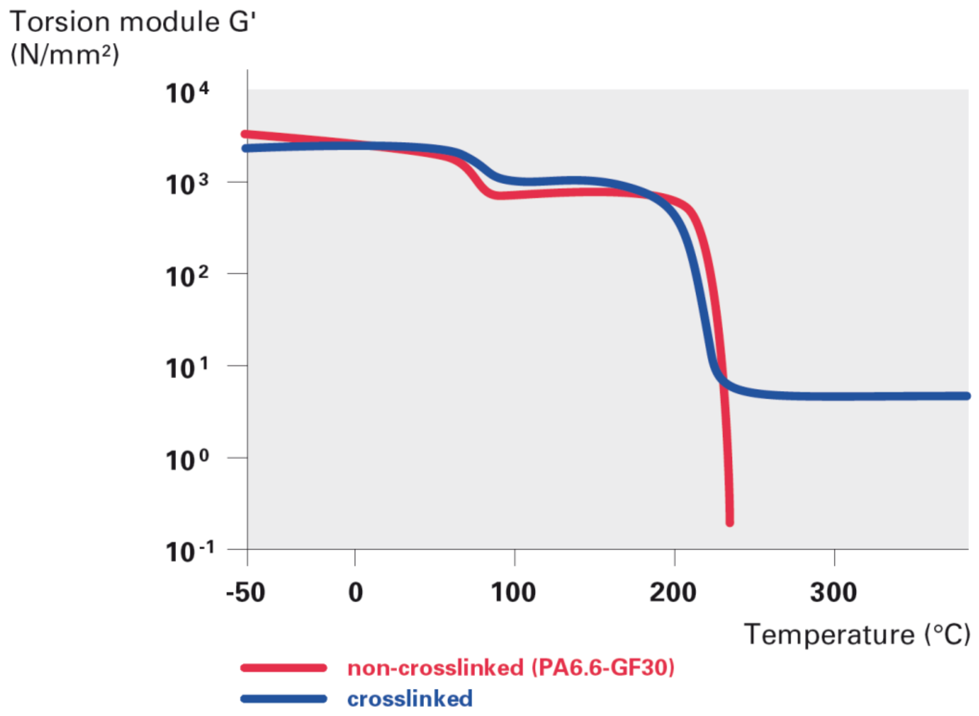


Polymers commercially suitable for radiation crosslinking

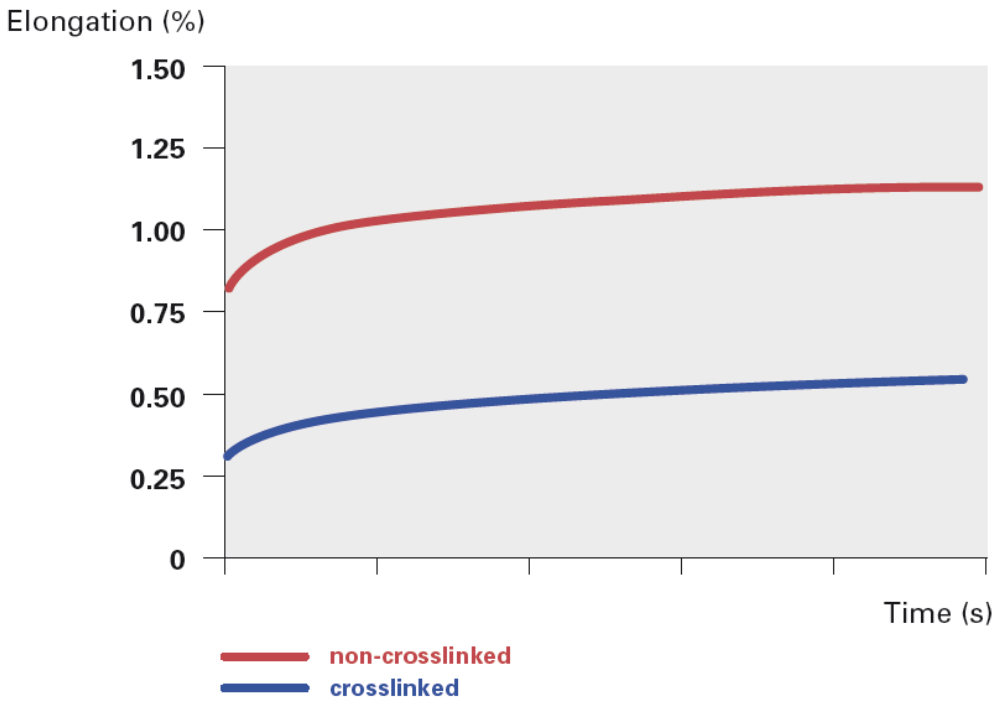
http://en.bgs.eu/wp-content/uploads/2017/02/BGS_radiation_crosslinking_en-1.pdf

