<u>GET1024 / GEC1036 Lecture 17</u>

Applications of Radiation in Agriculture & Food

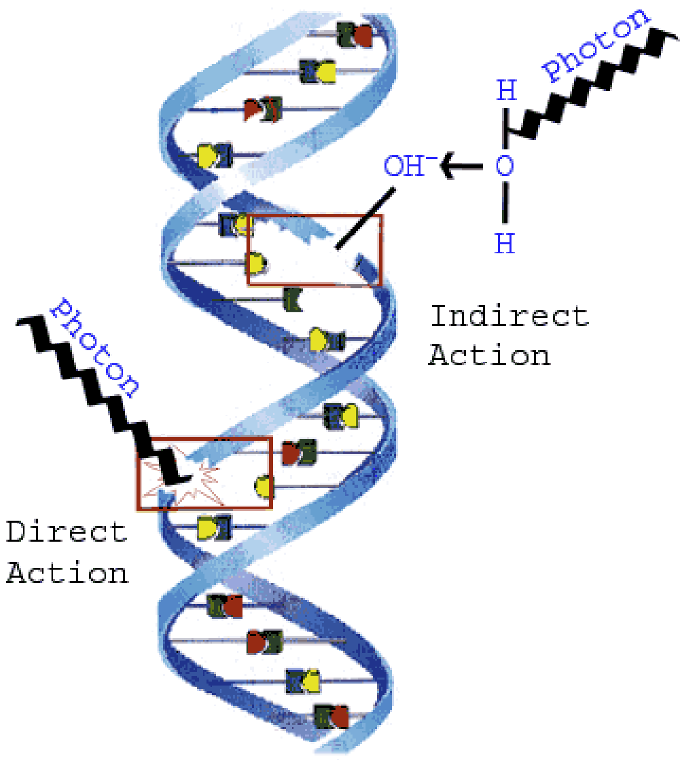
- Plant Breeding through Induced Mutation
- Soil-Nutrient-Plant-Water Management
  - Radioactive Tracers
  - Water Moisture Gauge
  - Radionuclide Fallout Technique
- Sterile Insect Technique
- Food Irradiation

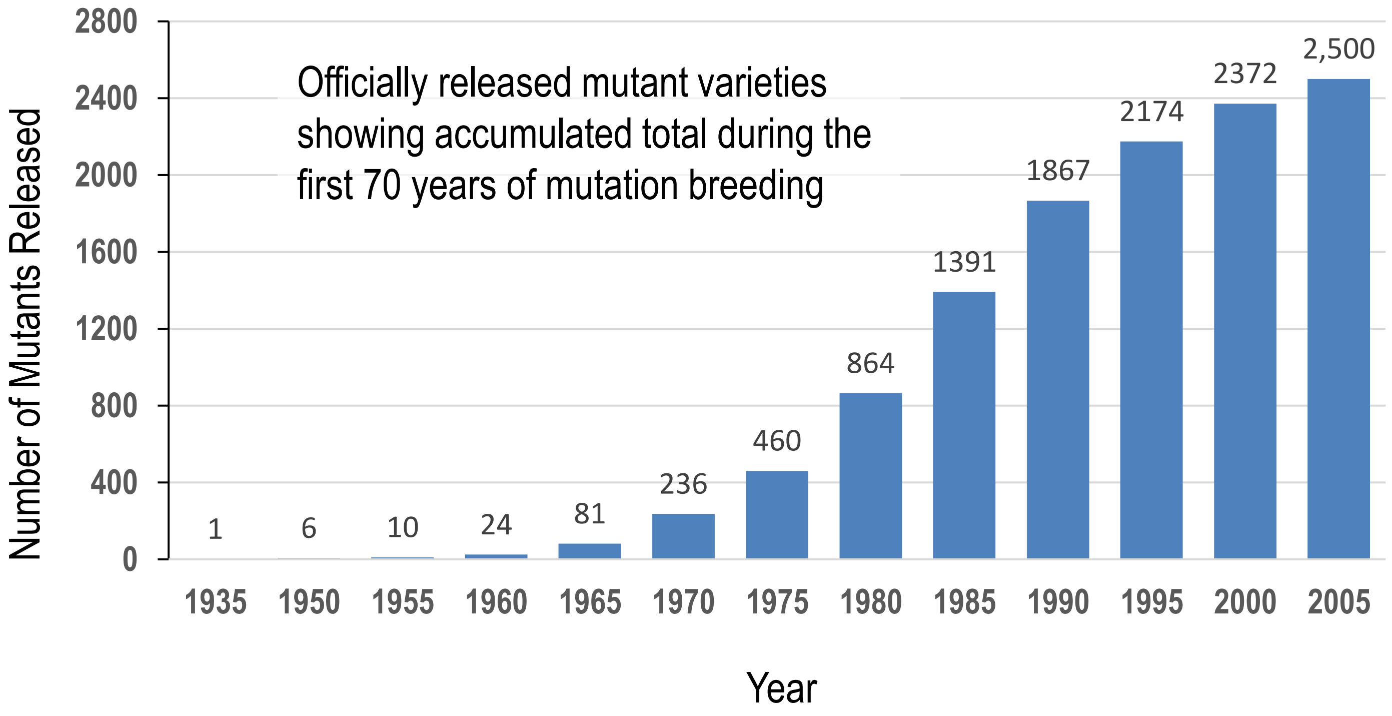
Introduction – Radiation and Food

- Recall the address by US President Eisenhower to the United Nations General Assembly in 1953: "… The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of **agriculture**, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world. …"
- Joint FAO (Food and Agriculture Organization of UN) / IAEA (International Atomic Energy Agency) Division of Nuclear Techniques in Food and Agriculture set up in 1964.
  - Application of nuclear science and technology in a safe and effective manner
  - To provide the global community with **increased production** of **better quality** and **safer food**, while sustaining natural resources.
  - Through many techniques such as
    - Plant Breeding through Induced Mutation
    - Nuclear and isotopic techniques in soil-nutrient-plant-water management
    - Fallout radionuclide to arrest land degradation
    - Sterile Insect Technique (SIT) for insect pest control, etc.

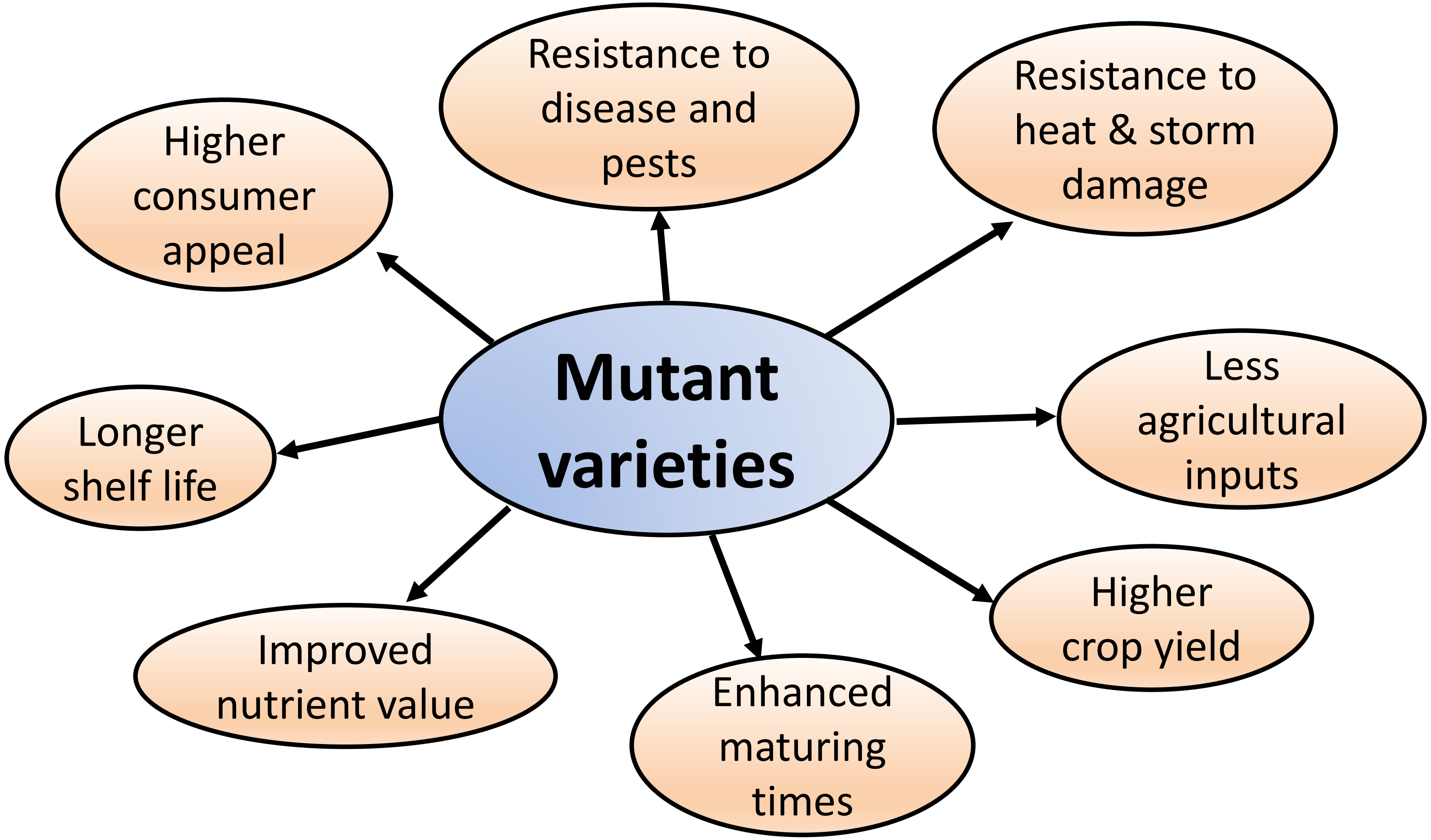
Plant Breeding and Mutation

- Late 1920's: Lewis John Stadler showed that radiation (x-rays or γ-rays with radium) can induce novel genetic variability in maize and barley.
- Radiation can increase the natural mutation rate by 1,000 to 1,000,000 fold, making the generation of genetic variation very effective.





