Doses to Public Arising From the Use of Radioisotopes in Radionuclide Laboratories and Hospitals in Finland

Hellstén, Santtu
STUK - Radiation and Nuclear Safety Authority
P.O. BOX 14
FI-00881 Helsinki, Finland

Key Words: radionuclide laboratory, medical isotopes, public exposure, liquid discharge, representative person

Abstract

Radiation doses to the public caused by emissions from radionuclide laboratories and hospitals that use radionuclides in treatment of patients were assessed. Emission limits do not apply to medical use of radioisotopes, so to that extent the results are mainly for informational purposes.
In this study, two kinds of discharges were considered. These were radioactive waste sent to a waste incineration plant and liquid discharges into sewage system. When sent to waste incineration plant, radionuclides can end up in either flue gases discharged into air, or in ash, which is deposited at landfill sites. Liquid discharges enter the waste water system and are separated between processed water and sludge. Doses to both workers and representative persons were assessed. The results obtained are used in updating of regulatory guides.

Introduction

In the study, the radiation doses to the public caused by emissions from radionuclide laboratories and hospitals that use radionuclides in treatment of patients are assessed. The study has been made in part to support renewal of regulations. Emission limits do not apply to medical use of radioisotopes, so to that extent the results are mainly for informational purposes.

In Finland, radionuclide laboratories are exempted from a waste management plan, if the doses caused by the radiation practice to the representative person of the public are less than 10 µSv / year. One of the aims of this study was to determine, as accurately as possible, the emissions [Bq/a], which cause a 10 µSv annual dose. Another goal was to see if nuclide specific exemption levels can be used as a basis for discharge regulations.

Screening calculations are commonly used in assessing the radiation doses caused by gaseous and liquid discharges due to radiation practices. In this study, two kinds of discharges were considered. These were radioactive waste sent to a waste incineration plant and liquid discharges into sewage system. When sent to waste incineration plant, radionuclides can end up in either flue gases discharged into air, or in ash, which is deposited at landfill sites. Liquid discharges enter the waste water system and are separated between processed water and sludge. Doses to both workers and representative persons were assessed. The considered exposure pathways include e.g. direct exposure to flue gas and consumption of affected foodstuff.

The calculation is mainly based on models developed by IAEA. A model by the Swedish Radiation Protection Authority was also applied, specifically when modeling the seepage of radionuclides from a landfill site into ground water.

For the calculation, an Excel-spreadsheet that utilizes macros was developed. The template allows one to calculate the radionuclide concentrations and doses in different situations. The purpose was to achieve results that are as realistic as possible. However, if this was impossible due to e.g. lack of information, a conservative approach was selected. For example, the half life is not always fully taken into account, resulting in an overestimation of radionuclide concentration.

The assessment was done for three cities; Turku, Tampere and Seinäjoki. Cities were selected on the basis that there are a large hospitals that use radioisotopes and different waste treatment systems. For example, in Turku the processed wastewater is discharged into sea, in Tampere into a lake and in Seinäjoki into a river. Although the calculations were based on city-specific information, the model is not restricted to the chosen cities. The exposure pathways assessed are presented in figure 1.