Improved Properties of Crosslinks in Plastic

- **Heat resistance**, e.g., PA-6.6.
  Non-crosslinked torsion modulus drops to zero above crystallite melting point (~230°C) while crosslinked polymer give sufficient strength even above 350°C.



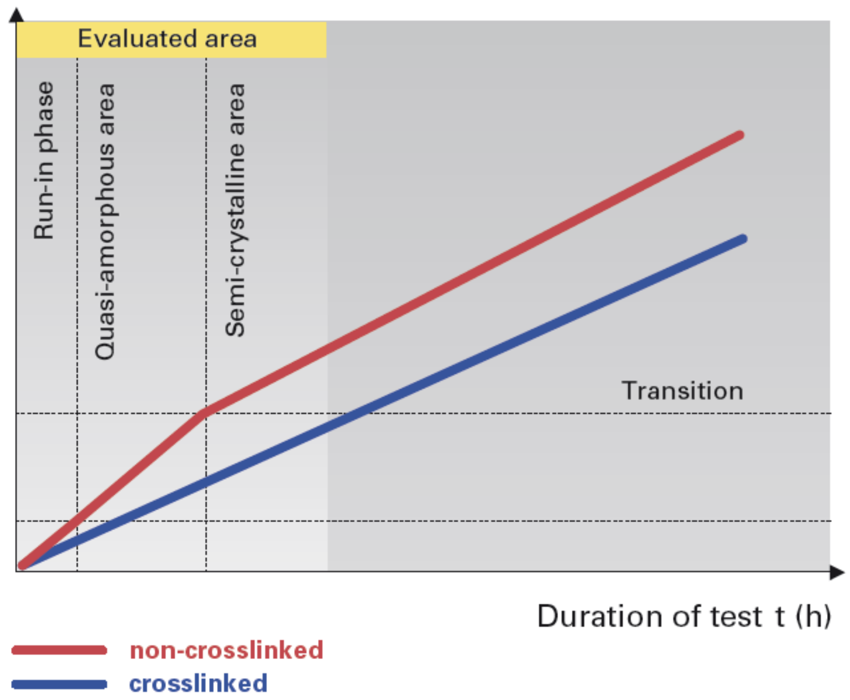
- **Creep Behavior**, e.g., PA-6 GF30.
  When subjected to mechanical load, plastics then to creep. Radiation crosslinking reduces the creep tendency as seen clearly for PA-6 GR 30 below.



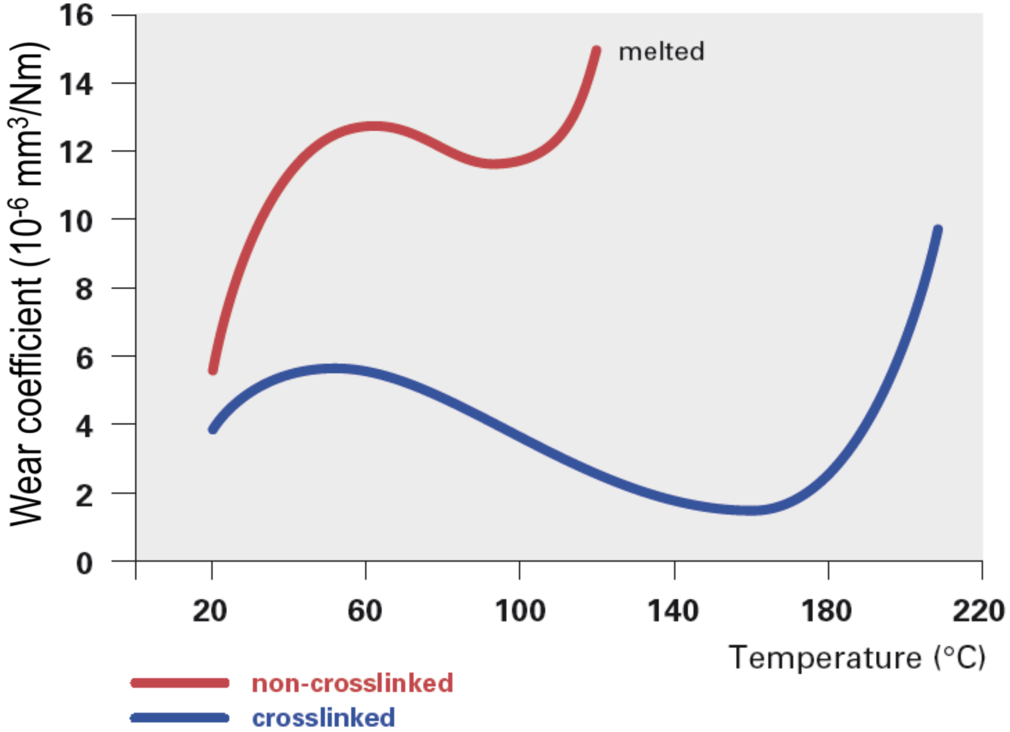
http://en.bgs.eu/wp-content/uploads/2017/02/BGS_radiation_crosslinking_en-1.pdf