Some Advantages of Mutant Varieties



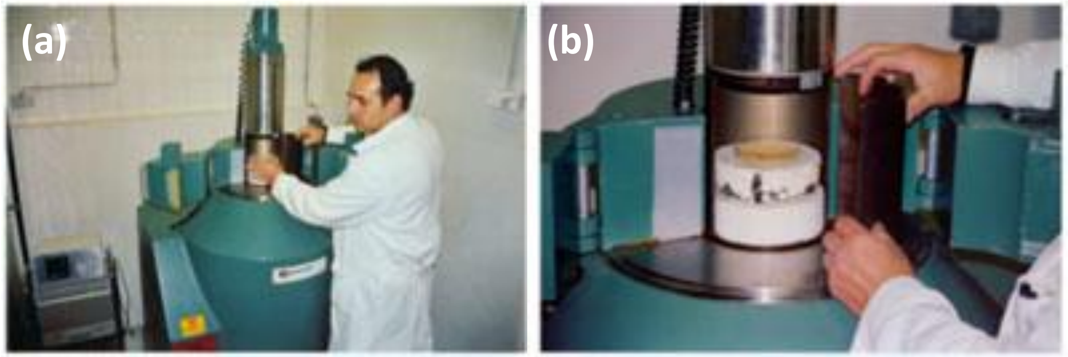
Types of Ionizing Radiation used

- Gamma rays is the most used ionizing radiation (64%) followed by x-ray (22%)

Types of Radiation	Energy Range	Penetration in plant tissue
Gamma rays	Up to several MeV	Through whole parts
X-rays	50 – 300 keV	A few mm to many cm
Neutrons (thermal, fast)	< 1 eV to several MeV	Many cm
Alpha particles	2 – 9 MeV	Small fraction of a mm
Beta particles (electrons)	Up to several MeV	Up to several cm
Protons or deuterons	Up to several GeV	Up to many cm
Ion beams	Up to several GeV	A fraction of cm

- Important to apply the right dose – continue to germinate, grow and reproduce but high enough to result in sufficient number of mutations.
- Other means such as chemicals are also used.

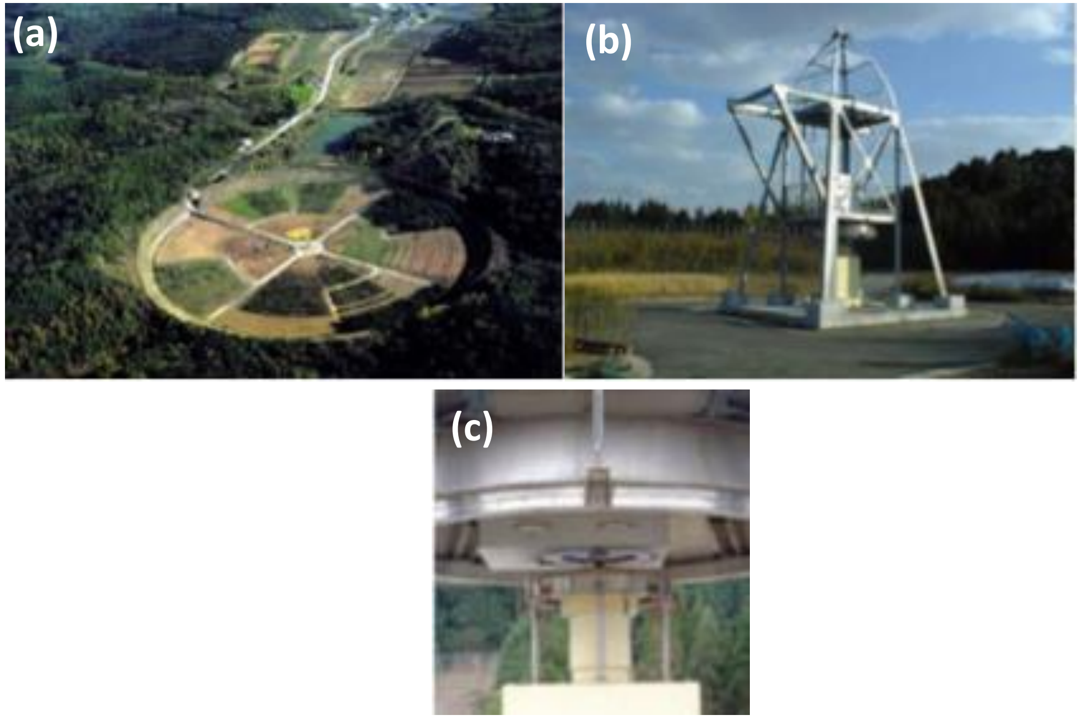
Plant Breeding and Mutation: Facilities



GammaCell (short, intense pulse)

(a) A ^{60}Co γ-source with a raised loading stage.

(b) Close-up of the raised loading stage showing rice grains in a petri dish.



Gamma field at the Institute of Radiation Breeding, Ohmiya, Japan (lower dose rate, chronic exposure)

(a) Aerial view of the facility showing concentric rings of crops (up to 100 m) grown in terraces around the irradiation source;

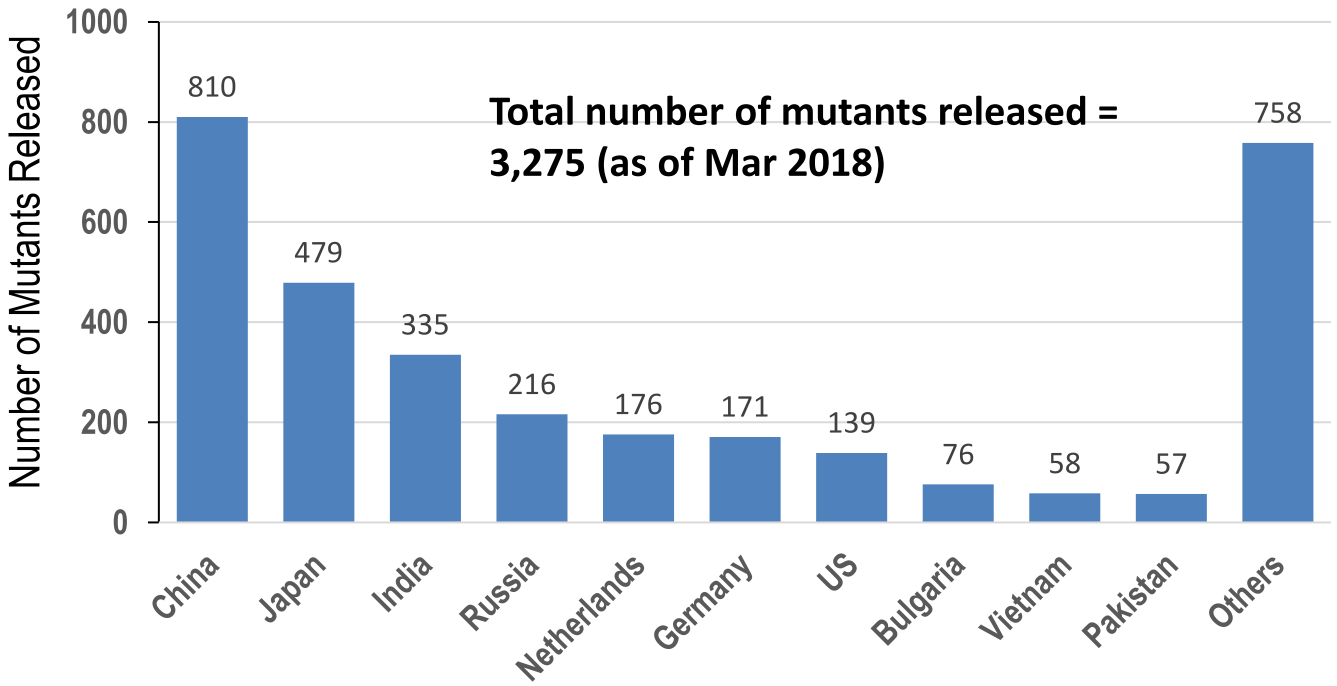
(b) Image of the facility showing the irradiation tower, crops being exposed to chronic irradiation and freshly prepared field for planting;

