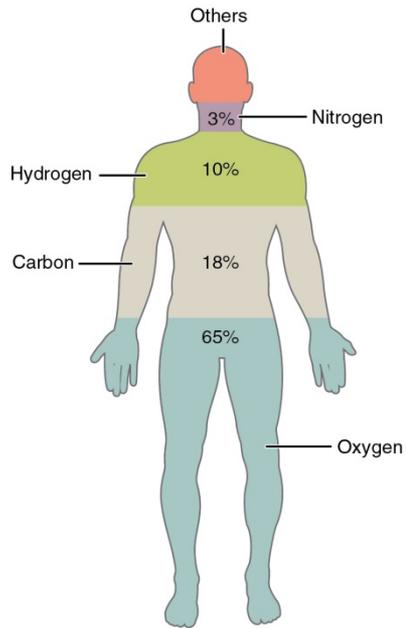


Radioactivity

Lecture 14

The Human Radioactivity Cycle

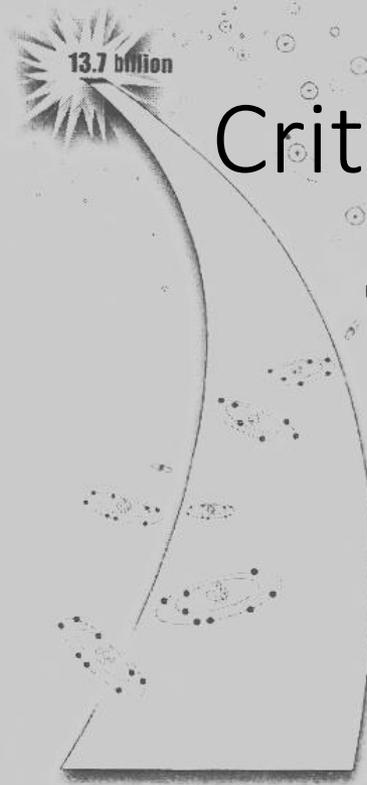
The Elements in the Human



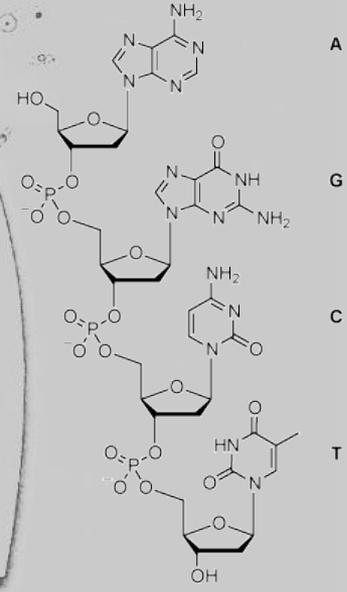
Element	Symbol	Percentage in Body	atomic percentage
Oxygen	O	65.0	25.5
Carbon	C	18.5	9.5
Hydrogen	H	9.5	63
Nitrogen	N	3.2	1.4
Calcium	Ca	1.5	0.31
Phosphorus	P	1.0	
Potassium	K	0.4	0.1
Sulfur	S	0.3	0.05
Sodium	Na	0.2	0.03
Chlorine	Cl	0.2	
Magnesium	Mg	0.1	0.01
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).			less than 1.0

The molecular structure and the body functions rely only on a few, but critical elements, **Carbon C**, **Oxygen O**, and **Hydrogen H** as the base elements for all the organic molecule components.

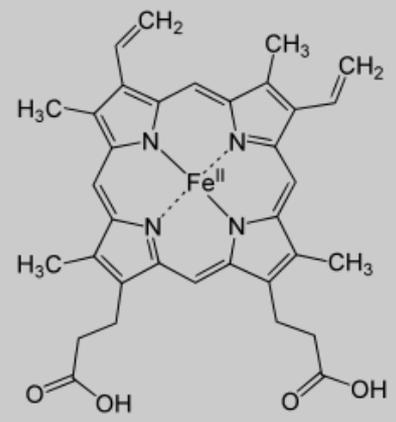
- **Nitrogen N:** allows the body to utilize the nitrogen, promoting protein synthesis and the creation of compounds and amino acids that influence growth, hormones, brain functions and the immune system.
- **Calcium Ca:** is the most plentiful mineral found in the human body. The teeth and bones contain the most calcium. Nerve cells, body tissues, blood, and other body fluids contain the rest of the calcium.
- **Phosphorus P:** is critical for the formation of bones and teeth. It plays an important role in how the body uses carbohydrates and fats. It is also needed for the body to make protein for the growth, maintenance, and repair of cells and tissues.
- **Potassium K:** is crucial to heart function and nerve system. It plays a key role in skeletal and smooth muscle contraction, making it important for normal digestive and muscular function.
- **Sulfur S:** is a part of some of the amino acids in your body and is involved in protein synthesis, as well as several enzyme reactions. It helps with the production of collagen, a substance that forms connective tissues, cell structure and artery walls.
- **Sodium Na:** regulates the total amount of water in the body and the transmission of sodium into and out of individual cells. It also plays a role in critical body functions for the muscle and nerve system.