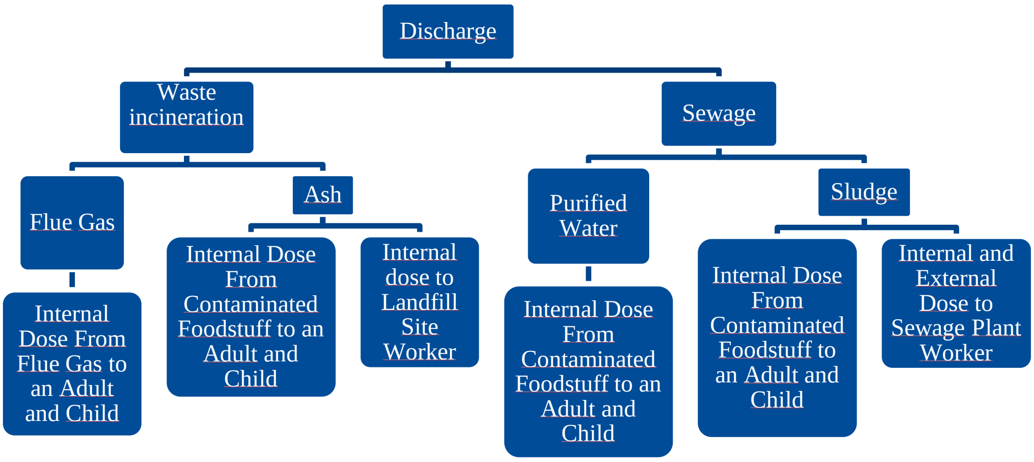

Figure 1. Assessed exposure pathways

Assessed discharges

The hospital discharge data used in this study was from 2006. The radionuclides and the activities used in the central hospitals in Turku, Tampere and Seinäjoki are presented in table 1. These nuclides and activities were used in city specific dose assessments.

Table 1. The radionuclides and their activities used in hospitals in 2006.

	Tampere / TAYS		Turku / TYKS		Seinäjoki / EPSHP	
Nuclide	**MBq**	**Bq**	**MBq**	**Bq**	**MBq**	**Bq**
Cr-51	8,40E+01	8,40E+07				
F-18	8,36E+04	8,36E+10	1,50E+05	1,50E+11		
I-123	1,15E+04	1,15E+10	3,70E+02	3,70E+08	9,84E+03	9,84E+09
I-131	2,39E+05	2,39E+11	2,14E+05	2,14E+11	7,85E+04	7,85E+10
In-111	2,73E+03	2,73E+09	2,09E+03	2,09E+09	1,30E+02	1,30E+08
P-32	8,40E+03	8,40E+09	5,85E+03	5,85E+09	1,04E+03	1,04E+09
Se-75	2,96E+00	2,96E+06	7,37E+00	7,37E+06	1,48E+00	1,48E+06
Tc-99m	9,48E+05	9,48E+11	1,14E+06	1,14E+12	3,36E+05	3,36E+11
Tl-201	1,60E+02	1,60E+08				
Y-90	2,66E+03	2,66E+09				

Further data for radionuclide laboratories in Turku was obtained from the radiation safety licenses. Turku was chosen as an example city because the relatively large number of radionuclide laboratories there. The radionuclides used in four laboratories are presented in table 2. It was assumed in this study that all the activity used in a year will enter the sewage system or be burned in a waste incineration plant. The assumption gives rise to conservative dose estimates.

Table 2. The radionuclides used in four laboratories in Turku.

	H-3	C-14	P-32	S-35	I-125	Ho-166	Ca-45	F-18	P-33	In use [Bq]	In storage [Bq]
Laboratory 1	x	x	x	x	x					2,50E+08	1,00E+09
Laboratory 2	x	x	x	x	x	x				4,20E+07	2,00E+08
Laboratory 3	x	x	x	x	x		x			2,63E+07	2,87E+08
Laboratory 4	x	x	x	x	x			x	x	4,44E+08	4,44E+09

Discharges from a waste incineration plant

The calculation aimed at the very beginning to produce a public dose data. The methology of the dispersion calculation is presented in reference [1]. The dispersion of the flue gas was taken into account from the beginning. Although in the study only undisturbed dispersion was considered, the created Excel-model can also take into account different building profiles and their effects. The half-life of the radionuclides was ignored, which leads to a conservative dose estimate. The dilution model used was the Gaussian plume model [1]. It was assumed that the atmosphere surrounding the flue stack was stable (Gifford-Pasquille class D stability).

When the waste is incinerated, the radionuclides are divided between ashes and the flue gas. The exact ratio depends among other things on the physical and chemical properties of the radionuclide. When possible, the ratio was taken from literature [2]. If no reference was found, full amount of radionuclides was assumed to be present in both ashes and flue gas, thus giving a conservative estimate.