Improved Properties of Crosslinks in Plastic

- **Linear abrasion**, e.g., PA-6.6.
  Crosslinked polyamides show an even level of abrasion over the duration of test and there is less abrasion. Quasi-amorphous non-crosslinks polyamides show less resistance and wear faster.



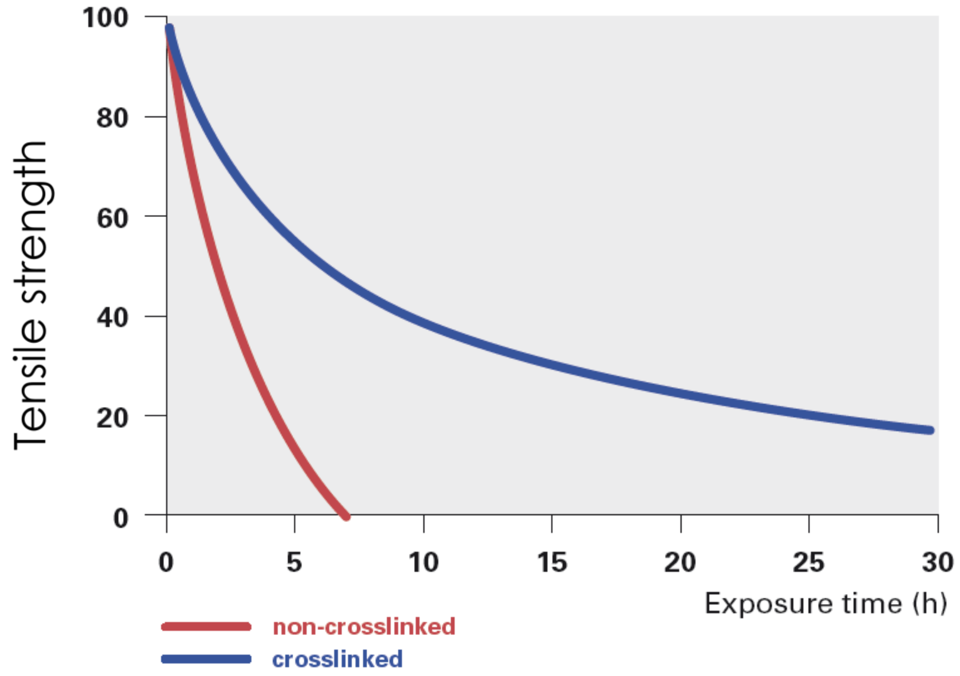
- **Wear Coefficient**, e.g., PA-6.6.
  Crosslinked polyamides show lower wear coefficient under tribological stress (under relative motion, e.g., in gears and bearings) and higher maximum temperature of operation



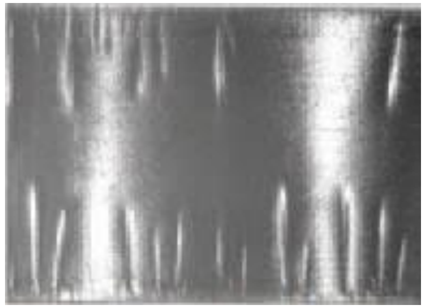
http://en.bgs.eu/wp-content/uploads/2017/02/BGS_radiation_crosslinking_en-1.pdf

Improved Properties of Crosslinks in Plastic

- **Hydrolysis resistance**, e.g., TPE-U
  Radiation crosslinking substantially improves hydrolysis resistance of many polymers in boiling water.