Critical Molecule Contamination



dAGCT (DNA)



Hemoglobin (blood)



$H_{375,000,000}$ $O_{132,000,000}$ $C_{85,700,000}$ $N_{6,430,000}$ $Ca_{1,500,000}$
 $P_{1,020,000}$ $S_{206,000}$ $Na_{183,000}$ $K_{177,000}$ $Cl_{127,000}$ $Mg_{40,000}$ $Si_{38,600}$
 $Fe_{2,680}$ $Zn_{2,110}$ Cu_{76} I_{14} Mn_{13} F_{13} Cr_7 Se_4 Mo_3 Co_1

The Human body contains about $7 \cdot 10^{21}$ hemoglobin molecules, carrying a total of $1.7 \cdot 10^{13}$ radioactive ^{14}C isotopes in our blood.

$$\frac{N(^{14}C)}{N(^{12}C)} = 8 \cdot 10^{-13} \Rightarrow 0.00007 \text{ } ^{14}C \text{ per DNA molecule}$$

The Human body has between 50 and 100 trillion cells, each cell has two sets of 23 chromosomes that consist of a tightly wound DNA molecules. That means we have about 320 billion ^{14}C isotopes embedded in our DNA material! Similarly each DNA molecule carries 21 radioactive ^{40}K isotopes, the body DNA contains therefore up to 10^{17} radioactive ^{40}K isotopes!

Intake through Food and Drinks

The body and its functions are maintained through food, drink, and air intake. It breaks up food molecules to facilitate body growth and function. Through food and other exchange processes with the outer environment radioactive isotopes with identical or similar chemical behavior gets into body material : ^{92}Sr with Ca, ^{40}K with potassium, ^{32}P with phosphorus, ^{226}Ra by inhaling.

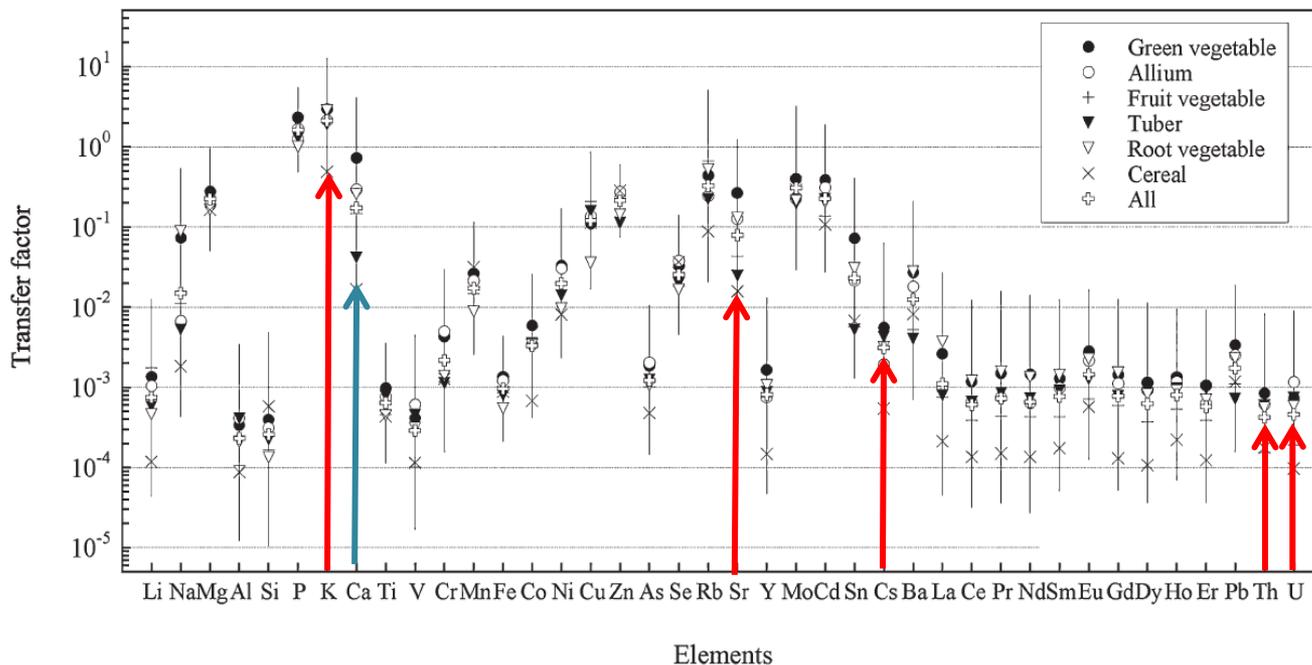
Radioactivity in your daily food and drink