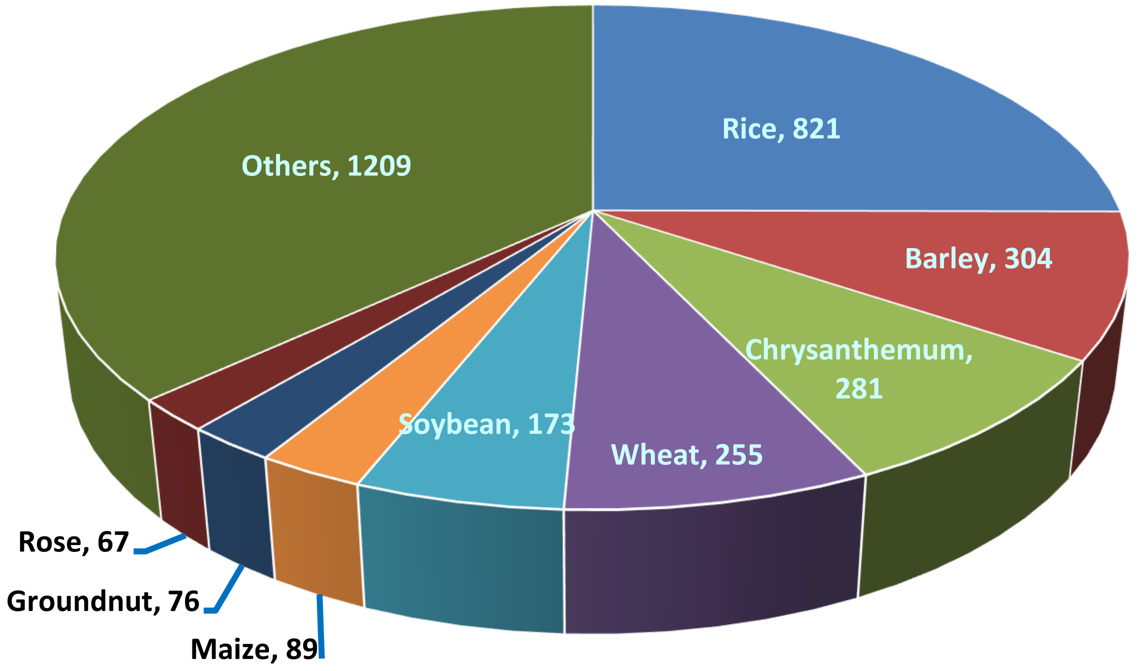
(c) A close-up image showing the reinforced steel casing housing the ^{60}Co source (88.8 TBq).

http://www-naweb.iaea.org/nafa/pbg/mutation-induction.html

Mutant Varieties

- Thousands of mutant varieties have been bred through use of ionizing radiation in many countries.
- Most are crops which form the staple diet, e.g., rice, barley and wheat, maize, soybean, millet, oat, sorghum, etc.
- Others include ornamental flowers such as chrysanthemum, rose, dahlia, carnation, begonia, azalea, bougainvillea, hibiscus, etc. and fruits such as apple, cherry, oranges, strawberry, etc. and vegetables.





Data from mutant variety database of Joint FAO-IAEA Programme (https://mvd.iaea.org/)

Example: Vietnam

- Agriculture remains important in Vietnam.
- Released 58 mutant varieties in FAO/IAEA database
  - Rice (36), Soybean (13), Chrysanthemum (3), Maize (2), Indian jujube (2), Field mint (1), Groundnut (1)
- E.g., ***VND9S-20***: Short duration (90-95 days), stiff stem, high yield (6-9 T/ha), good quality (long grain, amylose content = 20-22%), wide adaptation (tolerant to acid sulphate soil, salinity, rainy season), intermediate resistant to Brown Plant Hopper, Blast disease, some main pests.
- It is key variety for export since 2000. Cultivated area is more than 300,000 ha per year in Southern Vietnam. Cultivated in lowland, highland and remote mountain areas, where poor farmers can benefit.
- Also, more than 50% of soybean cultivated area is covered with mutant varieties.
- Led to increased income about US$374M (2008), with US$1 investment leveraged US$800 return.

Fig. 1 - Three-quarter of Vietnam populations are living in rural areas (Photo courtesy of Q. Liang, NAFA)

Fig. 4 - High yielding mutant rice varieties are being widely cultivated in remote mountain areas for the profit of poor farmers (Photo courtesy of Q. Liang, NAFA)

http://www-naweb.iaea.org/nafa/news/pbg-vietnam-story.html

Developing new varieties

Autumn season 2009: Dry seed DH18 irradiated by ^{60}Co (γ–rays) at 300 Grays

↓

Spring session 2010: M2

↓

Autumn session 2010: M3

↓ Individual selection

Autumn session 2013: M7

↓

Spring session 2013: Comparison

↓

Spring session 2013: National test VCU, DUS	Spring session 2014: National test VCU, DUS	Spring session 2014: National test VCU, DUS

The new varieties, NPT3, NPT4 and NPT5

- Have good yield 8.8 – 9.2 ton/ha,
- Short growth duration (103-110 days in Autumn and 130- 135 day in Spring season),
- Suitable to intensive practices
- Good grain quality properties as lightly scented grain, amylose content of 15- 23% to meet the consumer demand in Northern Vietnam

VCU – Value for cultivation and Use
DUS – Distinctness, Uniformity & Stability

Figures taken from presentation by Tran Duy Quy at the 12th Vietnam Conference on Nuclear Science and Technology (2017)

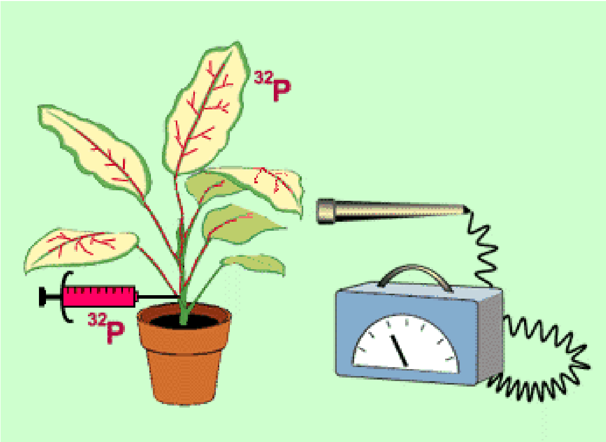
Soil-Nutrient-Plant-Water Management

- Approximately 75 – 80% of worldwide fresh water use is consumed by irrigated agriculture. Not sustainable due increasing needs and climate change.
- Land degradation (including soil erosion) affects 70% of world's rangeland, 40% of rain-fed agricultural land and 30% of irrigated land.
- Nuclear techniques used to
  - Measure rates of uptake, storage and cycling of water and nutrients in soil-plant and soil-plant-animal systems
  - Investigate changes in soil productivity and quantify organic matter turnover as influenced by farming systems and practices
  - Trace water movement and agricultural pollutant pathways and to quantify off-site losses of nutrients and water

Radioactive Tracers in Plants

- Detectors for ionizing radiation are very sensitive – each click (count) corresponds to the detection of one ionizing particle, e.g., α, β & γ particle. Very minute amount of radionuclides can be detected.
- Manmade radionuclides can be used as **radioactive tracers**.
- In agriculture (used as labels) attached to different fertilizers to determine whether absorbed at critical locations in the plants.

Example: Radioactive phosphorus ($^{32}_{15}\mathrm{P}$) added to phosphorus. As the plant grows, the location of the phosphorus could be detected by use of a Geiger counter or a piece of photographic film against the plant. Radiation from the phosphorus tracer would expose the film, in effect taking its own picture of its role in plant growth.



http://www.nuclearconnect.org/wp-content/uploads/2013/11/geiger_1.gif

- Can substantially reduce the amount of fertilizers to produce robust yields – lower cost to farmer, minimize environmental damage and reduce energy consumption.

http://www.scienceclarified.com/Qu-Ro/Radioactive-Tracers.html

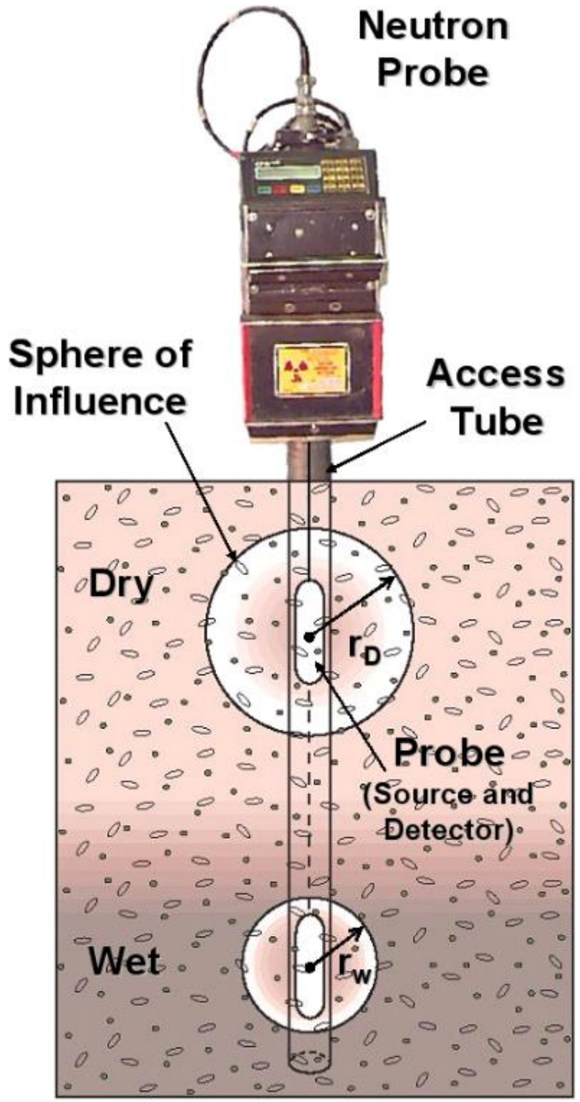
Improving Animal Production

- Radioactive tracer is also used to determine the best way of feeding the animals, especially in use of supplements. Food is labelled with specialty radioisotope such as C-14 to trace the paths of food within the animals' digestive systems.
- Determines where and how quickly the food is broken down into body tissues or milk – thus the nutritional values of feed to animals and also the nutritional value of the products such as milk or meat.
- In Asia – feed is mainly rice straw and native grass. Lacks sufficient proteins, energy and minerals for a balanced diet.

