Radioactivity

Lecture 16

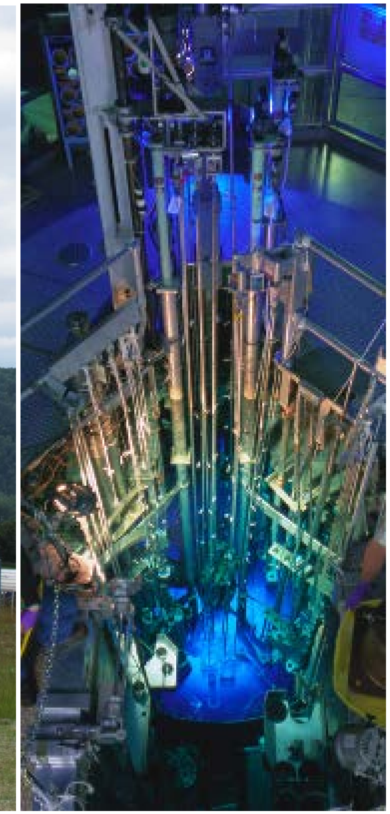
Radioactivity in Agriculture

Anthropogenic Radioactivity

Two classes of anthropogenic radioactivity:

- Technical enhanced natural radioactivity (TENR)
- versus Naturally Occurring Radioactive Material(NORM)
- Artificially induced radioactivity (AIR)

TENR basically covers the technological enhancement or re-distribution of natural radiation in mining and non-nuclear industries; radon indoors and outdoors of building materials; and the mobility and transfer of natural radionuclides.

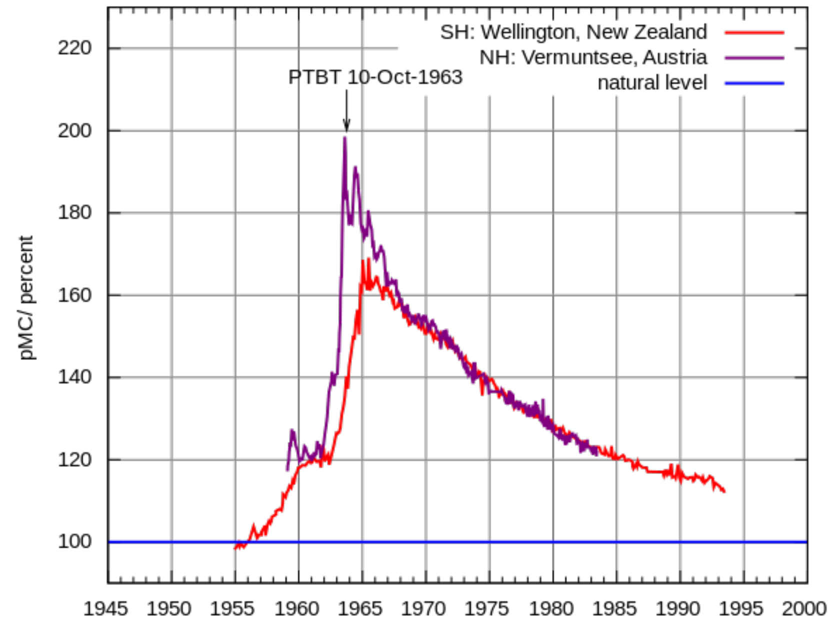


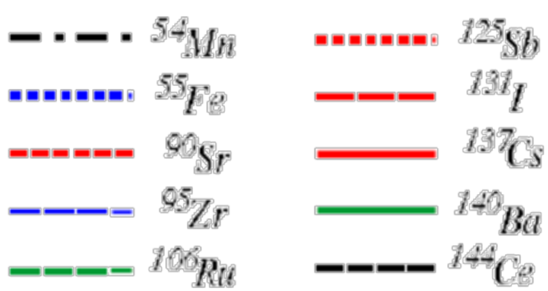
Induced radioactivity that is created when stable substances are bombarded by ionizing radiation. This is radioactive material that is produced and used for industrial, medical, or research purposes and applications.

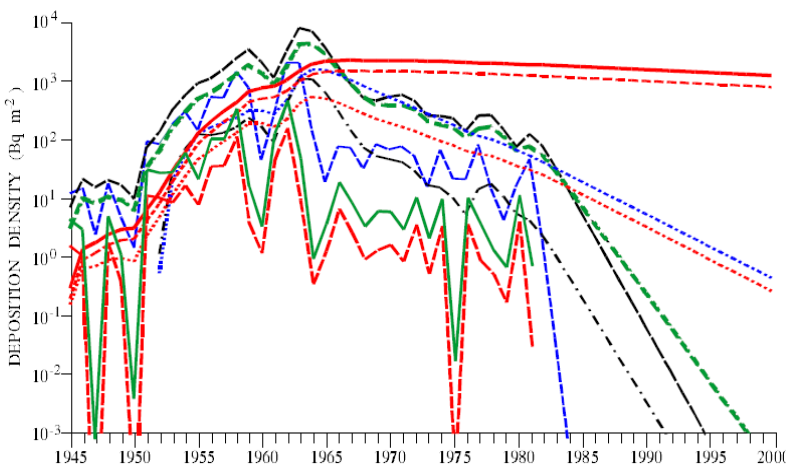
Nuclear Bombs, a Special Case

- The ^{14}C and ^{3}H production induced by the bomb released neutron flux counts as TENR since these isotopes are naturally produced by neutron induced reactions

- Radioactive fall-out from fission products that are produced in the explosion itself count as AIR.



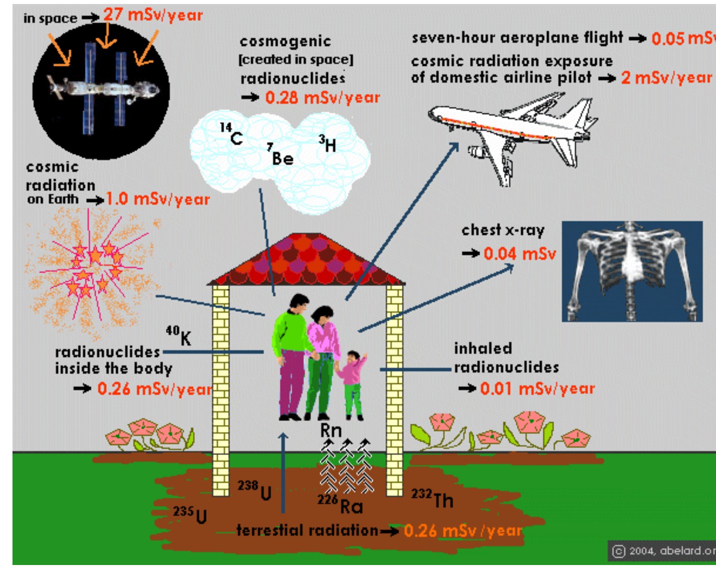




Comparison of Characteristic Activity Levels

- NORM

Cheese	20-40 Bq/kg
Milk	50 Bq/kg
Vegetable	30-3700 Bq/kg
Mushroom	30-400 Bq/kg
Banana	140 Bq/kg
Potatoes	165 Bq/kg
Brazil Nuts	50-200 Bq/kg
Coffee grounds	945 Bq/kg
Fish	56-127 Bq/kg
Pig	50-80 Bq/kg
Human	70-100 Bq/kg
Beef	125 Bq/kg