Food	^{40}K Bq/kg	^{226}Ra Bq/kg	Food and drink	^{40}K Bq/kg	^{226}Ra Bq/kg
Bananas	130	0.037	Beer	15	---
Nuts	207	37-260	Meat	110	0,02
Carrots	126	0.02- 0.08	Beans	172	0.07- 0.19
Potatoes	126	0.04- 0.1	Drinking Water	---	0-0.63



Uptake by Plant Material

Plants extract certain chemicals as nutrients out of the soil. The up-take of the radioactive isotopes depends on the chemical similarities between the isotope and the nutrient element. ^{40}K ($T_{1/2}=1.28\text{ Gy}$) is being absorbed at the same level of 80-100% as normal potassium, ^{90}Sr ($T_{1/2}=28.6\text{y}$) is absorbed similarly as calcium with an efficiency of around 10% depending on the plants. The up-take of ^{137}Cs ($T_{1/2}=30.2\text{y}$) is with about 0.5% considerably smaller. Uranium and Thorium have a very low up-take efficiency of 0.1%. This translates into relatively enhanced ^{40}K content in fruit and vegetable.



Fruit and vegetable from mineral rich soil has an enhanced level of radioactivity. The enrichment factor is in particular high for ^{40}K and ^{90}Sr , as well as ^{137}Cs as fall-out product from nuclear test and reactor incidents!

Specific Radioactivities in our bodies

Chemically our body consists of 60% to 70% water, of 16% of proteins, 10% lipides forming the cell and body structure, with 1% carbohydrates, nucleotides, and aminoacids each, and finally 5% minerals which are important for the electrical nerve and information transfer system. That immediately identifies ^3H , ^{14}C , ^{40}K as important radioactive isotopes in body water, organic materials of the body, and body minerals.

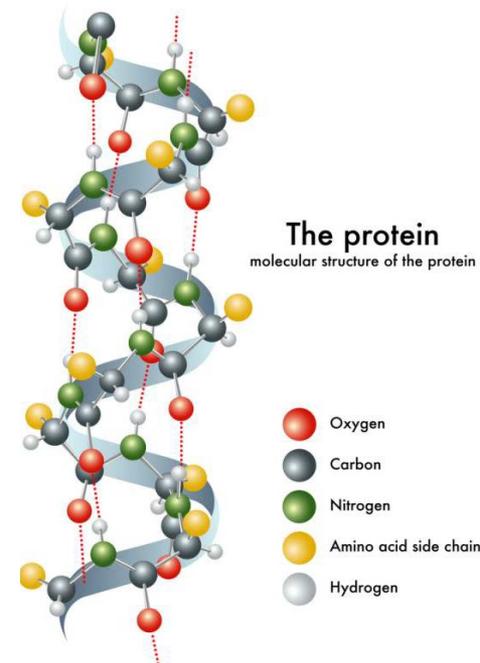
All food and drink materials contain a certain fraction of radioactive material that is partly deposited in body system, partly excreted.