In undisturbed dispersion the flue gas is diluted without interference from e.g. neighboring buildings. This is because the height of the flue stack (H) is high enough compared with any other buildings near. The dispersion can therefore be assumed to happen in accordance with the Gaussian bell curve. The concentration to which the representative person is exposed can be derived from equation (1).

$$C_A = \frac{P_P \times F \times Q_i}{u_a} \qquad (1)$$

in which

C_A is the concentration below wind at *x* m (Bq/m3)

P_P is the portion of time during which wind blows to the direction *p*

u_a is the geometrical average of the wind speed during the year (m/s)

F is a Gaussian diffusion parameter that depends on the height of the stack *H* and distance *x* (m^{-2})

Q is the release rate of the radionuclide (Bq/s)

Waste incineration results in quite a large amount of ash, approximately 20 – 30 % of the original waste mass. In Turku the resulting ash and slag has until 2007 been deposited at the Topinoja landfill site isolated from normal waste. From 2008 fly ash has been sent to a hazardous waste site. The slag is in an interim storage and will be deposited at Topinoja. It is therefore unlikely that the radionuclides contained in fly ash or slag could leach into ground water and foodstuff in significant quantities. In this study, however, leaching was assumed to take place. The assumption clearly leads to a conservative dose estimate to representative persons.

The Swedish Radiation Safety Authority has developed a model to describe the amount of radionuclides leaching into groundwater from a landfill site [3] through an unsaturated layer. The model was used in this study with some alterations. The model is based on two mass balances derived from differential equations and gives the concentration of a given radionuclide in ground water.

The exposure in this scenario is caused by contaminated ground water being consumed and used for vegetable irrigation. In addition, fish caught from a near by river is consumed. The dilution factor between ground water and river water is assumed to be $2{,}5\times10^{-5}$ [4]. The dose received from food and drink depends on both the concentration of radionuclides and the amount consumed yearly. The concentration of radionuclides in ground and vegetables can be obtained from equations (2) and (3):

$$C_{soil} = \frac{d_i\left[1-e^{(-\lambda_e\times t_b)}\right]}{\rho_{soil}\times\lambda_e} \qquad (2)$$

in which

C_{soil} is the concentration of the radionuclide in ground (Bq/kg)

di is the amount of irrigation in a year, di = Cw×Ir in which Cw is the concentration in well water (assumed equal to ground water) (Bq/m3) and *Ir* amount of irrigation during the growth season (m/d)

λ_e is the decay constant of the radionuclide (1/d)

t_b is the duration of the discharge (d)

ρ_{soil} is the density of the soil (kg/m3)

$$C_v = F_v \times C_{soil} \qquad (3)$$

in which

C_v is as above (Bq/kg)

F_v is the transfer factor of the radionuclide between the ground and the vegetable consumed (Bq/kg, dry) per Bq/kg, wet)

The concentration of the radionuclide in river water is obtained with equation (4). It is assumed that concentration in the unsaturated zone of the landfill site is diluted directly into a river.

$$C_r = \frac{F_{aq}}{1000\times U_s} \times f_d \qquad (4)$$

in which

C_r is the concentration in river (Bq/l)

F_{aq} is the flux of the radionuclide from the landfill site to the unsaturated zone (Bq/a)

U_s is the flow of water through the unsaturated zone (m3/a)

f_d is the dilution factor, $2{,}5\times10^{-5}$ (-)

The concentration in edible fish is obtained from the equation (5):

$$C_{fish} = C_r \times BF \qquad (5)$$

in which

C_{fish} is the concentration in fish (Bq/kg)

BF is the transfer factor between water and fish(Bq/kg per Bq/l)

After the relevant concentrations are obtained, the calculation of doses, both internal and external, is a fairly straightforward process. The concentration, the amount consumed / drank / breathed per year and the relevant dose conversion factors are multiplied. The method is widely used in literature, for example in reference [1]. The principle is presented in equation 6.

$$\mathrm{E_{ing,p}} = \mathrm{C_p} \times \mathrm{IR_x} \times \mathrm{DF_{ing}} \qquad (6)$$

in which

$E_{ing,p}$	is the dose received per year from foodstuff p
C_p	is the concentration of the radionuclide in foodstuff p
IR_x	is the consumption of the foodstuff p per year
DF_{ing}	is the internal dose coefficient of the radionuclide in foodstuff p

Discharges from a sewage treatment plant

Radionuclide laboratories can dispose their waste according to the Finnish regulatory guide ST 6.2 "Radioactive wastes and discharges". In addition to radionuclide laboratory discharges, hospitals also discharge radionuclides used in treatment or diagnosis through patient excreta. The concentration of these nuclides in waters depends on the mechanism of dilution. In this study this dilution is modeled using the methology described in reference [1]. In the sewage water treatment plants the radionuclides are divided between the purified water and sludge according to the distribution coefficient K_d. The distribution coefficient gives the ratio of radionuclides that go into the sludge. As with flue gas, the values of K_d were taken from literature [5], when possible. If none was found, it was assumed that all of the radionuclides go into both purified water and sludge, thus giving a conservative dose estimate. The doses estimated are also conservative, because the decay of the nuclides was not always taken into account. Discarges from hospitals are also overestimated because patients are often released before the nuclides have exited their body. Because of this, not all nuclides enter the same waste water treatment plant.