- Examples in using this technique:
  - Indonesia: scientists developed multi-nutritional block for buffaloes to lick – increase the weight gain by 3 kg/week and reduce grass consumption by 80%.
  - India: developed a food supplement that increased milk production by 30% at a production cost 25% lower than supplements that did not use the tracer technique.

Measuring Water Content in Soil

- Approximately 75 – 80% of worldwide fresh water use is consumed by irrigated agriculture. Not sustainable due increasing needs and climate change.
- To optimise the use of water in the ground, **neutron moisture gauges** are often used to determine the amount of water in the ground.
- The gauge contains one (or more) probe which has a neutron source as well as a detector that detects slow (moderated) neutrons as shown.
- The source contains a small amount of radioisotope such as californium ($^{252}_{98}\mathrm{Cf}$: $t_{1/2}$ = 2.65 years) which emits neutrons in spontaneous fission (3% of its decay) or Am-Be source (neutrons emitted from Be-9 after being bombarded by α–particle from Am-241).



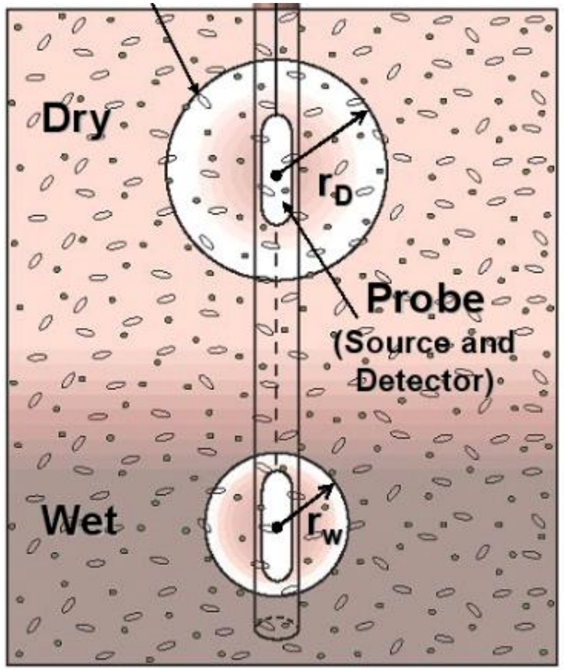
$$^{252}_{98}\mathrm{Cf} \rightarrow \, ^{144}_{56}\mathrm{Ba} + \, ^{106}_{42}\mathrm{Mo} + 2\mathrm{n}$$ (neutrons from spontaneous fission for $^{252}\mathrm{Cf}$)

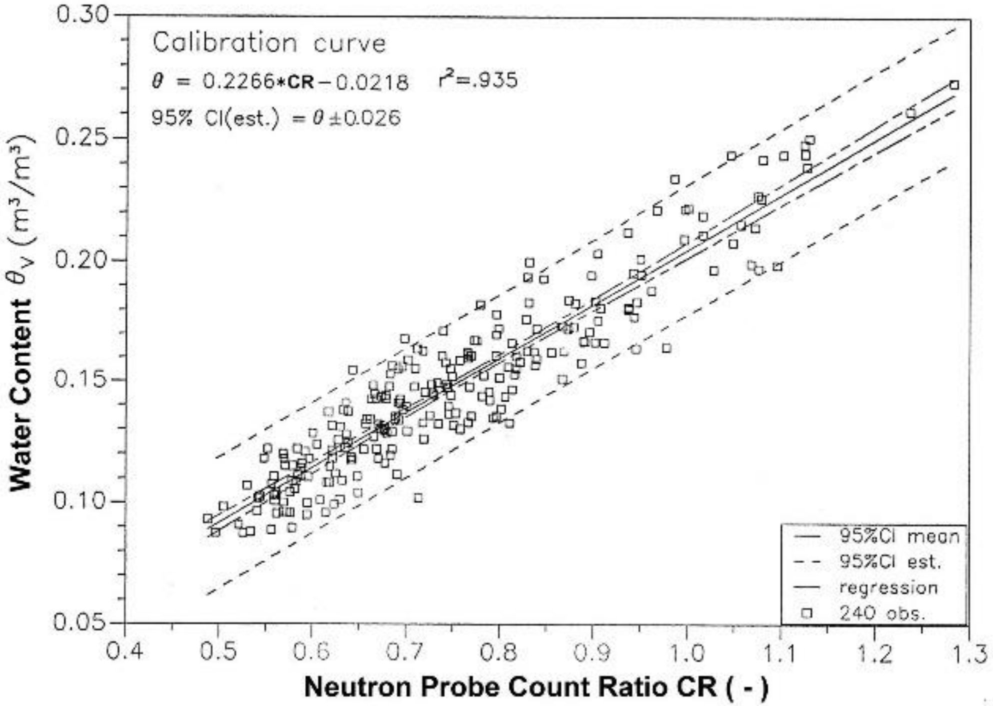
$$\left.\begin{aligned} &^{241}_{95}\mathrm{Am} \rightarrow \, ^{237}_{93}\mathrm{Np} + \, ^{4}_{2}\alpha \\ &^{4}_{2}\alpha + \, ^{9}_{4}\mathrm{Be} \rightarrow \, ^{12}_{6}\mathrm{C} + \, ^{1}_{0}\mathrm{n} \end{aligned}\right\}$$ (neutrons from Am-Be source)

Measuring Water Content in Soil

- If water is present, then neutrons are quickly slowed down by the hydrogen nuclei in the water molecules and reach thermal speed within a short distance from its source. Some of these neutrons hit the detector after being scattered by the hydrogen nucleus.
- If the ground is dry, neutrons move further away from the source before reaching thermal speed and much fewer neutrons are scattered back to the detector resulting in lower reading.

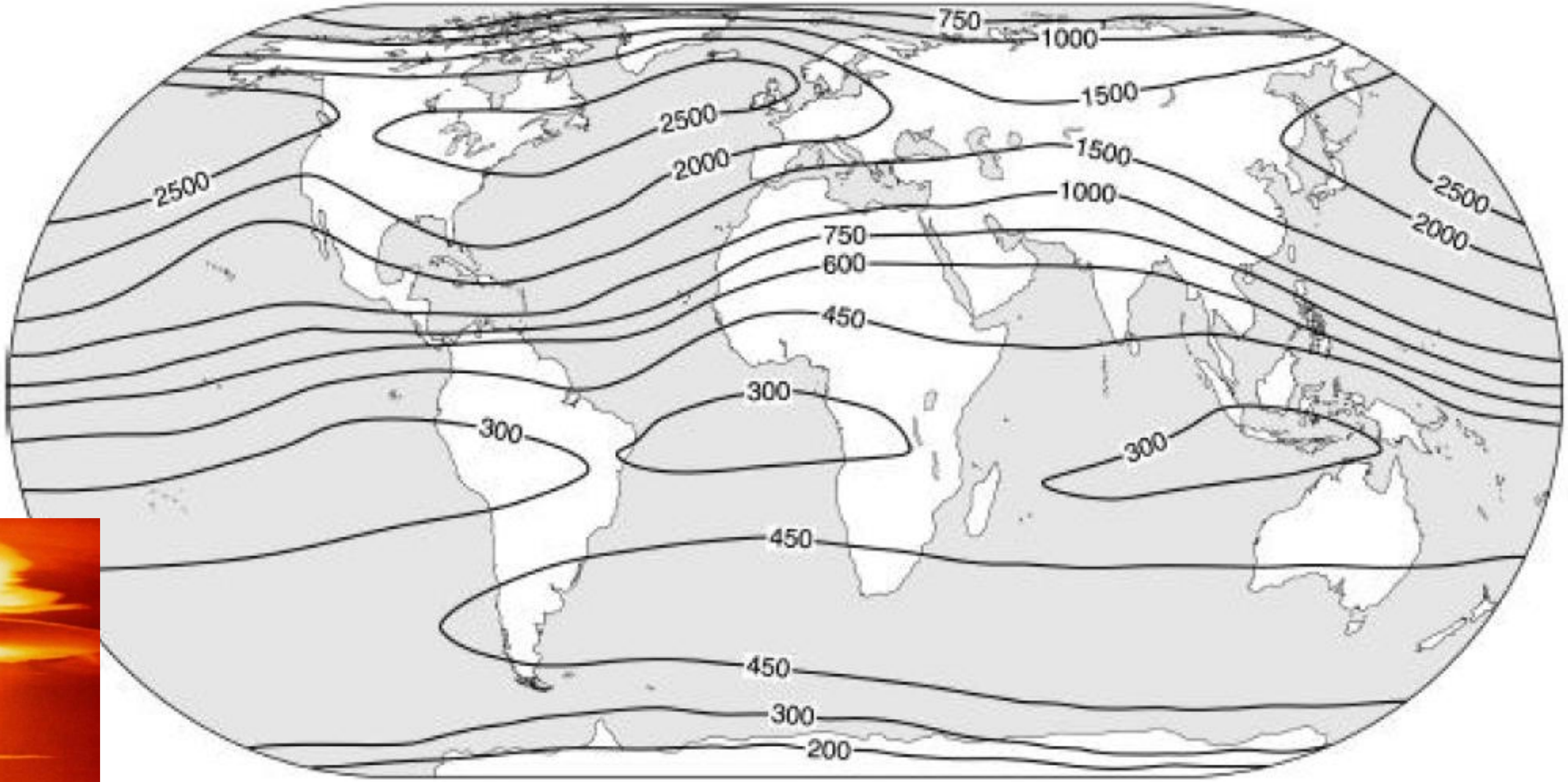
Knowing the moisture content in the soil allows us to make the best use of limited water supply, reduce energy costs in pumping water, and minimize runoffs of potential contaminants into nearby lakes, streams and rivers.