- **Stress cracking**, e.g., PA-6.
  Crosslinking markedly improves resistance to stress cracking as seen below after submersion in a 30% solution ($ZnCL_2$)



Non crosslinked

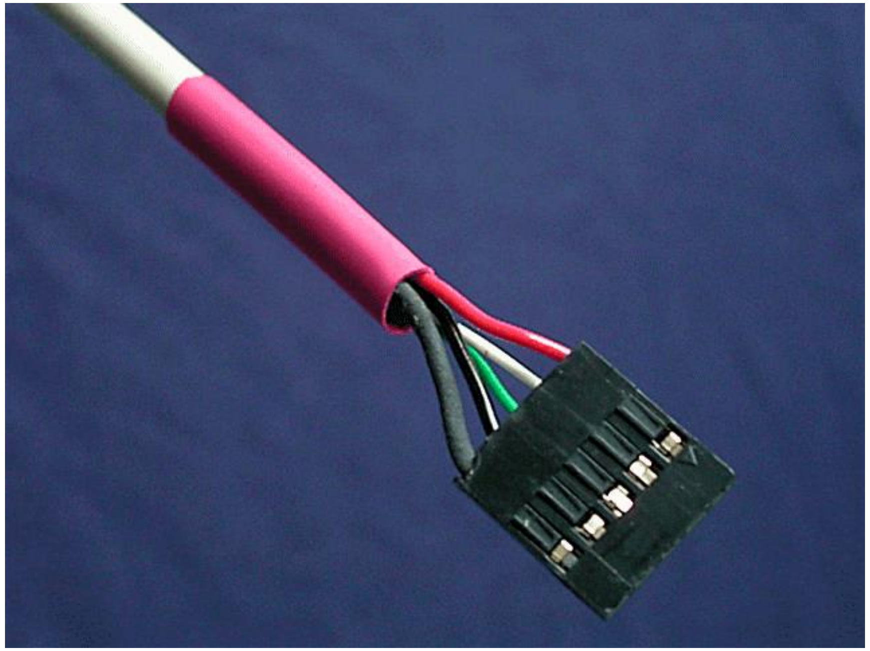
Crosslinked

Crosslinking of plastics substantially reduces their solubility and swelling in solvents. It also improves resistance to aggressive substances (e. g. brake fluid) and to hydrolysis.

http://en.bgs.eu/wp-content/uploads/2017/02/BGS_radiation_crosslinking_en-1.pdf

Heat Shrinks

- Heat shrink technology is an important area of application for radiation crosslinked polyolefins, for instance in the electrical industry and in pipeline construction.
- Typical ‘shrinkable’ products are tubes, foils and molded parts.
- In these heat shrink products, semi-crystalline materials are given a ‘shape memory’ by the selective formation of crosslinking points.
- When a product that has been crosslinked in this way is stretched under heat, this shape can be temporarily ‘frozen in’ by cooling it below the crystallite melting temperature.
- When the user then heats the product up again above the crystallite melting temperature, it returns to the original shape at the time of crosslinking.