Three different dilution mechanisms for the purified water were considered, based on the selected cities: dilution into river (Seinäjoki), lake (Tampere) and coastal water (Turku). Each dilution process was calculated separately. It was also difficult to get realistic dilution conditions in Seinäjoki because the flow of water in river Seinäjoki varies considerably during one year. The concentrations were calculated with a steady-state assumption taking decay into consideration.

Dilution into river, Seinäjoki

When the discharge from the water treatment plant dilutes in a river, the final concentration is affected not only the discharge rate but also the properties of the river such as total flow of water and the width of the river. If the distance where the concentration is calculated is less than 7 times the width of the river, practically no dilution has taken place. This is taken into account in the Excel macro used for calculation. The half-life of the radionuclides is, however, taken into account to some extent. The concentration when the river water is used from the opposite bank to the discharge point is given in equation (7):

$$\mathrm{C_{w,tot}} = \frac{\mathrm{Q}}{\mathrm{q_r}} \times \mathrm{e}^{\left(\frac{\lambda \quad \times \mathrm{x}}{\mathrm{U}}\right)} = \mathrm{C_t} \qquad (7)$$

in which

$C_{w,tot}$	is the concentration of the radionuclide (Bq/m3)
Q	is the discharge rate of the radionuclide (Bq/s)

q_r is the average flow of the river (m3/s)

λ is the decay constant of the radionuclide (1/s)

x is the distance from the discharge point where the concentration is calculated (m)

U is the average speed of he river flow (m/s)

Dilution into coastal water, Turku

Fishing is assumed to take place near the coast line. Because of this the concentration was only calculated near the coast line. The concentration is obtained from the equation (8):

$$C_{w,tot} = \frac{962U^{0,17}Q}{Dx^{1,17}} e^{\frac{\left(-7,28\times10^{5}U^{2,34}y_0^2\right)}{x^{2,34}}} e^{-\frac{\lambda\times x}{U}} \quad (8)$$

in which

y_0 is the distance between the discharge point and the beach (m)

U is the coastal flow (assumed to be constant 0,1 m/s)

D is the depth of the coastal water (m)

λ is the decay constant of the radionuclide (1/s)

Dilution into a lake, Tampere

In reference [1] lakes are classified into 3 groups depending on their area. In Tampere the lake in question, Pyhäjärvi, is classified as a “small lake”. When calculating the concentration in the lake a steady 30 year discharge was assumed. The concentration is time-dependant, but quickly achieves a constant steady-state. The concentration is obtained from the equation (9):

$$C_{w,tot} = \frac{Q}{q_r+\lambda\times V} \times \left[1 - e^{-\left(\frac{q_r}{V}+\lambda\right)t}\right] \quad (9)$$

in which

q_r is the average flow in the lake (m3/s)

V is the average depth of the lake (m)

t is the time from the beginning of the discharge (s)

λ is the decay constant of the radionuclide (1/s)

The concentration in sludge and ground

When waste water is treated, part of the radionuclides end up in the sludge. The sludge can be used for soil improvement. Some of the radionuclides can therefore end up in foodstuff e.g. grain, milk and meat. The assumption that all of the sludge in used for soil improvement in agriculture is very conservative because in real life the majority of the sludge is used in landscaping. The sludge used for soil improvement is dried during which time the activity decreases. The time chosen in this study was one month, which was considered to be a good approximation. However, the decay was not always taken into account again leading to a conservative dose estimate. The concentration in wet sludge is obtained from equation (10). The decay of radionuclides are taken into account by using a decay term.