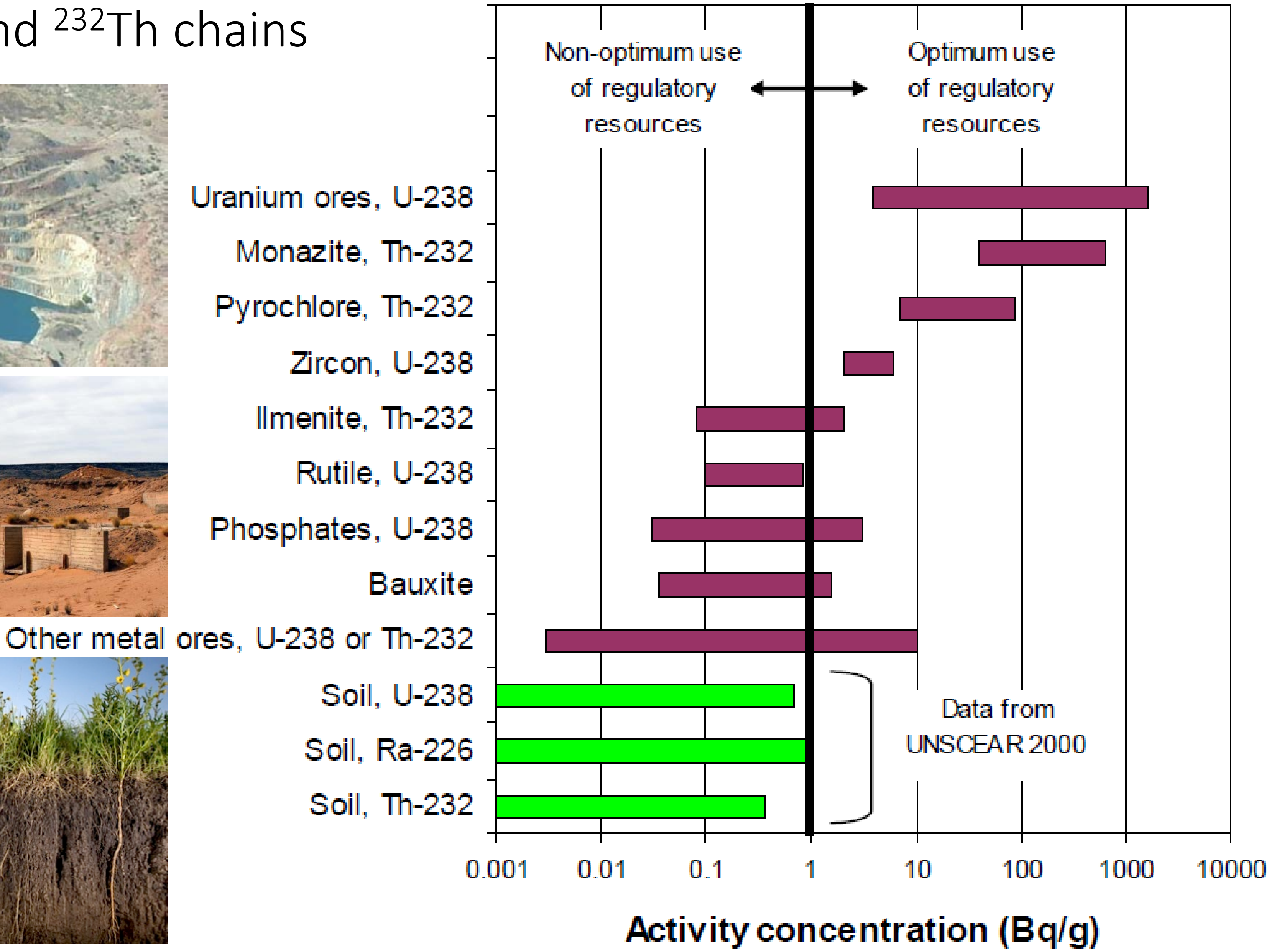


- TENR

Cat Litter	175 Bq/kg
Milk Powder	450 Bq/kg
Mineral concentrates	800-10,000 Bq/kg
Granite Counter Top	950 Bq/kg
Building materials	4000 Bq/kg
Rare Earth Mining	500-5,000,000 Bq/kg
Coal ash	200-1000 Bq/kg
Natural Gas	600-2,000,000 Bq/kg
Phosphate Fertilizer	4000-5000 Bq/kg
Low level nuclear waster	10^6 Bg/kg
High level nuclear waste	10^{12} Bq/kg

From NORM to TENR through Mining

From ^{238}U and ^{232}Th chains

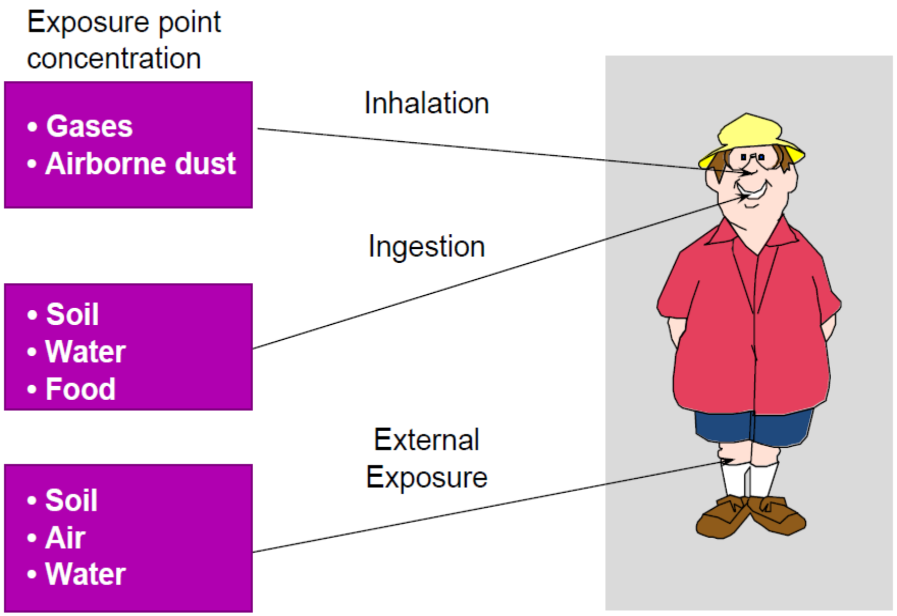


Dose Estimate from Exposure Radioactivity

- **For inhalation and ingestion**
  - Dose = Intake × Dose Conversion Factor (DCF)
  - Intake = Amount of radionuclide inhaled or ingested (Ci or Bq)
    - For inhalation:

      Intake = (Concentration of radionuclide in air in Ci/ft^3 or Bq/m^3) × (breathing rate in ft^3/s or m^3/s) × (exposure duration in s)
    - For ingestion:

      Intake = (concentration of radionuclide in food or water in Ci/lb or Bq/kg) × (consumption rate of water or food in lb/day or kg/day) × (exposure duration in day)
  - DCF is obtained from literature (e.g., ICRP 26/30 or the U.S. Environmental Protection Agency's Federal Guidance Report (FGR) No. 11)
    - Units are rem/Ci or Sv/Bq
- **For external exposure**
  - Dose = Concentration × DCF$_e$ × exposure duration
  - Concentration = Concentration of radionuclide in exposed media
    - Air: Ci/ft^3 or Bq/m^3
    - Water: Ci/ft^3 or Bq/m^3
    - Ground Surface: Ci/ft^2 or Bq/m^2
    - Soil: Ci/ft^3 or Bq/m^3
  - DCF$_e$ is obtained from literature (e.g., ICRP 26/30 or FGR No.12) in units of
    - Air: rem per Ci sec per ft^3 or Sv per Bq s per m^3
    - Water: rem per Ci sec per ft^3 or Sv per Bq s per m^3
    - Ground Surface: rem per Ci sec per ft^2 or Sv per Bq s per m^2
    - Soil: rem per Ci sec per ft^3 or Sv per Bq s per m^3



Reference for techniques
UNSCEAR Report 2000, Annex B
http://www.unscear.org/unscear/en/publications/2000_1.html

The conversion rates depend on the specific kind of radioactive decay and the associated energy release. The following examples use typical values.