Fallout Radionuclides from Weapon Tests

- In the 1950s and 1960s, radioactive cesium (Cs-137) was released into the atmosphere by nuclear weapon tests and deposited in soils worldwide.



The global pattern of bomb derived ^{137}Cs fallout – ranged between approx. 160 and 3,200 Bq/m^2

Fallout Radionuclides for Soil Erosion Studies

- There are no natural sources of ^{137}Cs. Indeed, it is an artificial or 'man-made' radionuclide generated as a product of nuclear fission. ^{137}Cs is also a component of the ^{137}I decay chain as outlined in equation.

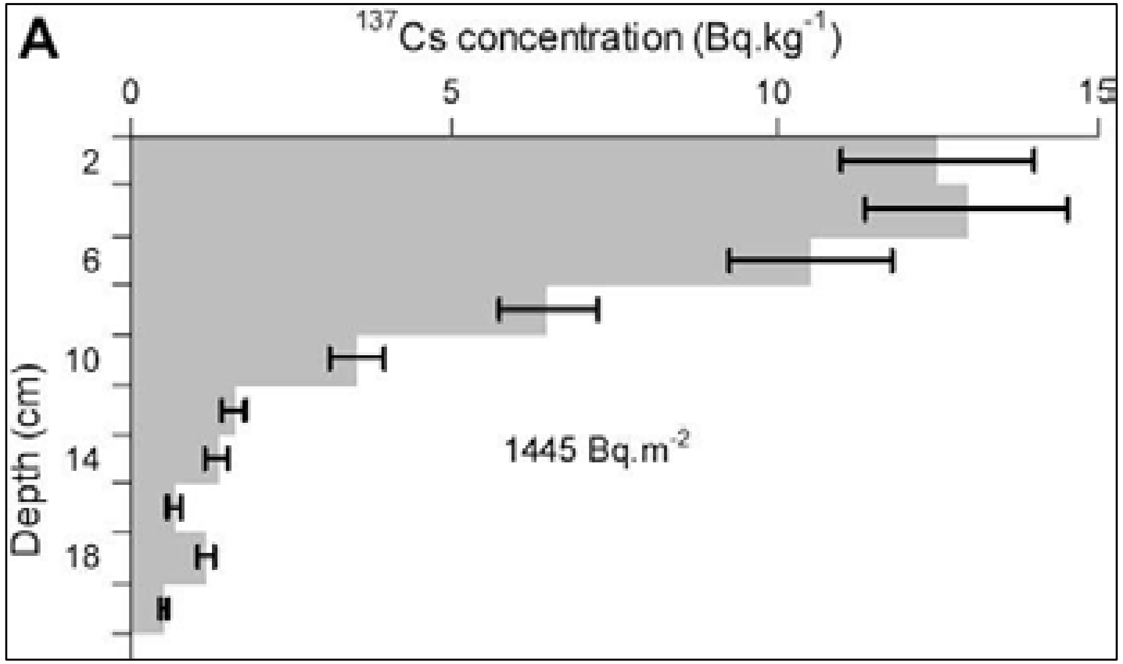
$$^{137}\mathrm{I} \xrightarrow{t_{1/2} = 24.1\ \mathrm{s}} {}^{137}\mathrm{Xe} \xrightarrow{3.8\ \mathrm{min}} {}^{137}\mathrm{Cs} \xrightarrow{30.2\ \mathrm{yr}} {}^{137m}\mathrm{Ba} \xrightarrow{153\ \mathrm{s}} \boxed{^{137}\mathrm{Ba}}\ \text{Stable}$$

- It emits a strong gamma-ray (663 keV) making its measurement in environmental samples using gamma detector facilities relatively easy without the need for special chemical preparation.

- ^{137}Cs has a limited mobility in soil. It is rapidly and strongly adsorbed on the fine soil particles

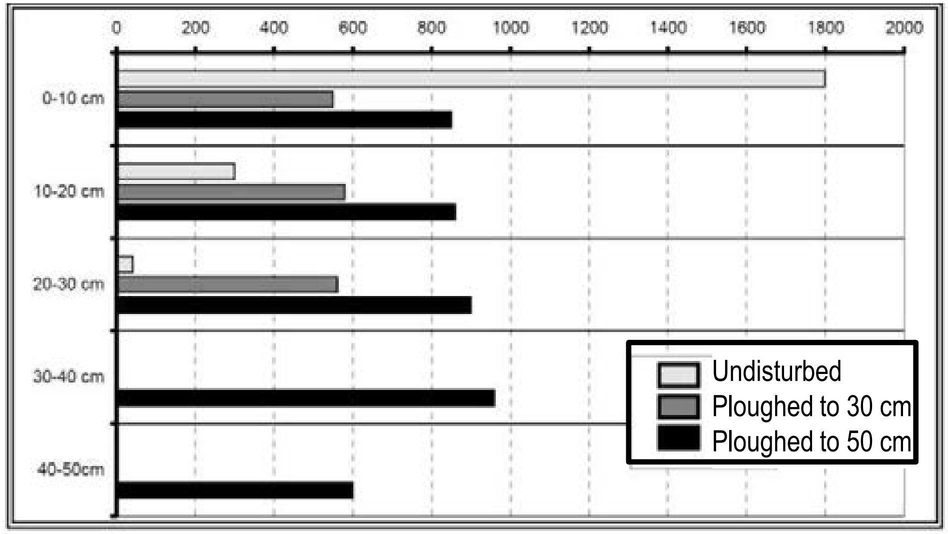
- ^{137}Cs intercepted by the plant canopy – transferred to the soil via wash-off. If adsorbed by the vegetation, the ^{137}Cs is released to soils when the vegetation dies and decays.

- ^{137}Cs is distributed mainly in the top 10 cm of the soil unless disturbed.



Fallout Radionuclides for soil erosion studies

- If the soil is ploughed, ^{137}Cs is distributed more or less evenly to the depth it is mixed.



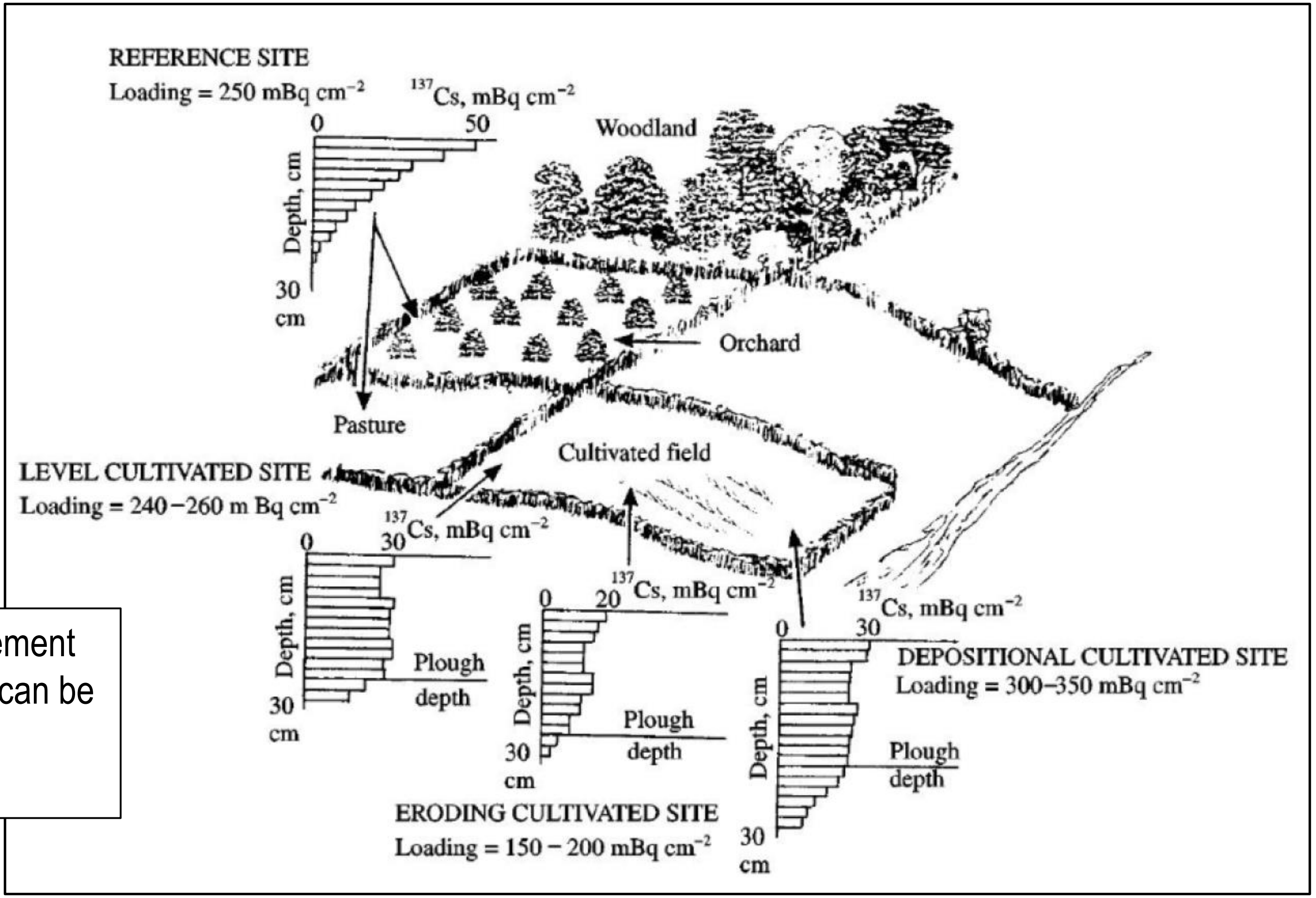


Illustration on how movement of soil in cultivated land can be measured by fallout radionuclide technique.

https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1741_web.pdf

Fallout Radionuclides for Soil Erosion Studies

- Land degradation costs US$10.6 trillion around the world each year, and soil erosion is the main contributor.
- About 75 billion tonnes of fertile soil is lost each year through soil erosion. Also increases sedimentation in streams and rivers, can lead to flooding.
- Fallout radionuclides are robust, cost effective tools for tracing and quantifying soil redistribution and sources of erosion within agricultural landscapes, so that soil conservation practices can be implemented to minimize this loss.