Quick estimate of the ^{14}C content assuming an a volume content of 18.5% and equilibrium between consumption and excretion.

$$N(^{12}\text{C}) = 80\text{kg} \cdot 0.185 \cdot \frac{6.023 \cdot 10^{23}}{12 \cdot 10^{-3} \text{kg}} = 7.43 \cdot 10^{26} \text{ }^{12}\text{C atoms}$$

$$\frac{N(^{14}\text{C})}{N(^{12}\text{C})} \approx 8 \cdot 10^{-13} \quad N(^{14}\text{C}) = 5.94 \cdot 10^{14} \text{ }^{14}\text{C atom}$$

$$T_{1/2} = 5730\text{y} \quad A(^{14}\text{C}) = \frac{\ln 2}{5730 \cdot 3.14 \cdot 10^7 \text{s}} \cdot 5.94 \cdot 10^{14} = 2290\text{Bq}$$



A body of 80 kg contains 14.8 kg ^{12}C of $7.43 \cdot 10^{26}$ atoms generating an activity of 2290 Bq!

and the radioactive heavy water ...

Hydrogen has a weight percentage of 9.5% in the human body which corresponds to 7.6 kg of weight. The hydrogen is primarily in form of H₂O and OH molecules, tritium contamination comes as HTO or HT.

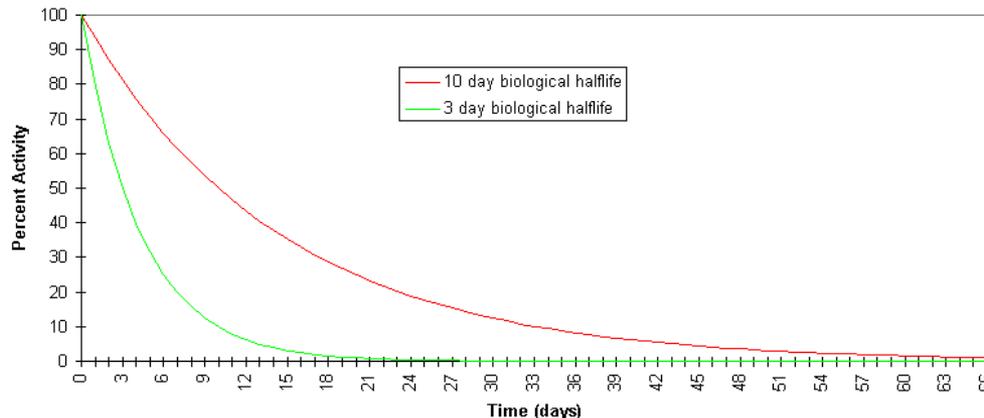
$$N(^1H) = 7600 \cdot 6.022 \cdot 10^{23} = 4.58 \cdot 10^{27} \text{ } ^1H \text{ atoms}$$

$$\frac{N(^1H)}{N(^3H)} = 10^{18} \quad N(^3H) = 4.58 \cdot 10^9 \text{ } ^3H \text{ atoms}$$

$$T_{1/2} = 12.3 \text{ y} \quad A(^3H) = \frac{\ln 2}{12.3 \cdot 3.14 \cdot 10^7 \text{ s}} \cdot 4.58 \cdot 10^9 = 8.21 \text{ Bq}$$



Increased tritium intake would increase the internal body activity but tritium is part of the body fluid system with relative rapid exchange within 10 days (George de Hevesey)

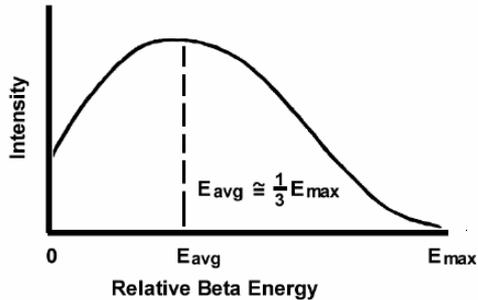


The natural excretion can be accelerated by the additional intake of liquids.