Examples for Simple Dose Estimates

- Inhalation
  - Concentration of Radionuclide 1 in air = 10^6 Bq/m^3
  - Breathing rate = 8,400 m^3/yr = 2.7×10^{-3} m^3/s
  - Exposure duration = 2 hr = 7,200 s
  - Intake = (10^6 Bq/m^3) × (2.7×10^{-3} m^3/s) × (7,200 s) = 1.9×10^6 Bq
  - DCF for inhalation = 1×10^{-10} Sv/Bq
  - Inhalation dose from Radionuclide 1 = (1.9×10^6 Bq) × (1×10^{-10} Sv/Bq) = 1.9×10^{-4} Sv

- Ingestion
  - Concentration of Radionuclide 2 in tomatoes = 10^3 Bq/kg
  - Consumption rate = 0.5 kg tomatoes/day
  - Exposure duration = 10 days
  - Intake = (10^3 Bq/kg) × (0.5 kg/d)*10 d = 5×10^3 Bq
  - DCF for ingestion = 5×10^{-9} Sv/Bq
  - Ingestion dose from Radionuclide 2 = (5×10^3 Bq) × (5×10^{-9} Sv/Bq) = 2.5×10^{-5} Sv

- External Exposure
  - Concentration of Radionuclide 1 on ground surface = 10^6 Bq/m^2
  - Exposure duration = 10^5 s
  - DCF = 1×10^{-17} Sv/Bq s per m^2
  - Dose from external exposure to Radionuclide 1 = (10^6 Bq/m^2) × (10^5 s) × (1×10^{-17} Sv/Bq s m^{-2}) = 10^{-6} Sv
- Total Dose assuming the same individual is exposed to Radionuclide 1 through inhalation and external exposure and Radionuclide 2 through ingestion
  - Total Dose = 1.9×10^{-4} Sv + 2.5×10^{-5} Sv + 10^{-6} Sv = 2.16×10^{-4} Sv

Radioactivity in Agriculture

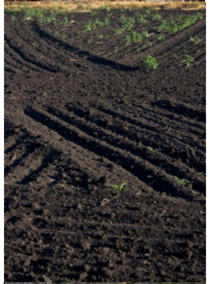
This is mainly a phenomenon of technologically enhanced radioactivity due to the need of fertilizers in agriculture. Fertilizers are made industrially from mining products or are based on biological materials used for fertilizing purposes. In both cases the radioactive components in the initial material are redistributed to agriculturally used soil and cause an enhancement of the radioactivity level of soil, ground water, and food.

Irradiation of agricultural products and tools destroys germs and increases the longevity of fruit, and food, and ensures the sterility of food handling tools.

Natural Soil Activity

Name of country	Mean specific activity (Bq kg^{-1})		
	^{238}U	^{232}Th	^{40}K
United States[11]	40	35	370
China[11]	32	41	440
India[11]	29	64	400
Japan[11]	33	28	310
Iran[11]	28	22	640
Denmark[11]	17	19	460
Belgium[11]	26	27	380
Switzerland[11]	40	25	370
Poland[11]	26	21	410
Romania[11]	32	38	490
Greece[11]	25	21	360
Portugal[11]	44	51	840
Bangladesh[18]	30.93	61.65	467.8
Bangladesh (Dhaka)[17]	33	16	574
Bangladesh (Ship yards)[16]	31	63	364
Worldwide mean[3]	33	45	412

[11] UNSCEAR 2000 Annex B



soil type	^{40}K	^{232}Th	^{238}U
	Bg/kg		
Forest Soil	650	50	35
Black Earth	400	40	20
Bleached Earth	150	10	7
Bog Soil	100	7	7

Different types of soil contain different elemental and chemical components, which effects the specific radioactivity level due to absorption through plant-uptake or bleaching.

Fertilizers

- Fertilizers have been used since antiquity to improve the soil quality and enhance soil fertility
- Traditional fertilizer was animal dung, manure, and excrements with high nitrogen, potassium and phosphorus content
- In medieval times the three-field-system helped to increase the agricultural production by growing a series of different types of crops in the same area in sequential seasons. The arable land was divided into three large fields: one was planted in the autumn with winter wheat or rye; the second field was planted with other crops such as peas, lentils, or beans; and the third was left fallow, in order to allow the soil of that field to regain its nutrients. With each rotation, the field would be used differently, so that a field would be planted for two out of the three years, the third year it was allowed to recover.

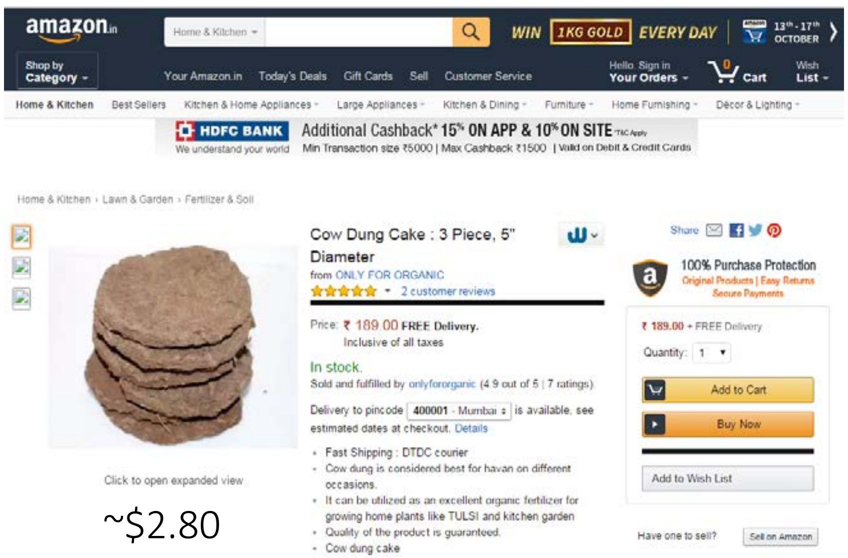
Hour book of the Duc de Berry

Radioactivity in or radioactive shielding by Cow Dung?

Shankar Lal, president of Akhil Bharatiya Gau Sewa Sangh, an outfit associated with the Rashtriya Swayamsevak Sangh (RSS), claimed that dung produced by Indian cows has the power to absorb harmful radiation. "We drink cow urine and have extracts from her dung, which has kept me healthy even at the age of 76," he said. "We make pregnant women eat cow dung and urine paste to ensure a normal delivery. We treat all deadly diseases with cow dung. "A report in *The Times of India* in 2011 quoted a physicist, K.N. Uttam, as saying that cow dung can absorb alpha, beta and gamma rays. This, according to him, is the reason why millions of rural houses have cow dung cakes plastered on their outer walls.

Natural Fertilizers (Cow Dung)

The average radioactivity in natural (organic) fertilizer material is
^{226}Ra with **40 ± 1.6 Bq/kg,**
^{232}Th with **3.1± 1.2 Bq/kg** and
^{40}K with **427.1± 20 Bq/ kg**. This compares well with soil and grass radioactivities!



One dung cake is about 500 g, therefore contains a radioactivity level of 235±11.4 Bq, a cow dung cake shipment amounts to 705 ±34 Bq! The cow cake producer is exposed to 155,100±7600 Bq and the cow dung house dweller to 28,200±1380 Bq. The dung pile contains about 5 to 10 MBq on radioactivity, depending on dimensions.

Liquid Organic Fertilizers (Slurry)

Animal slurry contains 10% of solid material, 10% ammonia and 8% n in different chemical configurations and 4% phosphorus. In addition there is potassium, primarily in the form of potash a mixture of different salt components K_2CO_3, KN_3, K_2SO_4. The average amount of potassium (K) is 4 kg/m^3 of slurry.

This corresponds to $1.8 \cdot 10^{25}$ K atoms/m^3, with 0.012% radioactive ^{40}K isotopes; this translates into $2.1 \cdot 10^{21}$ of ^{40}K isotope/m^3. With a halflife of $1.25 \cdot 10^{9}$ Jahren this corresponds to a total activity of 37 kBq/m^3 or 37Bq/l.

For an average fertilized area of 20 acres (≈ 162,000 m^2) (using a „light" spread of 2000 gal/acre for a typical Indiana farm) a total of 5.9 million Bq (MBq) annually is distributed and enriches the soil in radioactive content. (Compare that with the natural soil activity (400 Bq/kg!)