Scientists in Sri Lanka used fallout radionuclides to identify specific locations for the deployment of conservation measures, which included changing the shape and orientation of fields.

It was estimated that soil conservation activities in Central Highland tea plantations minimized annual soil erosion by 42%.

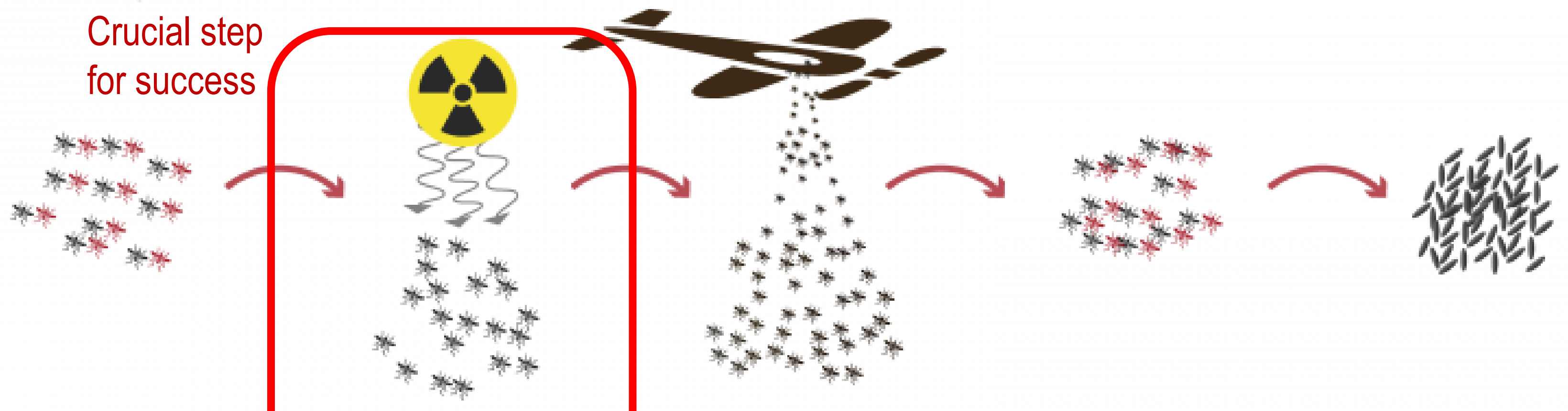
https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1741_web.pdf

Controlling Insect Pests

- Estimate of harvest loss due to unwanted insects range from 10% to 30% in developing countries.
- Synthetic pesticides – destroy also the pollinators and other beneficial insects, creating environmental pollution, toxic residues in food chain. Also some insects develop enough resistance.
- The Sterile Insect Technique was first developed in the USA by Edward Fred Knipling in 1940 – 50s, and it has been used for 50 years.
- Sterile insects are categorized as beneficial organisms as the SIT is among the most environment-friendly insect pest control methods ever developed. It differs from classical biological control, which involves the introduction of non-native biological control agents, in the following ways:
  - Sterile insects are not self-replicating and cannot become established in the environment
  - Autocidal control is by definition species-specific or intra-specific, and
  - SIT does not introduce non-native species into an ecosystem
- It is currently applied on six continents, and the four strategic options in which sterile insects are being deployed as a component of Area-wide Integrated Pest Management (AW-IPM) for insect pest control are: suppression, eradication, containment and prevention.

Sterile Insect Technique

Crucial step for success



Mass-rearing of insects takes place in special facilities.

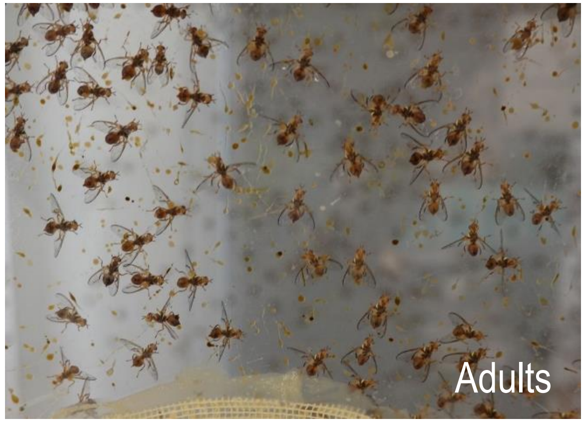
Male and female insects are separated. Ionizing radiation is used to sterilize the male insects.

The sterile male insects are released over towns or cities...

...where they compete with wild males to mate with females.

These females lay eggs that are infertile and bear no offspring, reducing the insect population.

Separation of males and females at pupa stage is efficient due to colour difference!



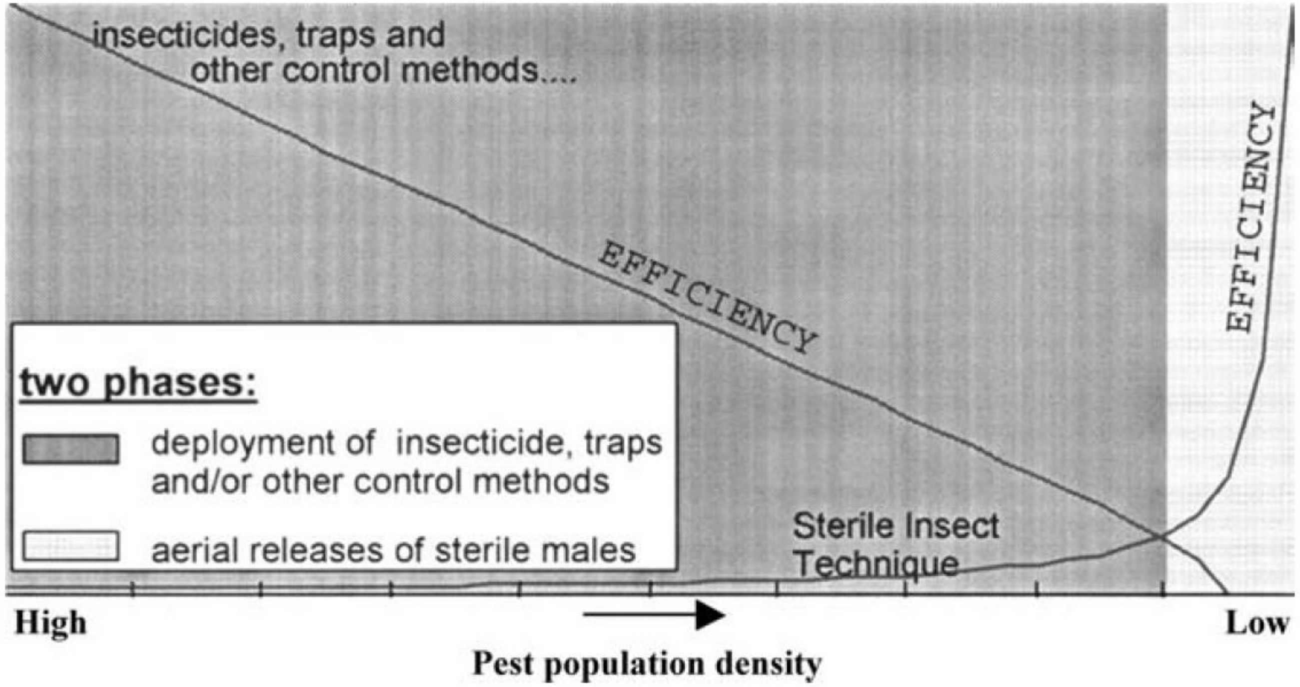
All photos taken at IAEA Nuclear Applications Lab at Seibersdorf

Sterile Insect Technique

Generation	Uncontrolled natural population (5 X increase rate)	Controlled population: Natural population		Controlled population: Sterile population	Ratio of sterile to fertile
1	1 000 000	1 000 000		9 000 000	9:1
2	5 000 000	500 000		9 000 000	18:1
3	25 000 000	131 625	131,579	9 000 000	68:1
4	125 000 000	9535	9,480	9 000 000	942:1
5	625 000 000	50	50	9 000 000	180 000:1

$$= \frac{1,000,000}{1,000,000 + 9,000,000} \times 1,000,000 \times 5$$

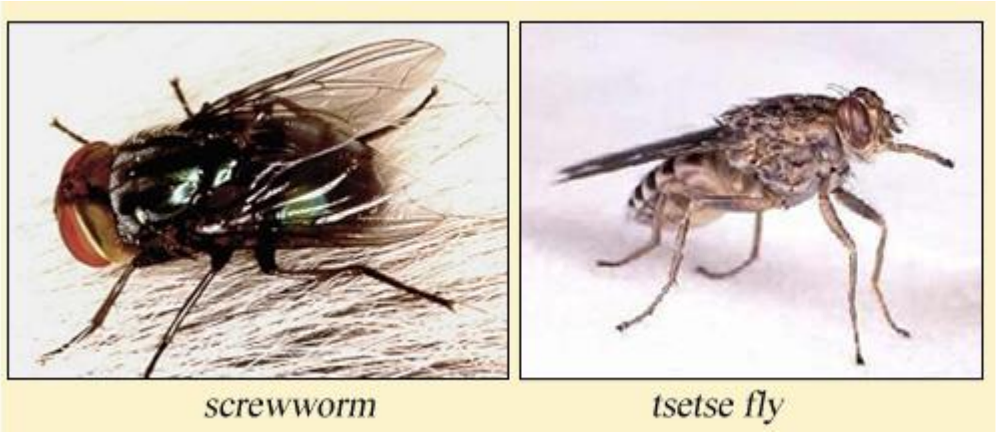
Large number of sterile insects must be produced and applied for a few generations.