Annual Dose from ^{14}C and ^3H in body

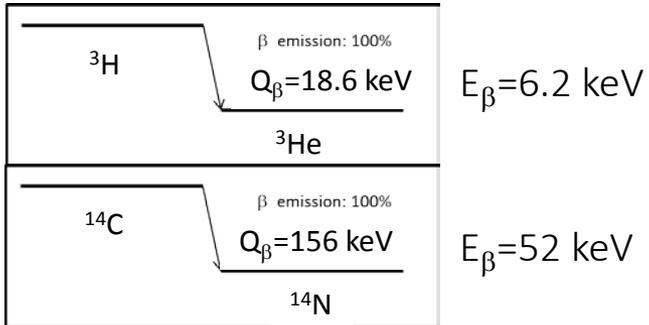
Low energy β^- emitters, therefore low energy deposition in body material

Representative Beta Spectrum



$$\text{Dose } D = \frac{E_{\text{absorbed}}}{m_{\text{body}}} = t \cdot A \cdot \frac{E_{\text{avg}}}{m_{\text{body}}}$$

$$D(^{14}\text{C}) = 1\text{y} \cdot 2290\text{Bq} \cdot \frac{52\text{keV}}{80\text{kg}} = 3.14 \cdot 10^7 \cdot 2290 \cdot \frac{52000\text{eV}}{80\text{kg}}$$



$$E_{\beta} = 6.2 \text{ keV}$$

$$D(^{14}\text{C}) = 4.67 \cdot 10^{13} \frac{\text{eV}}{\text{kg}} = 7.48 \cdot 10^{-6} \frac{\text{J}}{\text{kg}} = 7.48 \mu\text{Sv}$$

with $1\text{eV} = 1.6 \cdot 10^{-19} \text{J}$

$$D(^3\text{H}) = 1\text{y} \cdot 8.21\text{Bq} \cdot \frac{6.2\text{keV}}{80\text{kg}} = 3.14 \cdot 10^7 \cdot 8.21 \cdot \frac{6200\text{eV}}{80\text{kg}}$$

$$D(^3\text{H}) = 2 \cdot 10^{10} \frac{\text{eV}}{\text{kg}} = 3.2 \cdot 10^{-9} \frac{\text{J}}{\text{kg}} = 3.2 \text{nSv}$$

Very small, if not negligible radiation dose inside body from cosmic ray induced radioactive ^{14}C and ^3H nuclei.

Potassium in Human Body

- Potassium is an extremely important mineral in the body. As positively charged Kation K^+ that is responsible for transferring information along the nerve system. It controls the muscle system, controls the cell growth, releases the hormones, and controls the production of proteins and the dissemination of carbohydrates.
- The total amount of potassium in the body is self-regulated too much or too little potassium (Hypokalemia) can lead to heart problems. The typical blood potassium level is 0.14 to 0.21 gram per liter (g/L).
- Too much potassium intake will lead to increase in potassium excretion.
- Intake of potassium increases the intake of radioactive ^{40}K .

Foods High in Potassium



Avocado



Banana



Potatoes



Spinach



Beans



Citrus juices



Fish

The ^{40}K in your body

- * *mass of the body* : m_{body}
- * *mass of potassium K in the body* : $m_K = 0.0027 \cdot m_{\text{body}}$
- * *mass of radioactive ^{40}K in the body* : $m_{^{40}\text{K}} = 0.00012 \cdot m_K = 3.24 \cdot 10^{-7} \cdot m_{\text{body}}$

$$40 \text{ g of } ^{40}\text{K} \equiv 6.023 \cdot 10^{23} \text{ atoms}$$

$$m_{^{40}\text{K}} = 5.67 \cdot 10^{-7} \cdot m_{\text{body}} [\text{g}] \equiv \frac{6.022 \cdot 10^{23} \cdot 3.24 \cdot 10^{-7} \cdot m_{\text{body}}}{40} [\text{particles}] = N_{^{40}\text{K}}$$

$$\frac{N_{^{40}\text{K}}}{m_{\text{body}}} = 4.88 \cdot 10^{15} [\text{particles} / \text{g}]$$

to calculate $N_{^{40}\text{K}}$, you need the body mass m_{body} in gramm.

$$\text{for } 80 \text{ kg body} : N_{^{40}\text{K}} = 3.9 \cdot 10^{20} [\text{particles}]$$