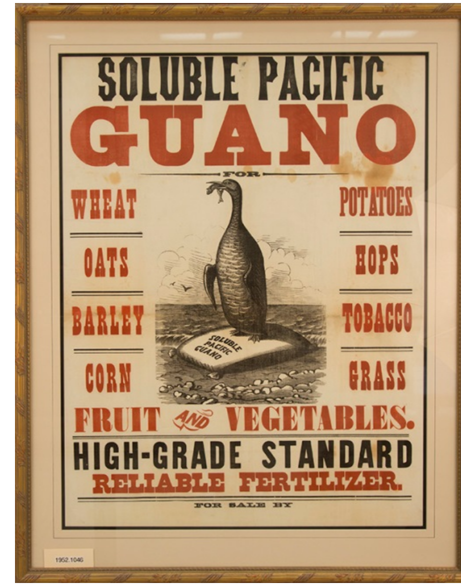
19th Century Import Fertilizer (Guano)

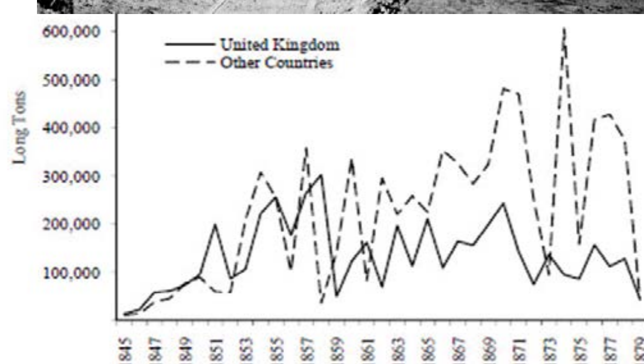
In the early 19th century the industrial revolution required an increase in agricultural production. Organic nitrates were imported, primarily from the western shorelines of South America. **Guano** is the accumulated excrement of seabirds, bats, and other sea animals. Guano was recognized as a highly effective fertilizer with an exceptionally high content of nitrogen, phosphate and potassium: nutrients essential for plant growth.

Besides it’s value for the fertilizing industry, Guano served also as valuable import product for the gun powder industry. The Guano trade drove the Peruvian and Ecuadorian Industry for nearly 6 decades until the invention of modern fertilizers through the Haber-Bosch technique.

Guano Harvesting and Trade

making a profit of millennia of bird-shit deposition





Peruvian guano exports 1845-1879

The Guano Shipping as TENR

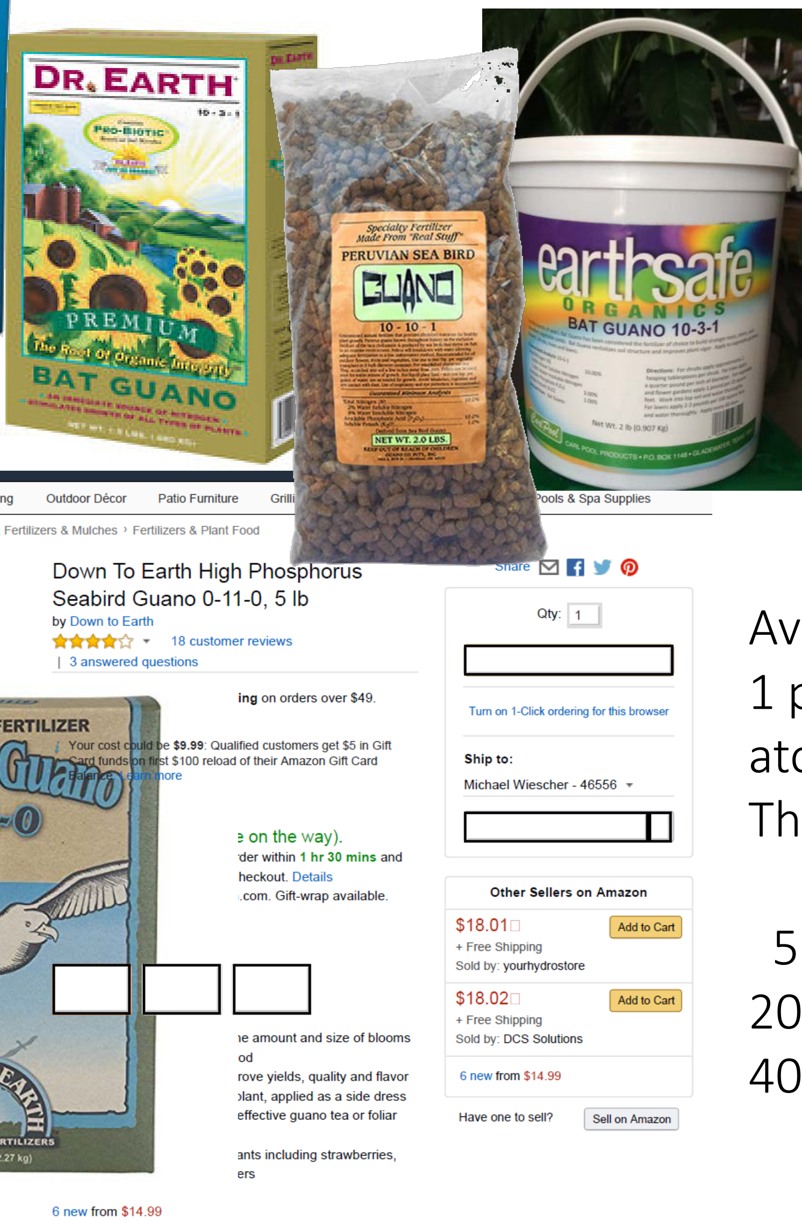
The Guano trade was a new boom of the shipping industry after whaling up to half a million ton of Guano was transported annually to Europe and North America! Between 1840 and 1880 12.7 Million Tons of Guano were shipped from Peru alone. In 1865 Guano import represented 1.0 % of the import of Great Britain, 0.6 % of France, 1.5 % of Belgium, and 1.9 % of the German states. Guano contains about 7-10% of KNO_3 and other nitrates which contain 0.012% radioactive ^{40}K isotopes

$$N(K) = N(KNO_3) = \frac{6.022\cdot 10^{23}}{101g}\cdot 0.1\cdot M_{Guano}[g] = 5.96\cdot 10^{20}\,\frac{M_{Guano}[g]}{g}$$

$$N\left({}^{40}K\right) = 1.2\cdot 10^{-4}\cdot 5.96\cdot 10^{20}\,\frac{M_{Guano}[g]}{g} = 7.15\cdot 10^{16}\,\frac{M_{Guano}[g]}{g}$$

1 ton contains $7.2\cdot 10^{22}$ ^{40}K atoms with an activity of $1.3\cdot 10^{6}$ Bq = **1.3 MBq**
12.7 Mt contain $9.1\cdot 10^{29}$ ^{40}K atoms with an activity of $1.6\cdot 10^{13}$ Bq = **16 TBq**

Modern Organic Fertilizers



Average costs \$3 per pound.
1 pound contains $3.6 \cdot 10^{19}$ of ^{40}K atoms with an activity of 631 Bq.
The typical shipment is offered as:

5 Lbs	3,155 Bq
20 Lbs	12,620 Bq
40 Lbs	25,240 Bq

Modern Fertilizers are based on Phosphate Harvesting

Modern fertilizers contain nitrates that are extracted from air using the Haber-Bosch-process. These nitrates need to be enriched with phosphate to get the optimized nutrition value for the crop. These phosphates are mined as phosphate minerals and chemically processed with the nitrates to produce mineral fertilizer. Without this kind of fertilizer the agricultural production increase of the 20th century would not have been possible.