- SIT should be used together with other methods of controlling the insect population.
- Success depends on being able to apply to large areas and insects not re-introduced into area from outside.

Successful Implementations of SIT

- Example. Mexico – against Medfly (Mediterranean Fruit Fly) and screwworm – by 1982 essentially complete success declared . Screwworm essentially eradicated by 1991. Allow Mexico to expand its horticulture export to over US$3.5b/yr. (Yielding about US$1b benefits each year.) Now applied to other regions in the world.
- The Tsetse fly, which transmits disease in cattle and sleeping sickness in humans, once prevented the settlement and development of large areas of Africa. The SIT technique has successfully eradicated one species of tsetse flies in parts of Nigeria.



http://www.radioactivity.eu.com/site/pages/In_Industry.htm

http://www.hungrypests.com/the-threat/mediterranean-fruit-fly.php#

Food Processing

- At least ¼ of food production is wasted – infestation or spoilage. Especially high (sometimes > 50%) for seafood.
- Some food are also unsafe due to contamination by bacteria, parasites, viruses and insects.
- Estimated that 5,000 Americans died annually due to food-borne diseases. 67 millions become sick due to food-related diseases (325,000 hospitalized) each year.
- Huge recalls of food, e.g., 25 million pounds of hamburger patties in 1997 due to E Coli outbreaks, and 27 million pounds of turkey and chicken products in 2002 due to Listeria poisoning (8 died).
- Food Preservation Methods – Sun drying, salting, smoking, canning, heating, freezing and addition of chemicals such as methyl bromide.
- Food irradiation is the process in which a product or commodity is exposed to ionizing radiation to improve its safety and to maintain its quality.
- The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture estimates that the quantity of food irradiated in 2013 was approximately 700 000 tonnes.

Effects of Food Irradiation

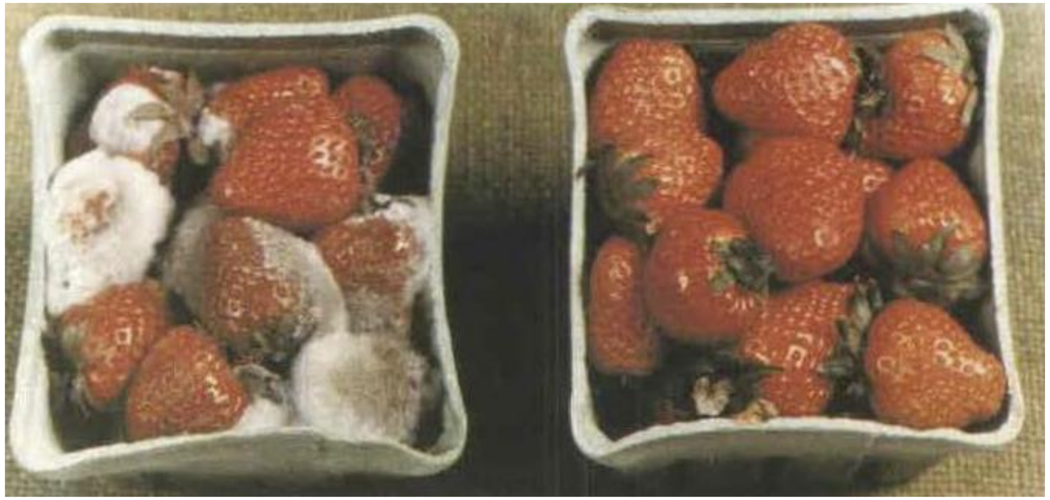
- Sanitary measures include applications based on the lethal effects of irradiation on:
  a) Microorganisms, such as those causing foodborne disease, reducing storage time or shelf life, or contaminating products to an unacceptable level for the intended use;
  b) Parasites, such as the helminths that can infest carcasses or protozoa present in fresh cut vegetables;
  c) Insects that cause post-harvest losses.
- Phytosanitary measures relate to the health of plants (include preventing the introduction or spread of regulated pests). Realized by triggering certain response in the targeted pests:
  a) Preventing successful development (e.g. no emergence of adults),
  b) Inability to reproduce (e.g. sterility) or
  c) Inactivation (rendering microorganisms incapable of development).
- Other applications are based on the physiological effects of irradiation on plants such as:
  a) Inhibition of sprouting;
  b) Delayed senescence;
  c) Delayed ripening.

Dose Range for Food Irradiation

Dose Range (kGy)	Effects	Examples
0.1 – 1 (low dose)	Sprouting inhibited	Potatoes, onions, garlic & yams
	Ripening delayed	Banana and papaya
	Insects unable to reproduce	Fresh produce
	Insects killed	Dried fish, dried fruits and legumes
	Parasites inactivated (helminths and protozoa)	Meat products, fresh fruit and vegetables
1 – 10 (medium dose)	Number of spoilage organisms reduced	Strawberries
	Shelf-life extended	Refrigerated meats and fish, ready to eat meals
	Non-sporulating microorganisms inactivated	Refrigerated or frozen meats, fish and seafood, pre-cut fruit and vegetables
	Microbiological contamination reduced	Spices and dried food ingredients
More than 10* (High dose)	Reduce microorganisms to the point of sterility	Hospital diets, emergency rations and food for astronauts

* Not used commercially

Examples of Food Irradiation



Without treatment

Irradiated (2 kGray)

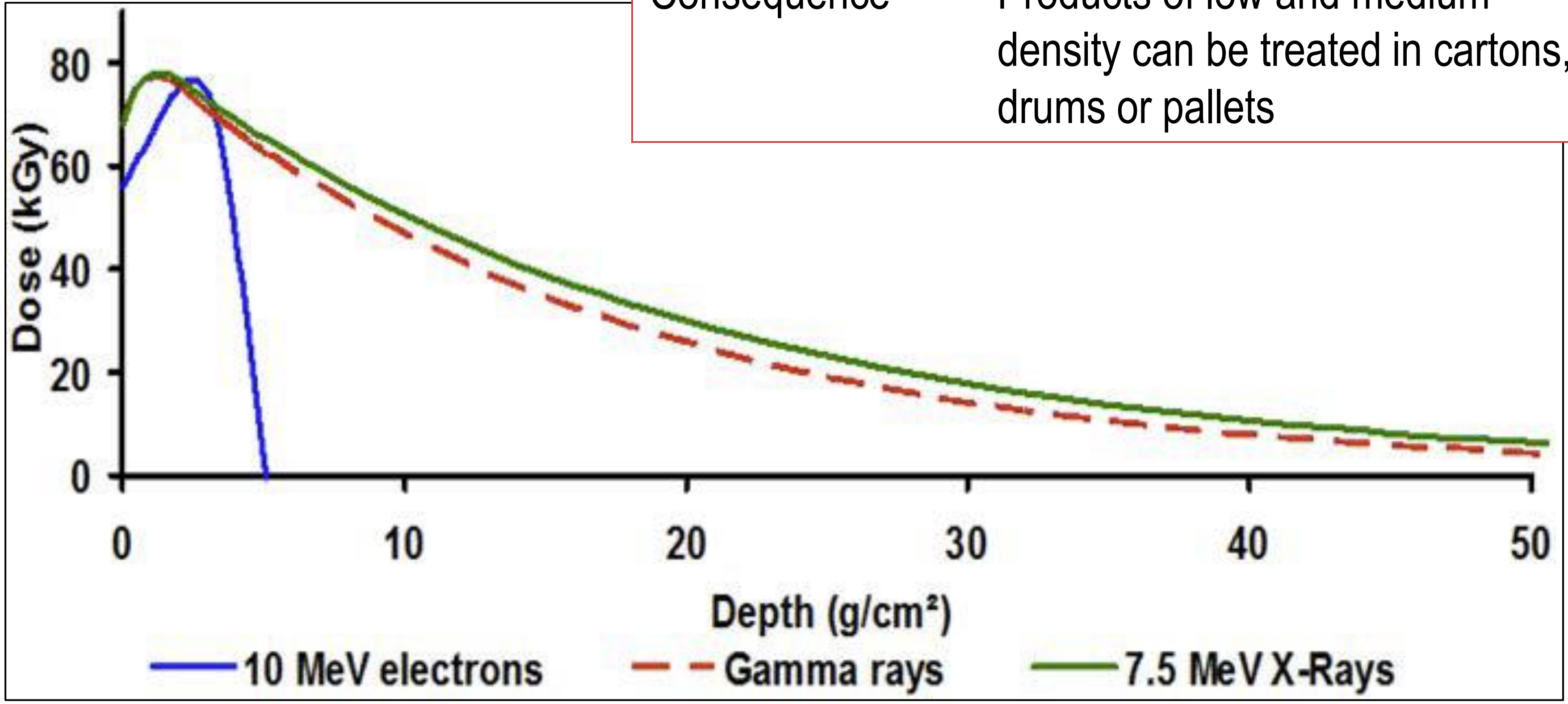
Strawberries (after 15 days of storage)