$$C_{sludge,wet} = \frac{Q \ \times e^{-\lambda \ \ t_{sludge}}}{m_{sludge,dry}\times X} \times K_d \quad (10)$$

in which

$C_{sludge,wet}$	is the concentration in the wet sludge (Bq/kgWW)
Q	is the rate with which the radionuclide enters the treatment plant (Bq/d)
λ	is the decay constant (1/d)
t_{sludge}	is the residence time of the sludge at the treatment plant [d]
$m_{sludge,dry}$	is the amount of sludge produced (kgDW/d)
X	is the density ratio between wet and dry sludge (assumed 0,25 kgDW / kgWW)
K_d	is the distribution coefficient of the radionuclide between sludge and purified water

The final concentration when the slugde is used for soil improvement is obtained from equation (11). It should be noted that the fact that farming in Finland takes place only in summertime is not taken into account. This leads again to a conservative dose estimate.

$$C_{final} = C_{sludge,wet} \times e^{-\lambda t_{storage}} \tag{11}$$

in which

C_{final}	is the final concentration (Bq/kg)
$t_{storage}$	is the assumed time for drying, assumed 30 d

The calculation of doses received by farmers and their children from the contaminated foodstuff is a straightforward process and is described e.g. in reference [6]. The ingestion parameters, such as e.g. annual consumption of foodstuff, is also taken from reference [6].The exposure from purified water is assumed to be caused by the use of contaminated river water for fishing and irrigation.

Results

The ratio between a discharge that causes a 10microSv annual dose from a waste incinerator plant in Turku and the exemption limit [Council Directive 96/29/Euratom] of the particular radionuclide is presented in figure 2. The exposure caused by the main radionuclides is presented.

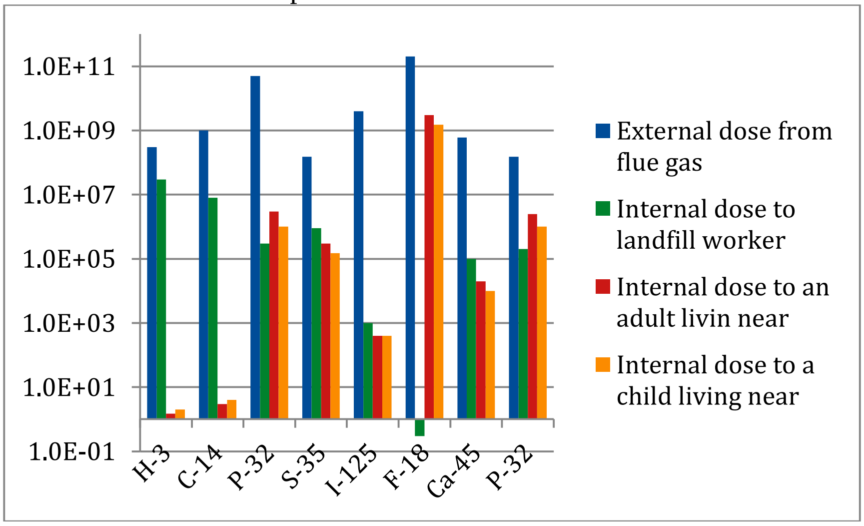

Figure 2. The ratio between an annual discharge that causes a 10microSv annual dose from a waste incinerator plant in Turku and the exemption limit of the particular radionuclide

The doses originating from hospital discharges are presented in tables 4, 5 and 6.

Table 4. The doses received in Turku due to hospital discharges.

Nuclide:	F-18	I-123	I-131	In-111	P-32	Se-75	Tc-99m	
Annual Dose (Sv/a)								**Total Dose: (Sv/a)**
Adult, through purified water	1,8E-129	4,3E-29	9,0E-09	2,7E-12	6,6E-09	1,3E-12	1,4E-47	**1,6E-08**
Child, through purified water	4,4E-129	1,6E-28	2,9E-08	6,4E-12	2,1E-08	2,7E-12	3,3E-47	**5,0E-08**
Water treatment plant worker	3,0E-51	4,4E-14	1,6E-06	1,6E-08	6,9E-08	3,1E-10	3,0E-17	**1,7E-06**
Adult, foodstuff through soil improvement	2,9E-168	1,0E-35	1,8E-11	4,4E-16	3,4E-20	4,6E-13	1,4E-58	**1,9E-11**
Child, foodstuff through soil improvement	2,9E-168	1,0E-35	1,8E-11	4,4E-16	1,5E-19	4,6E-13	1,4E-58	**1,9E-11**
Adult, internal dose from soil improvement (directly)	2,8E-218	4,0E-39	2,4E-07	4,0E-15	1,4E-06	1,8E-09	3,8E-69	**1,6E-06**
Child, internal dose from soil improvement (directly)	7,8E-218	1,6E-38	8,8E-07	1,0E-14	4,6E-06	4,7E-09	1,0E-68	**5,5E-06**