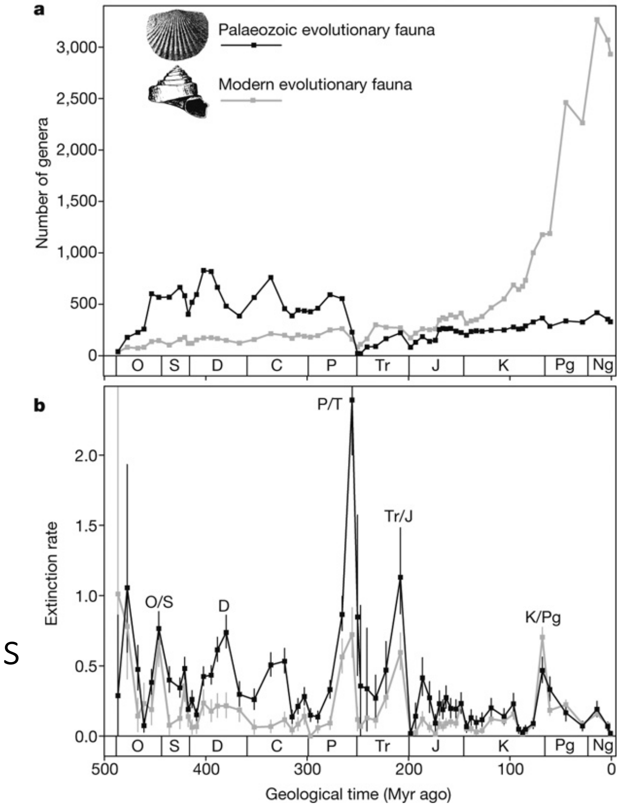
Concentration of NORM radionuclides in phosphate rock

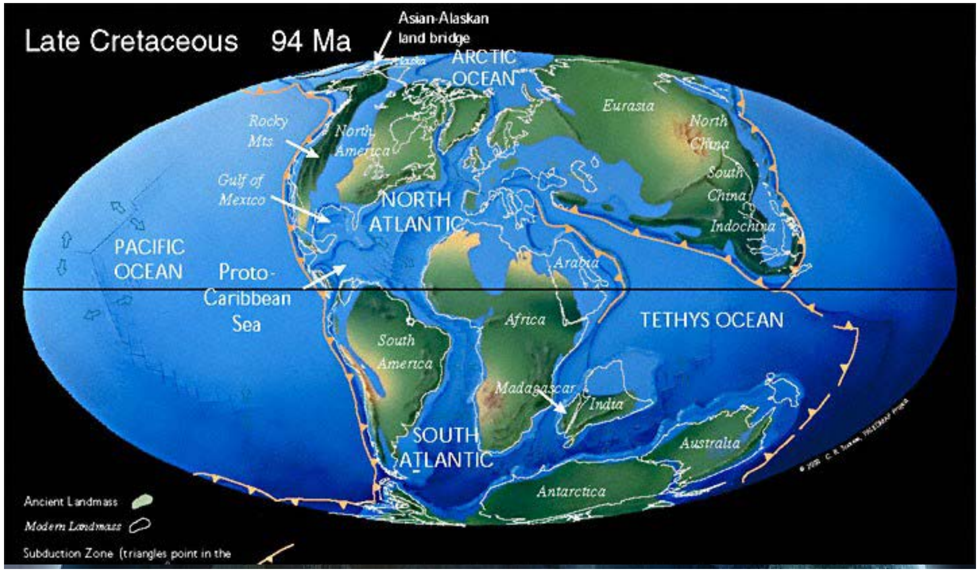
source: IAEA Tech Report 419, p90

Country	Uranium (Bq/kg)	Thorium (Bq/kg)	Ra-226 (Bq/kg)	Ra-228 (Bq/kg)
USA	259-3700	3.7-22	1540	
USA: Florida	1500-1900	16-59	1800	
Brazil	114-880	204-753	330-700	350-1550
Chile	40	30	40	
Algeria	1295	56	1150	
Morocco	1500-1700	10-200	1500-1700	
Senegal	1332	67	1370	
Tunisia	590	92	520	
Egypt	1520	26	1370	
Jordan	1300-1850			
Australia	15-900	5-47	28-90	

Phosphorus Deposition

The majority of known phosphorus depositions have formed over the last two billion years and are of organic origin. Main sources are periods of mass extinctions. The total biomass on earth is about 600 billion tons. Indication of carbon deposition at KT boundaries suggests similar levels 100 million years ago. The fraction of phosphorus is about 3 %, about 10 billion tons phosphorus deposition worldwide/extinction or about 400 billion tons total. The world resource on phosphorus minerals is estimated to 500,000 million tons; about 200 million tons are harvested per year, this is considered an unlimited resources.





Natural Radioactivity of Phosphorus Minerals

Large phosphorus mineral depositions are in Northafrica and North America, in particular in Florida. 20% of phosphates are produced in the US (90% in Florida) 25% in Sahara countries, 31% in southern Asia. In average there are 1-400 mg uranium per kg phosphate (in soil 1-5 mg/kg, in slurry 0.15-1.5 mg/kg). Radioactivity level is dominated by uranium content.

Typ	P-Konzentration [% P] Spannweite	U-Gehalt [mg/kg P] Spannweite	U Eintrag [g/ha*a] Spannweite	U-Eintrag [g/ha*a] Mittelwert
TSP (Triple-Superphosphat)	16,6 – 20,6	52,3 - 362	5,6 - 48	22
NP (Stickstoff-Phosphat-Dünger)	5,3 – 25,8	0,62 – 198	0,05 - 82	7,0
PK (Phosphat-Kalium-Dünger)	5,8 – 13,4	31,2 - 163	5,1 - 61	23
NPK (Stickstoff-Phosphat-Kalium-Dünger)	1,5 – 13,5	0,04 - 113	0,01 - 166	8,0
Rindergülle	0,43 – 2,1	0,15 – 1,4	0,16 - 7	2,9
Klärschlamm	2,1 – 2,2	0,0005 – 18,5	0,001 - 19	3,2

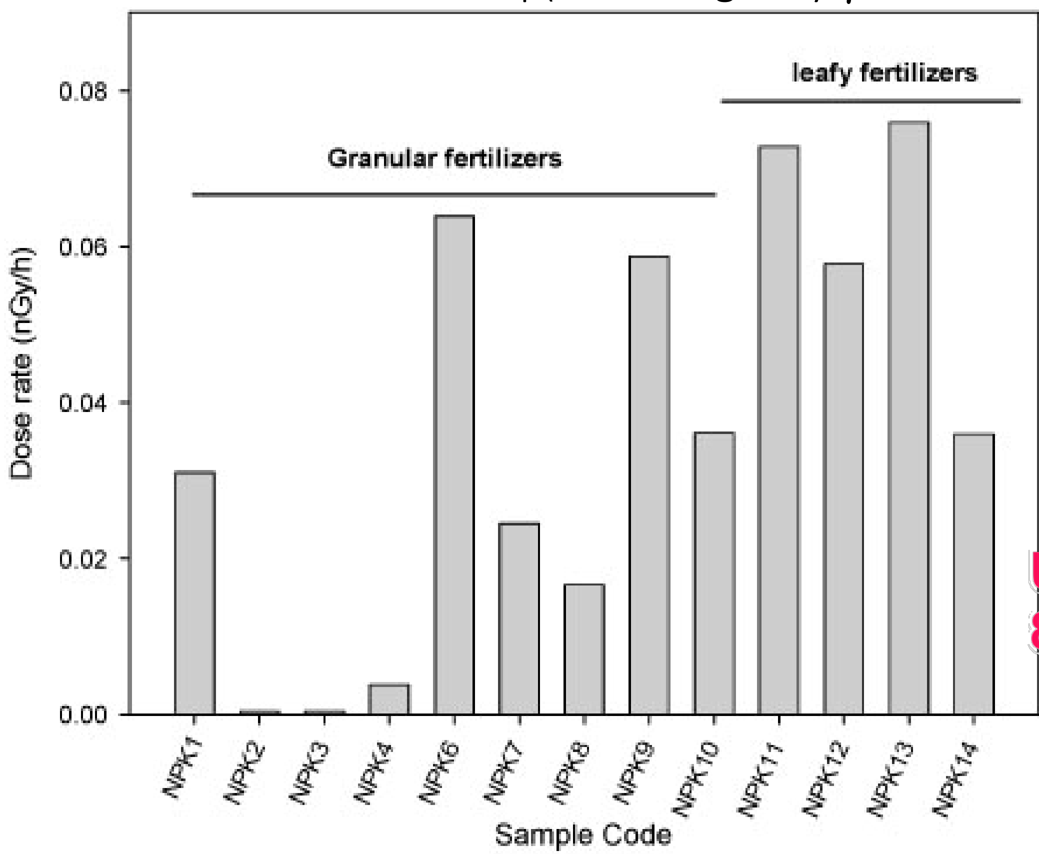
The potassium content in phosphates is often small, in so-called NPK fertilizers it is added to the phosphorus nitrogen composition. The distribution in weight is:

18% Nitrogen
22% Phosphorus
17% Potassium
0.001445% ^{40}K
14.4 mg/kg NPK
or 0.2-2.0 mg/kg P in NPK

Typical concentrations in phosphate fertilizer are 4000 Bq (= 0.32 g) ^{238}U per kg phosphate and 1000 Bq ^{226}Ra per kg phosphate.