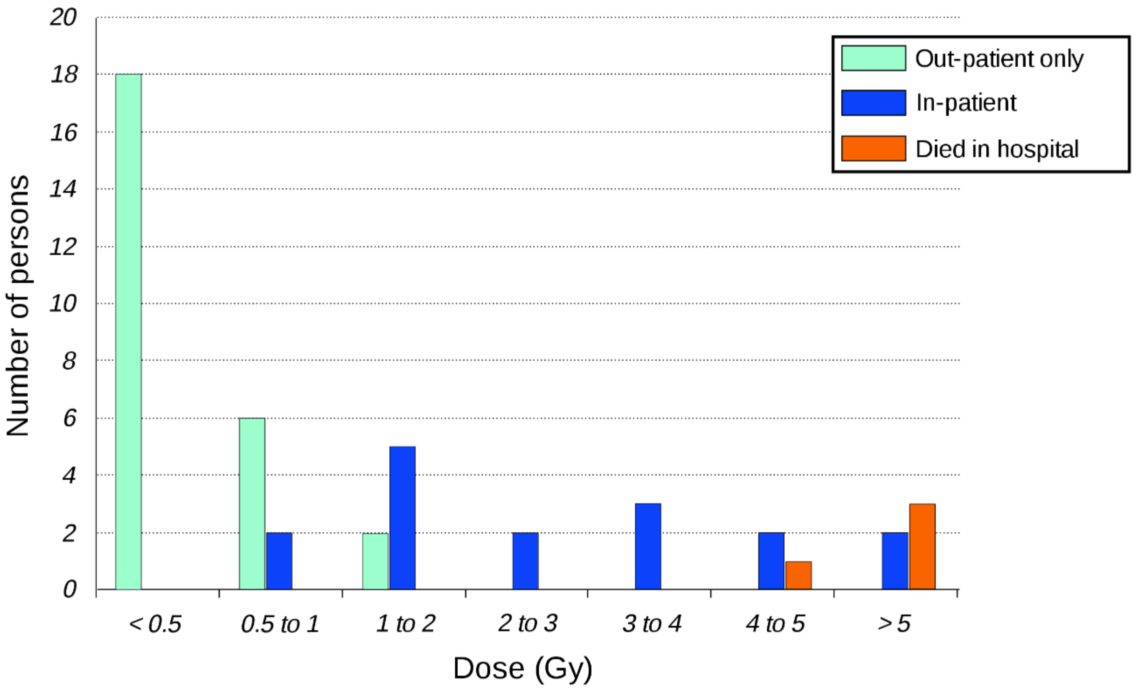
https://en.wikipedia.org/wiki/Heat-shrink_tubing

Risks in Using High Activity Sources

- Many applications used very high radioactive sources
- Import, export, sale, dealing in, possession and use of radioactive materials and irradiating apparatus and the transport of radioactive materials are strictly regulated, e.g., by NEA in Singapore.
- Disposal of these sources has to be done carefully.
- Risks including stolen sources dismantled from protective casings, especially by individuals who are not aware of the danger.
- List of orphan source incidents (https://en.wikipedia.org/wiki/List_of_orphan_source_incidents)

Goiania Accident

- One famous case happened in Goiania, Brazil in 1987 and rated at INES Level 5 (similar to TMI).
  - Radiotherapy irradiator source: Cs-137 (74 TBq/2000 Ci in 1971)
  - Purchased in 1976, abandoned in 1985 – hospital moved to new location (still guarded)
  - Sep 13, 1987 – two thieves broke in, disassembled the teletherapy unit and took source assembly home for scrap value and tried to dismantle source. [Radiation sickness set in.]
  - Sep 18 – 29, 1987 – sold to scrapyards / brought home and source dismantled. Powder with blue glow was played with and distributed. [More people got sick.]
  - Sep 29 – source radioactivity detected by medical physicist using scintillation counter.
  - 4 dead in Oct 1987: 18 yo (5.3 Gy), 6 yo (6.0 Gy), 37 yo (5.7 Gy), 22 yo (4.5 Gy)
  - 112,000 people examined, 250 individuals contaminated including 12 with radiation sickness.
  - Some with high doses survived (could be due to fractionated dose)
  - Decontamination: top soil removed, houses demolished, personal possessions were seized and incinerated ?? (7 TBq still unaccounted for)



Source : http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf

[Goiânia accident - Wikipedia]

Lost / Stolen Sources (1)

February 9th 2017

- 2 units of gamma projectors model Sentinel 880 Delta belongs to an industrial radiography company was stolen from a vehicle parked at commercial building in Klang, Selangor.
- Sources involved were Iridium-192 with activities of 43.6 and 35.8 Ci respectively
- After extensive searching effort, the housing of gamma projector was first found at an illegal scrap metal premise close to the licensee premise
- The Ir-192 sources was found at a residential area adjacent to the scrap metal premises
- The suspects did not receive excessive dose. One public (a cleaner) also received radiation exposure
- Worst Case Scenario: In the event of exposure at 1.0 m for 8 hours, dose could be as high as 2,658 mSv; or if exposed at 0.1 m for 1 hour, the dose could go up to 33,347 mSv (which would be fatal).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RADIOACTIVE BOMB THREAT?

EXCLUSIVE

A SECURITY expert warns that radioactive material stolen from a company in Klang is much sought after by terror groups which want to make dirty bombs. The material, Iridium-192, is easily found in Malaysia, but not in other Asean countries, he says.