What is the absorbed lifetime body dose

Average lifetime is 70 years

Body mass 80 kg

1 eV = $1.602 \cdot 10^{-19}$ J

Average decay energy 0.5 MeV
from γ and β decay channels

Close to dangerous
dose level

$$\text{Dose} \quad D = \frac{E_{\text{absorbed}}}{m_{\text{body}}} = t \cdot A(^{40}\text{K}) \cdot \frac{E_{\text{avg}}}{m_{\text{body}}}$$

$$\text{Activity} \quad A(^{40}\text{K}) = \lambda \cdot N(^{40}\text{K}) = \frac{\ln 2}{T_{1/2}} \cdot 3.9 \cdot 10^{20}$$

$$A(^{40}\text{K}) = \frac{0.69}{1.25 \cdot 10^9 \cdot 3.14 \cdot 10^7} \cdot 3.9 \cdot 10^{20} = 6860 \text{ Bq}$$

$$D = 70 \cdot 3.14 \cdot 10^7 \text{ s} \cdot 6869 \text{ Bq} \cdot \frac{0.5 \text{ MeV}}{80 \text{ kg}} = 9.42 \cdot 10^{16} \frac{\text{eV}}{\text{kg}}$$

$$D = 0.0151 \frac{\text{J}}{\text{kg}} = 0.0151 \text{ Gy} = 15.1 \text{ mGy}$$

Annual dose is: 215 μGy ; 30 times higher than the dose from the ^{14}C and ^3H radioactivity in the human body!

Average numbers from literature

Nuclide	Total Mass of Nuclide Found in the Body	Total Activity of Nuclide Found in the Body	Daily Intake of Nuclides
Uranium	90 μg	1.1 Bq	1.9 μg
Thorium	30 μg	0.11 Bq	3 μg
Potassium 40	17 mg	4.4 kBq	0.39 mg
Radium	31 pg	1.1 Bq	2.3 pg
Carbon 14	22 ng	3.7 kBq	1.8 ng
Tritium	0.06 pg	23 Bq	0.003 pg
Polonium	0.2 pg	37 Bq	\sim 0.6 fg

The highest activities come from ^{40}K and ^{14}C , the remaining activity in the body material is two to three order of magnitude smaller. However, Uranium, Thorium, Radium, and Polonium are alpha emitters which have a larger energy deposition and a much larger damage factor $Q=20$. This will increase the effective dose deposited into the body system.

Drinking Water

Radioactive materials are contained in all water sources, due to natural solution of minerals in water – Mineral Water!

They cannot be removed chemically nor is that desirable since minerals provide a certain level of taste.



The radioactivity of ^{238}U in water

Uranium and thorium is a natural component of dissolved minerals in water. There are substantial local variations which trace the variations in the geological mineral patterns. Legal requirements limit the ^{238}U content to $10\mu\text{g}/\text{l}$.

$$N(^{238}\text{U}) = \frac{10 \cdot 10^{-6}}{238} \cdot 6.022 \cdot 10^{23} = 2.53 \cdot 10^{16} \text{ particles } / \text{ l}$$

$$A(^{238}\text{U}) = \lambda \cdot N(^{238}\text{U}) = \frac{\ln 2}{4.5 \cdot 10^9 \cdot 3.14 \cdot 10^7} \cdot 2.53 \cdot 10^{16} = 124 \text{ mBq } / \text{ l}$$

$$D(^{238}\text{U}) = n \cdot \frac{E}{m} \cdot A(^{238}\text{U}) = 14 \cdot \frac{3.5 \text{ MeV}}{80 \text{ kg}} \cdot 0.124 \text{ Bq } / \text{ l} = 0.0762 \frac{\text{MeV}}{\text{kg s l}}$$

$$D(^{238}\text{U}) = 1.22 \cdot 10^{-14} \frac{\text{J}}{\text{kg s l}} = 1.22 \cdot 10^{-14} \frac{\text{G}}{\text{s l}}$$

with $n = 14$, $E = 2.5 \text{ MeV}$, $m = 80 \text{ kg}$, $1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$

Annual Dose

$$D(^{238}\text{U}) = 0.382 \frac{\mu\text{Gy}}{\text{l}}$$

for 1 liter of water; if a person drinks $\frac{1}{2}$ liter per day the total annual Dose is $68 \mu\text{Gy}$! If you take the effective Dose $H = 20 \cdot D = 1.4 \text{ mSv}$.

Body Excrements

There is a balance between the up-take of chemical elements with food and drinks and the defecation process. Overabundances of most elements are being discharged. That includes also the radioactive components following the same physiological processes of the digestive system. The elemental distribution in solid and liquid excrements differs which means that solid and liquid excrements are loaded with different level of radioactive waste!