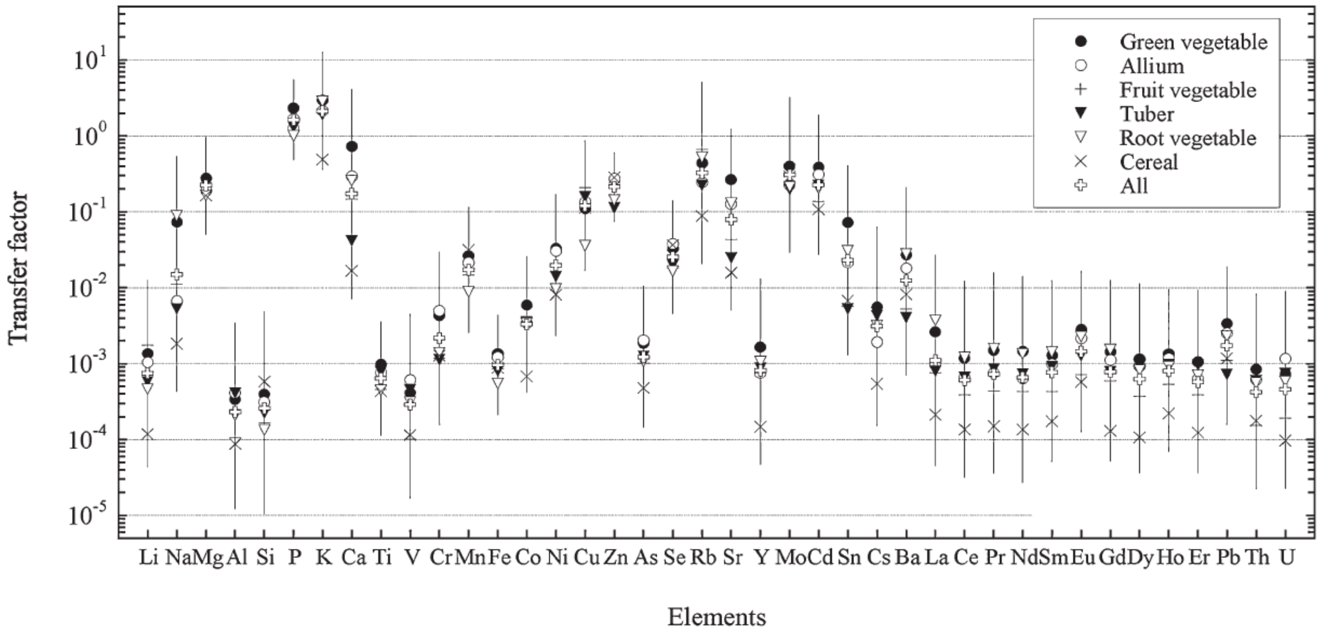
Dose Rate from Inhaling Fertilizer Dust

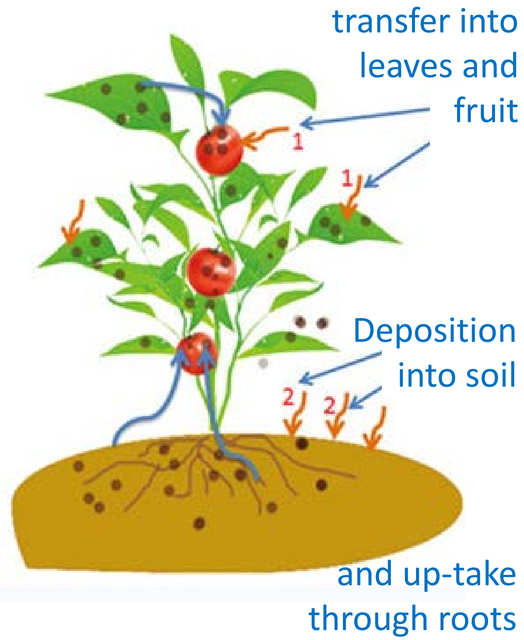
Using conversion techniques as described before with DCF=$1.3 \cdot 10^{-15}$ Sv/Bq (assuming only γ radiation



Absorbed dose rate 1 m above the ground surface (nGy/h) originated from NPK fertilizers agricultural applications.

Up-Take of Vegetable Plants

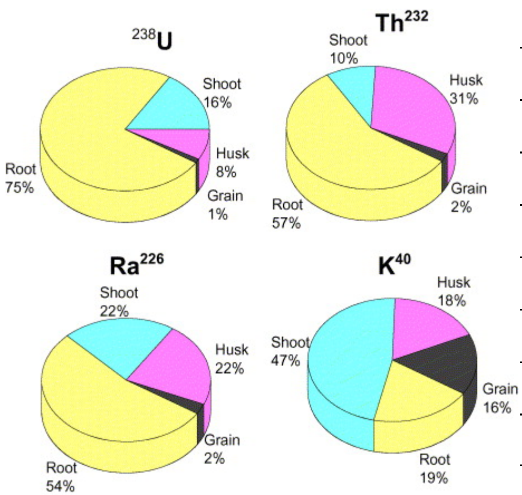




Potassium and with it ^{40}K has a 100% up-take and is built into the plant and by that gets into the food cycle. However, no enrichment in human body since the typical potassium in-take is 2-5 g (60 - 150 Bq) controlled by physiological processes.

^{238}U, ^{232}Th components have a very limited up-take of 0.1% due to its size, through the normal food process an average of 1 – 5 μg gets into the digestion system which translates into a daily in-take rate of 20 – 100 mBq.

The activity concentration of ^{226}Ra, ^{210}Pb, ^{232}Th, and ^{40}K (in Bq,kg) in some fresh vegetables and fruits and the resulting annual effective dose in µSv/y.