Potatoes (after 6 months of storage)

http://apps.who.int/iris/bitstream/10665/38544/1/9241542403_eng.pdf

Ionizing Radiation used for Food Irradiation

Characteristics	Gamma or X-rays	Accelerated electrons
Comprised of	Photons	Electrons
Mass	None	Yes
Electric Charge	None	Yes
Penetration	Good/Very good	Limited
Consequence	Products of low and medium density can be treated in cartons, drums or pallets	Products of low density can be treated in cartons



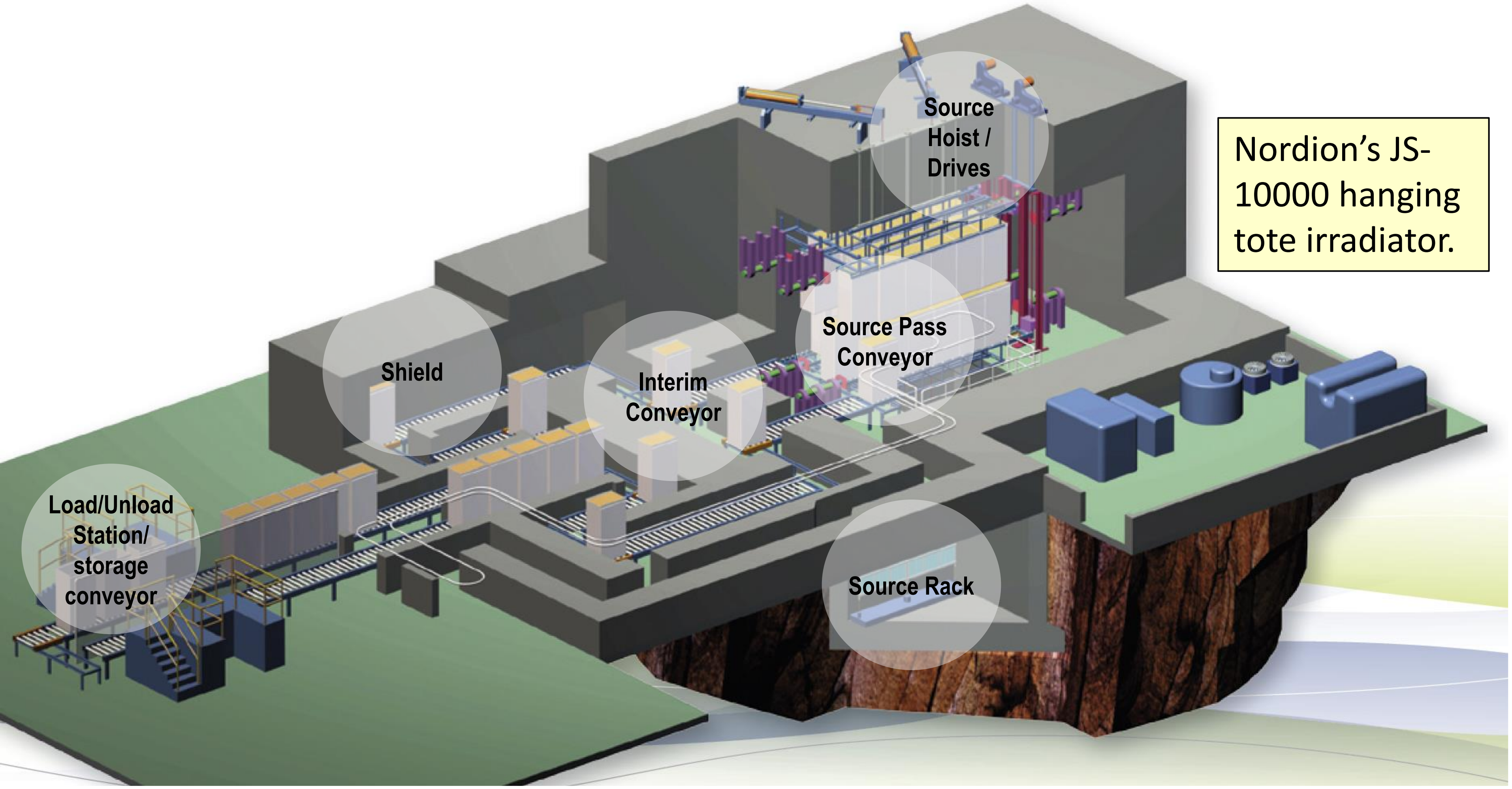
Comparing the dose at different depths of the irradiated object for gamma radiation, x-rays and energetic electrons

Comparing different irradiators

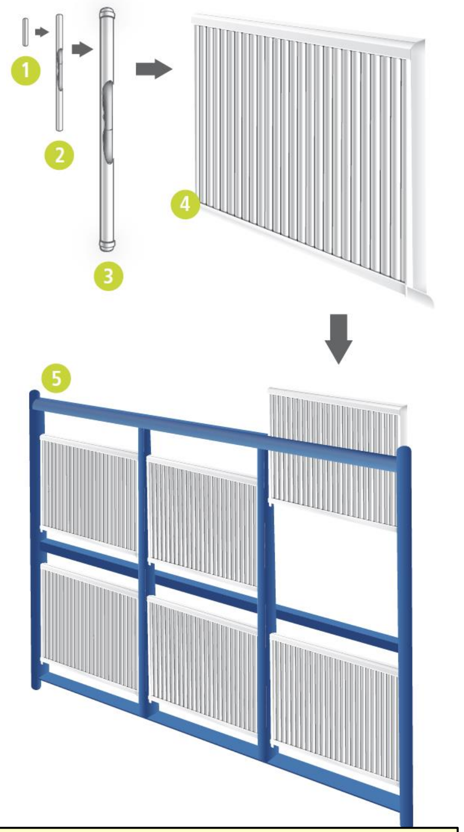
	Radioisotopes from sources (Co-60 or Cs-137 – gamma rays)	Machine using electricity (accelerated electrons or x-rays)
Emission of radiation	Cannot be switched off	Can be switched off
	Isotropic	Unidirectional
	Direction cannot be controlled	Direction can be controlled (beam)
Consequence	Non-stop operation (24/7) to optimize source use	Flexible operation schedule A truckload can be processed within hours
Dose Rate	kGy/h	kGy/s (electrons) and kGy/min (x-rays)

Note: Half life of Co-60 is 5.3 years and half life of Cs-137 is 30.2 years

Example of Food Irradiator



Nordion's JS-10000 hanging tote irradiator.



Source: Nordion C-188 double-encapsulated Cobalt-60 with activity up to 14,500 Ci or 527 TBq

Image taken from http://www.nordion.com/wp-content/uploads/2014/10/GT_JS10000_Irradiator_datasheet.pdf

Comments on Food Irradiation

- > 60 countries have approved irradiation for more than 60 food productions up to 10 kGrays (e.g., see WHO reference below for list of countries in 1988 and food approved).
- Some exports become possible (e.g., dragon fruits from Vietnam to US) if they are irradiated.
- Irradiation may be done during export or import (if the exporting countries do not have the facilities to do so).
- Cost is an issue that may hinder more food to be irradiated.
- Additional risks in accidental exposure to radiation for workers, and in transporting gamma irradiator.
- Gamma sources used in irradiators have very high activity.
- Public acceptance in some countries is not high – possibly due to misunderstanding of the risk of taking irradiated food.
- Regulations in most countries required irradiated to be labeled with the international Radura logo, used to show a food has been treated with ionizing radiation.

http://apps.who.int/iris/bitstream/10665/38544/1/9241542403_eng.pdf

Some “Questions” on Irradiated Food

- Does irradiated food becomes radioactive?
  - **NO!** – irradiation done with γ-rays, x-rays and electrons (under current range of energy) does not change the nucleus – food does not become radioactive.
- Is there any long term effect in eating irradiated food?
  - Long term tests with animals fed with irradiated food showed no effects.
- How about “radiolytic products” (chemical compounds formed by exposure to ionizing radiation)?
  - Some chemicals are formed. They are similar to compounds commonly found in food. They are not unique in the sense that they occur only as a result of irradiation. And, moreover, there is no evidence that any of these substances poses a danger to human health.
- Does the irradiation kill all the microorganisms? If not, are those left behind more dangerous?
  - Not all but most of them. Those left behind would have been there originally, and are not modified by the radiation to become more dangerous. Still needs to handle food properly, e.g., in refrigerating and cooking.
- Is irradiated food still nutritious?
  - Yes, very little nutrients are lost – loss is not more than other means of preservation.

http://apps.who.int/iris/bitstream/10665/38544/1/9241542403_eng.pdf

Announcement: Group Projects

1. **Video (25%)**
   - Duration of video: ~ 4 minutes
   - Target audience: **General public** (Keep it simple and interesting)
   - Video to be uploaded ~~7 April (Friday of Week 12)~~ **14 April (Friday of Week 13)**

2. **Report (20%)**
   - ~ 3,000 words in main text (excluding illustrations, appendices, etc.)
   - Target readers: **Classmates in this module** (Need not explain what was covered in lectures.)
   - Softcopy to be uploaded by 14 April (Friday of Week 13)

(Variation of ± 20% on duration of video or number of words in report is allowed)