Table 5. The doses received in Seinäjoki due to hospital discharges. .

Nuclide:	I-123	I-131	In-111	P-32	Se-75	Tc-99m	
Annual Dose (Sv/a)							**Annos yht: (Sv/a)**
Adult, through purified water:	4,7E-15	4,7E-06	4,6E-09	8,2E-07	8,6E-11	1,4E-23	**5,5E-06**
Child, through purified water:	1,7E-14	1,5E-05	1,1E-08	2,6E-06	1,7E-10	3,4E-23	**1,8E-05**
Water treatment plant worker:	3,5E-08	4,6E-06	2,3E-08	7,2E-08	2,8E-10	8,6E-09	**4,7E-06**
Adult, foodstuff through soil improvement	8,1E-30	5,1E-11	6,5E-16	3,5E-20	4,0E-13	4,1E-50	**5,2E-11**
Child, foodstuff through soil improvement	8,1E-30	5,1E-11	6,5E-16	1,6E-19	4,0E-13	4,1E-50	**5,2E-11**
Adult, internal dose from soil improvement (directly)	3,2E-33	6,7E-07	5,8E-15	1,4E-06	1,6E-09	1,1E-60	**2,1E-06**
Child, internal dose from soil improvement (directly)	1,3E-32	2,5E-06	1,5E-14	4,8E-06	4,1E-09	3,0E-60	**7,3E-06**

Table 6. The doses received in Tampere due to hospital discharges.

Nuclide:	Cr-51	F-18	I-123	I-131	In-111	P-32	Se-75	Tc-99m	Y-90	
Annual Dose (Sv/a)										**Total Dose: (Sv/a)**
Adult, through purified water	1,E-14	7,E-107	1,E-25	4,E-09	2,E-12	5,E-09	5,E-13	6,E-42	3,E-14	**9,E-09**
Child, through purified water	4,E-14	2,E-106	4,E-25	1,E-08	4,E-12	1,E-08	9,E-13	1,E-41	9,E-14	**3,E-08**
Water treatment plant worker	9,E-10	7,E-20	6,E-08	6,E-06	2,E-07	2,E-07	2,E-10	2,E-07	7,E-08	**7,E-06**
Adult, foodstuff through soil improvement	2,E-13	7,E-137	1,E-29	7,E-11	7,E-15	1,E-19	3,E-13	7,E-49	4,E-24	**7,E-11**
Child, foodstuff through soil improvement	2,E-13	7,E-137	1,E-29	7,E-11	7,E-15	5,E-19	3,E-13	7,E-49	2,E-23	**7,E-11**

Adult, internal dose from soil improvement (directly)	5,E-12	7,E-187	5,E-33	9,E-07	6,E-14	5,E-06	1,E-09	2,E-59	3,E-13	**6,E-06**
Child, internal dose from soil improvement (directly)	1,E-11	2,E-186	2,E-32	3,E-06	2,E-13	2,E-05	3,E-09	5,E-59	1,E-12	**2,E-05**

The doses from laboratory discharges in Turku, Seinäjoki and Tampere are presented in figures 3, 4 and 5. The ratio between the dose that causes 10 microSv annual dose and the dose caused by annual discharge of the exemption limit is presented. As can be seen in the graphs, for Ca-45 not all relevant data for dose calculation was available.