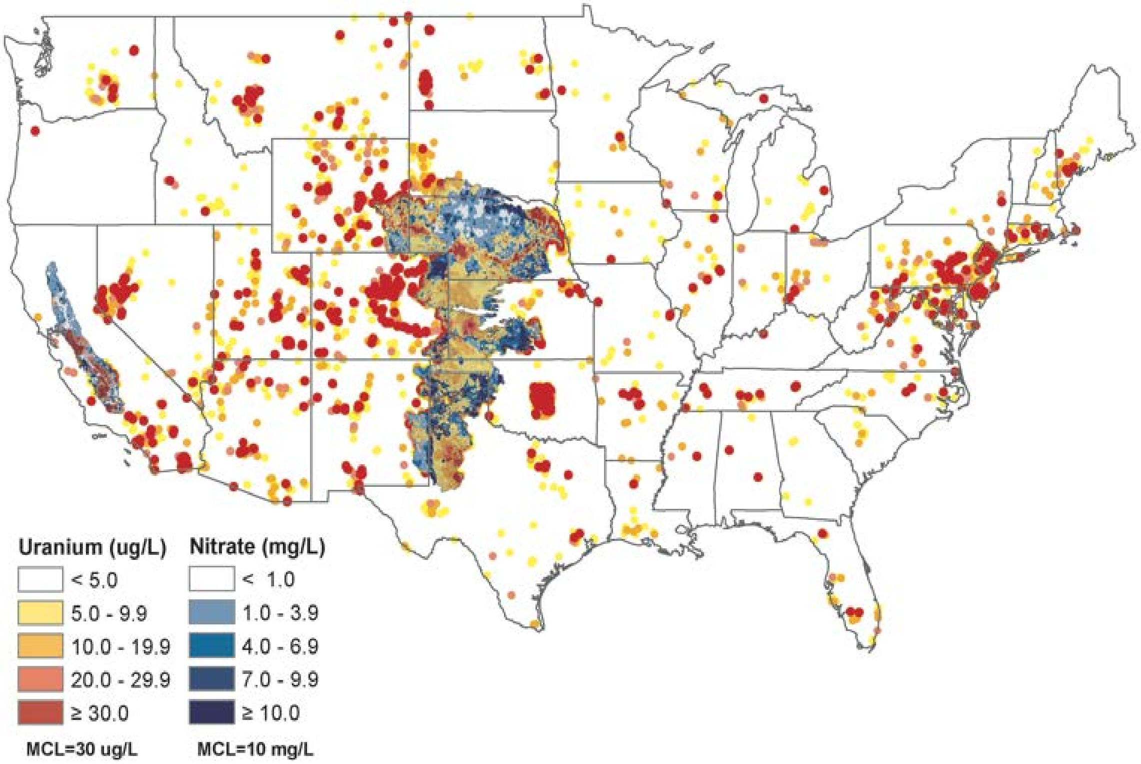


Radioactivity distribution in wheat

Name of samples	Ra-226	Pb-210	Th-232	K-40	consumption rates kg per year	Annual effective dose µSvy-1
Vegetables						
Tomato	ND	**0.03±0.06**	0.02±0.05	63.00±2.45	**4.2**	0.082
Potatos	ND	0.07±0.05	0.06±0.06	121.68±4.57	**23.9**	17.525
Carrot	0.29±0.15	ND	0.05±0.05	126.15±4.71	**3.7**	2.992
eggplan	**0.01±0.02**	ND	0.05±0.05	60.62±2.37	**24**	8.601
Zucchini	ND	0.14±0.08	0.04±0.06	136.91±4.67	-	
watercress	**0.89±0.28**	ND	ND	305.04±13.03	**0.13**	0.259
Lettuce	0.18±0.07	ND	ND	59.79±2.10	**0.63**	0.248
Papper	0.01±0.02	0.07±0.09	0.07±0.07	52.31±2.21	**0.1**	0.033
Cabbage	0.21±0.11	ND	0.24±0.73	76.77±3.07	**0.96**	0.481
Cueumber	0.05±0.03	0.11±0.06	**0.01±0.03**	58.80±2.07	-	
coriander leaves	2.56±1.11	ND	1.22±0.56	**536.6±23.03**	-	
Okra	ND	0.16±0.13	0.23±0.11	115.6±4.55	**10.054**	7.224
Onion	0.25±0.05	0.44±0.12	ND	79.7±2.81	**24.2**	15.102
Jew's Mallow	0.04±0.03	0.04±0.03	0.02±0.03	**41.46±1.55**	**19.178**	5.015
Fruits						
Apple	0.09±0.04	0.13±0.08	**0.01±0.05**	26.65±1.24	**6.9**	1.428
Orang	**0.35±0.11**	0.22±0.11	0.04±0.05	64.62±2.32	**8.1**	4.134
Apricot	0.06±0.09	ND	**0.24±0.17**	114.9±4.52	-	
Banana	0.30±0.09	**0.39±0.21**	ND	**197.6±6.85**	**10.60**	14.005
Cantalop	**0.03±0.02**	0.14±0.09	0.09±0.07	95.91±3.58	-	
dates	ND	0.12±0.07	0.04±0.03	50.29±2.02	**14.7**	4.770
Strawberry	0.05±0.04	**0.08±0.08**	0.02±0.05	52.59±2.10	**9.58**	3.246
Figs	0.05±0.02	0.01±0.06	0.10±0.05	37.25±1.56	**0.685**	0.161

Impact on Aquifers

Mineral fertilizer gradually increases uranium content in agricultural regions, through rain and drain it gets into the aquifer system. This affects in particular the large agricultural regions of the prairielands.



Typical Values of Radioactivity in Drinking Water and Mineral Water

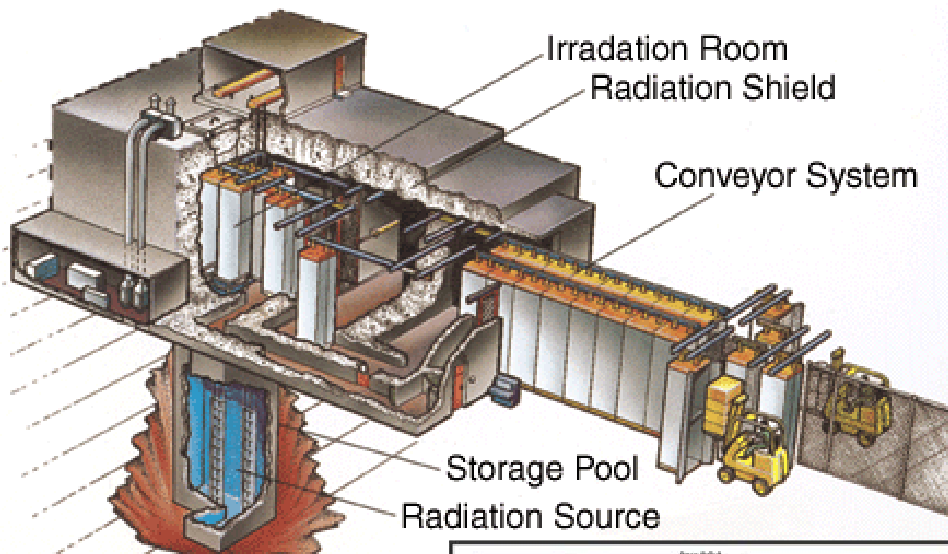
Radionuclide	Average Value	Value Range
	Specific Activity (mBq/l)	
Uran-238	16 (5)*)	< 0,5 - 310
Uran-234	18 (6)*)	< 0,5 - 350
Uran-235	1 (0,3)*)	< 0,2 - 16
Radium-226	5	< 0,5 - 32
Radium-226 (Mineral Water)	23	< 0,5 - 310
Thorium-232	0,5 (0,1)*)	< 0,1 - 4
Thorium-228	1 (0,2)*)	< 0,2 - 6
Radium-228	12 (3)*)	< 0,5 - 23
Radon-222	5900	<1 000 - 160 000
Blei-210	7 (1,5)*)	< 0,2 - 170
Polonium-210	2 (0,5)*)	< 0,1 - 40
Kalium-40	70	3 - 800
Kalium-40 (Mineral Water)	1500	30 - 16 000

An increase is possible due to slurry run-off!

2 l mineral water per day adds 3 Bq to the digestive system

Food irradiation

Food irradiation is a technology that improves the safety and extends the shelf life of foods by reducing or eliminating microorganisms and insects. Like pasteurizing milk and canning fruits and vegetables, irradiation can make food safer for the consumer!



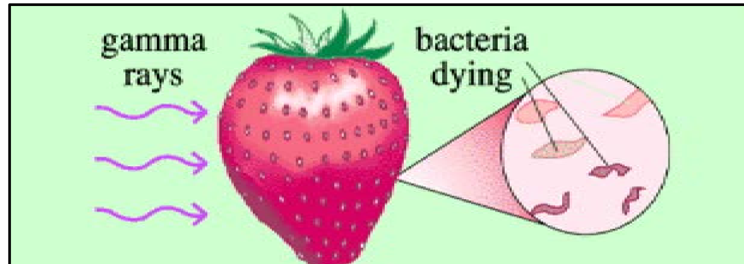
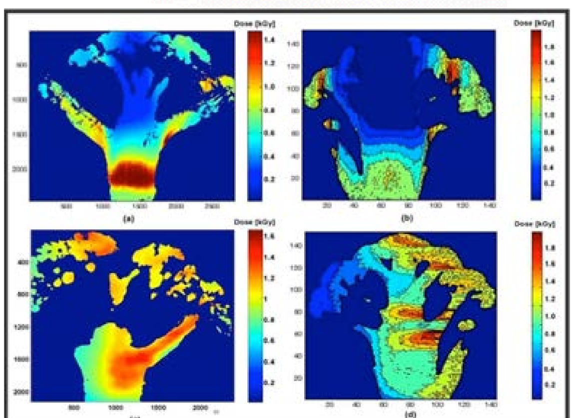


Table 1 Applications of Ionizing Radiation Accepted in the U.S. by the Food and Drug Administration.