The daily average on solid excrements ranges between 150 g and 270 g with 70% to 80% water content. Organic materials are 21.6% , solid carbon content is 50%, 5% calcium, 4% phosphorus, 2% potassium.

The deposited amount of ^{40}K is: $3.6\text{-}6.5 \cdot 10^{-4}\text{g}$ per day; that translates into deposited activity of 95-172Bq per day.

Uranium has no body function, on average the human uptake is $2\mu\text{g}/\text{day}$, 98% is excreted, 2% end up in hair.

The deposited amount of ^{238}U is: $1.96 \cdot 10^{-6}\text{g}$ per day; that translates into a deposition activity of 0.024 Bq per day.



Radioactivity Deposition

Urine has a water content of 95%, solid material content is about 70 g/day containing 4% of potassium with 0.0012% ^{40}K , which corresponds to 0.34mg of ^{40}K . (The ^{14}C content is negligible).

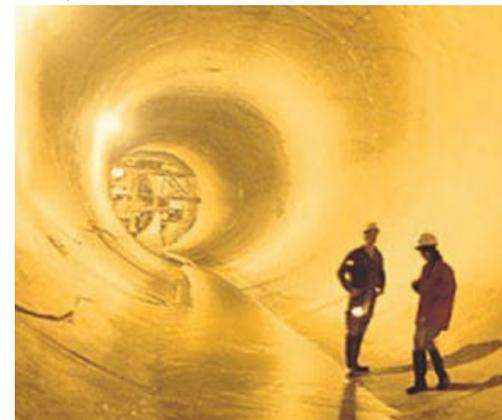
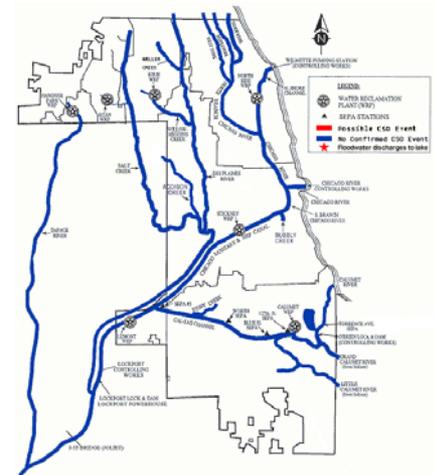
$$N(^{40}\text{K})/d = \frac{70\text{g} \cdot 0.04 \cdot 0.00012}{40\text{g}} \cdot 6.022 \cdot 10^{23} = 5 \cdot 10^{18} \text{ particles} / d$$

$$A(^{40}\text{K}) = \frac{\ln 2}{1.25 \cdot 10^9 \cdot 3.14 \cdot 10^7 \text{ s}} \cdot 5 \cdot 10^{18} = 88\text{Bq per day}$$

The daily radioactivity deposition of a single person into the sewer system is about 222 Bq!

Notre Dame has about 10,000 employees and 12,000 students. The Notre Dame community deposits a daily radioactivity of about 5 Million Becquerel into the ND sewer system.

Chicago has a population of 2.7 million people depositing daily nearly 600 Million Becquerel into the sewer system, the water treatment plant, the Chicago Sanitary and Ship Canal to the Des Plaines River, further to the Illinois River, and eventually into the Mississippi River; 214 billion Bq= 0.214 TBq or 6 Ci annually!



Combined sewer overflows are a water pollution concern for more than 700 cities with combined sewer systems.

Radioactive contamination of O'Hare

O'Hare is the fourth busiest airport in the world with about 77 Million passengers annually.

Assuming that 25% use the restrooms, generates a radioactivity out-put of 4.3 GBq annually, also eventually being deposited into Mississippi River.

To put things in relation!

Mississippi water contains on average 3mg/l on potassium, 0.36 μ g/l on ^{40}K . With an average water flow rate of 320,000 l/s, this translates into a transport rate of 0.12g/s of ^{40}K or 3060 Bq/s. The annual transport of "natural" ^{44}K activity is $9.6 \cdot 10^{11}$ Bq or nearly 1 TBq annually. Human excrements add an appreciable amount of about 25% to the activity load.