» REPORTS BY C. PREMANANTHINI & FERNANDO FONG ON PAGES 2 & 3

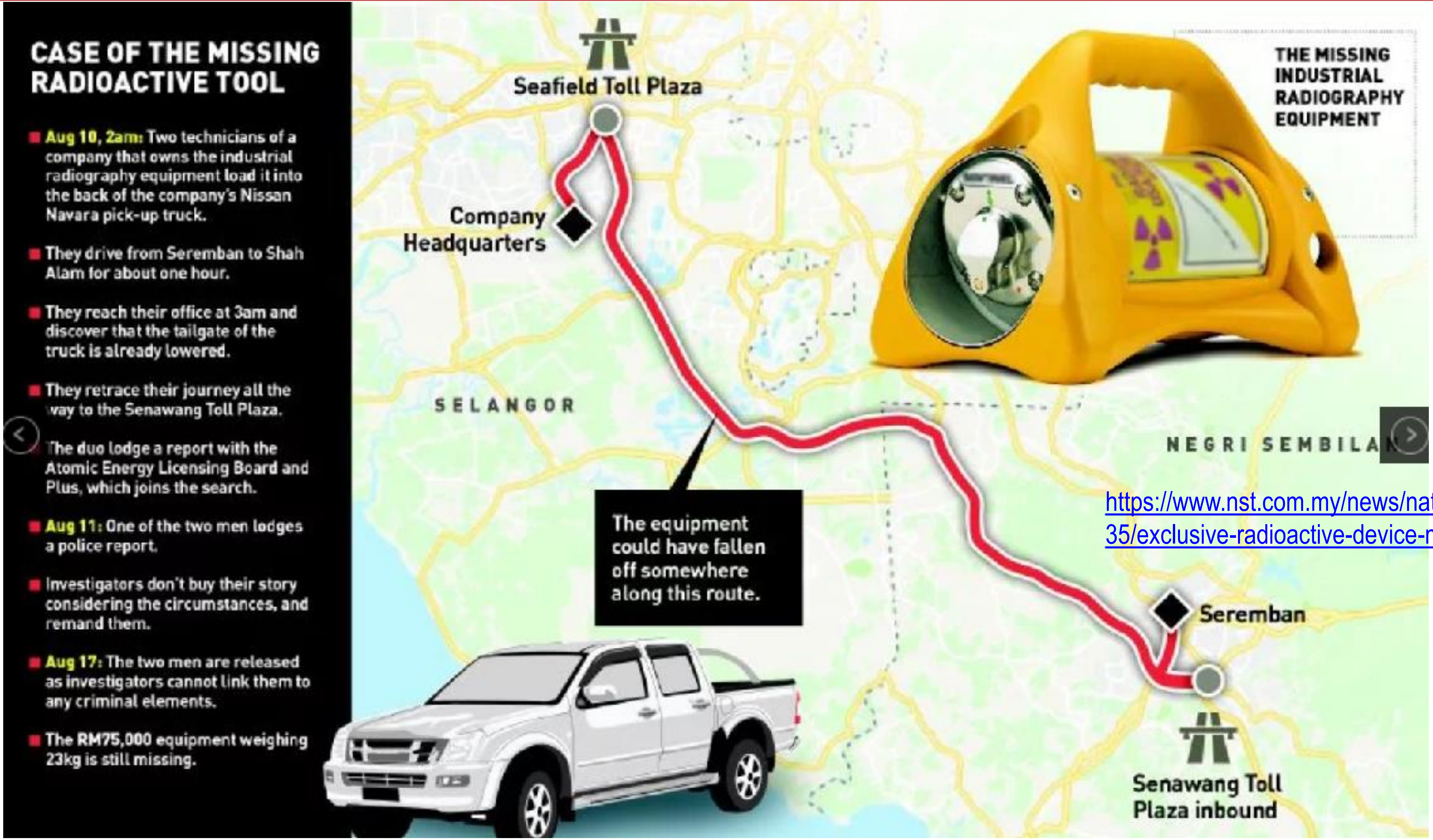
A replica of a projector that contains the radioactive material, Iridium-192. The projector was stolen from a company in Klang.


Housing of gamma projector found at illegal scrap metal premise


Ir-192 sources found at a residential area

https://www.amssnursecurityconference.org/sites/default/files/sessions/3_T7_Noor%20Fitriah%20Binti%20Bakri.pdf

Lost / Stolen Sources (2)



https://www.nst.com.my/news/nation/2018/08/403235/exclusive-radioactive-device-missing