Product	Dose (kGy)	Purpose	Date
Wheat, wheat flour	0.2 - 0.5	Insect disinfestation	1963
White potatoes	0.05 - 0.15	Sprout inhibition	1964
Pork	0.3 - 1	*Trichinella spiralis* Control	7/22/85
Enzymes (dehydrated)	10 max.	Microbial Control	4/18/86
Fruit	1 max.	Disinfestation, Ripening Delay	4/18/86
Vegetables, fresh	1 max.	Disinfestation	4/18/86
Herbs	30 max.	Microbial Control	4/18/86
Spices	30 max.	Microbial Control	4/18/86
Vegetable Seasonings	30 max.	Microbial Control	4/18/86
Poultry, fresh or frozen	3 max.	Microbial Control	5/2/90
Meat, frozen, packaged[a]	44 min.	Sterilization	3/8/95
Animal Feed and Pet Food	2 - 25	*Salmonella* Control	9/28/95
Meat, uncooked, chilled	4.5 max.	Microbial Control	12/2/97
Meat, uncooked, frozen	7.0 max.	Microbial Control	12/2/97

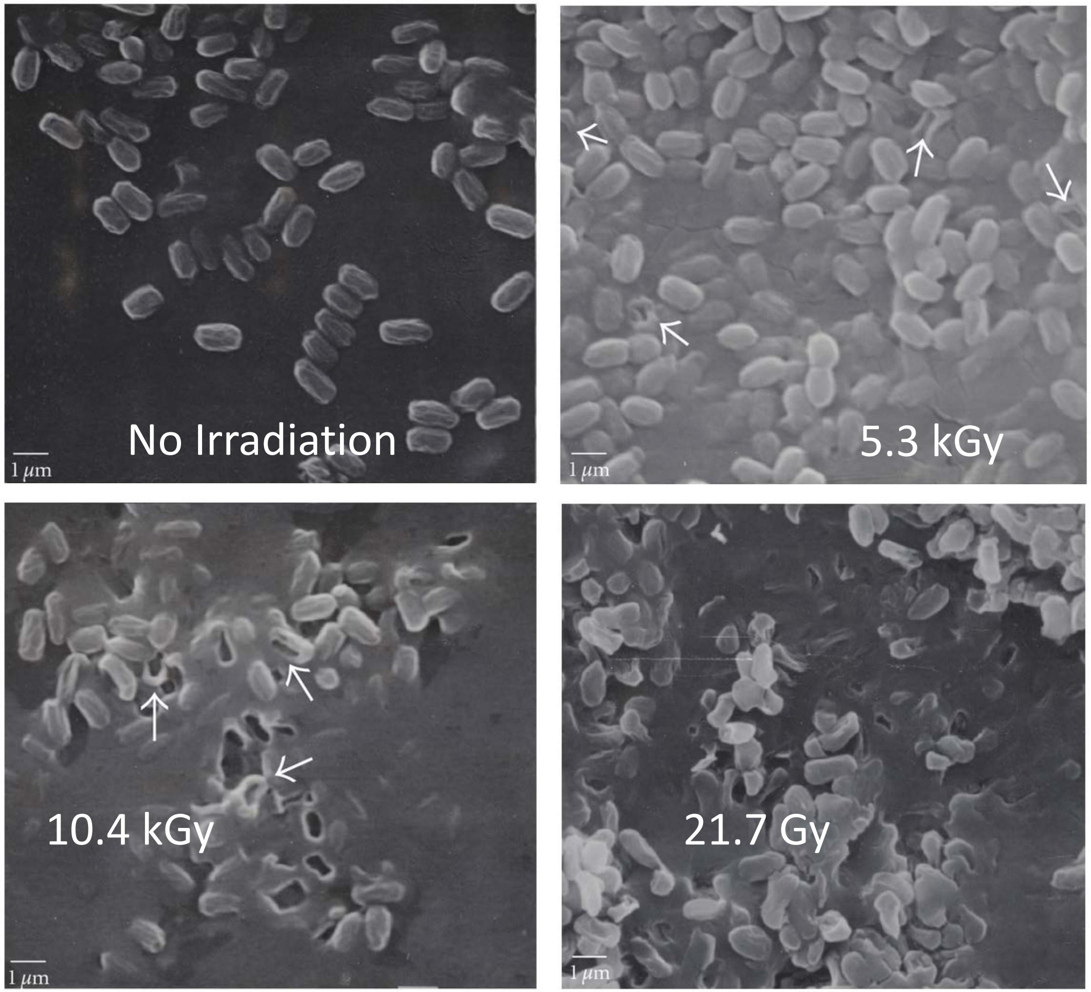
[a] For meats used solely in the National Aeronautics and Space Administration space flight programs.

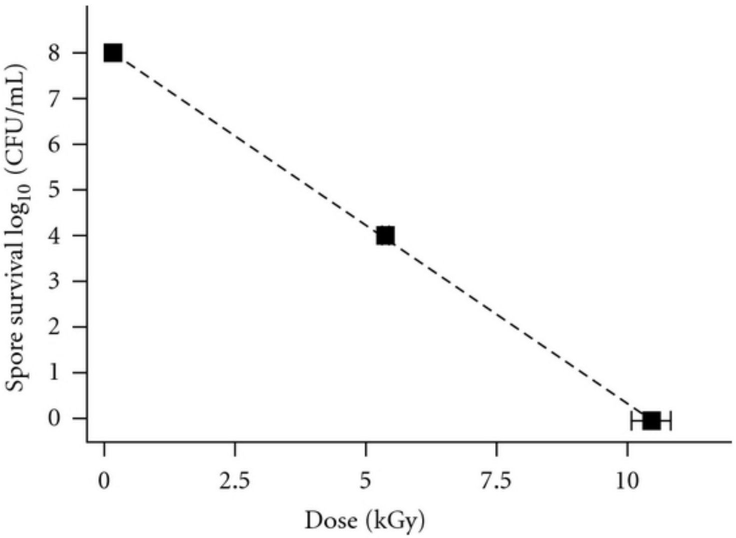
The radiation has to penetrate the entire food body as the dose distribution in Broccoli demonstrates



measured   simulation

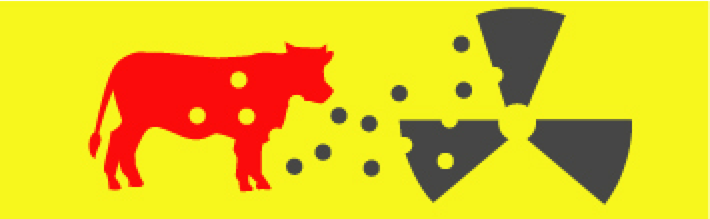
Spore and Bacteria Survival Chance





The irradiation studies also show that too much irradiation attacks the chemical structure of the plant itself which can lead to the change in taste and influence the storage time.

Quantities and Dose



Main potential applications and dose requirements	
Application	Dose requirement (kGy)
Inhibition of sprouting	0.03–0.12
Insect disinfestation	0.2–0.8
Parasite disinfestation	0.1–3.0
Shelf-life extension (“radurization”)	0.5–3.0
Elimination of non-sporeforming pathogenic bacteria (“radicidation”)	1.5–7.0
Reduction of microbial population in dry food ingredients	3.0–20
Production of meat, poultry and fishery products shelf-stable at ambient temperature (“radappertization”)	25–60

Quantities of irradiated foods (in 2005)		
Regions	Quantity in tons	%
Asia and Oceania	183.309	45
America	116.4	29
Africa, Ukraine and Israel	90.035	22
Europe	15.06	4
Total	404.804	100

Global quantities of irradiated food items.		
Food items	Quantity in tons	%
Spices and dry vegetables	186	45
Garlic and potato	88	22
Grains and fruits	82	20
Meat and seafood	33	8
Others	17	4
Total	406	100

Concerns of the population

Consequences of Food Irradiation?

- Typically ^{60}Co γ sources are being used that emit a high flux of 1.17 and 1.33 MeV γ radiation.
- A typical irradiation dose is 1 kGy.
- Bacteria, insects and germs are being killed.
- Radiation can break up fruit specific molecules, which can cause secondary chemical effects.
- Radiation **does not** produce new radioactivity that might be transferred to the consumer.