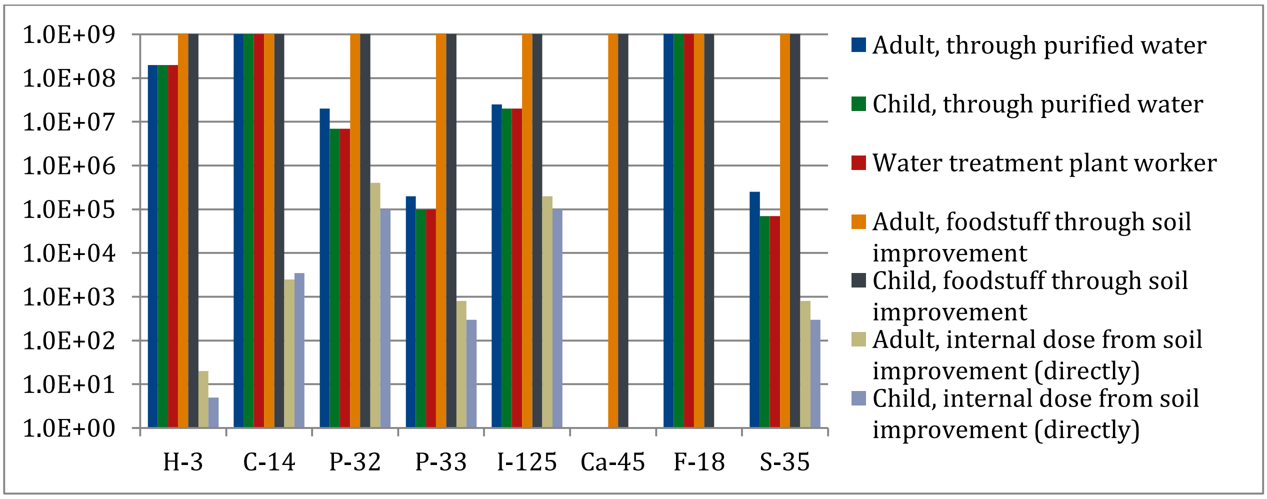

Figure 3. The ratio between a discharge that causes 10 microSv annual dose and annual discharge of the exemption limit. Laboratory discharges from Turku.

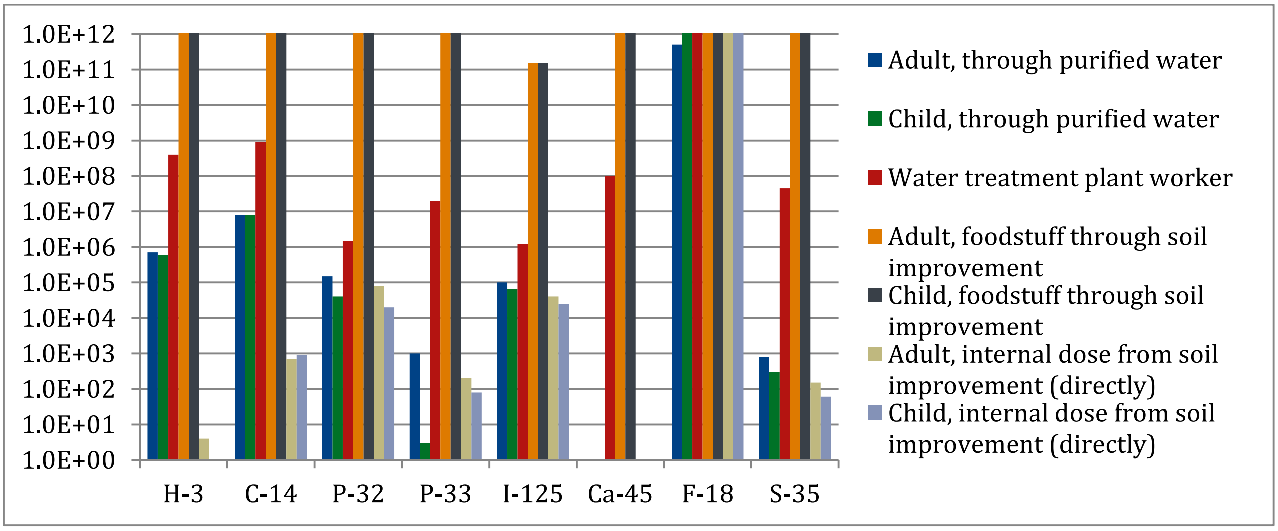

Figure 4. The ratio between a discharge that causes 10 microSv annual dose and annual discharge of the exemption limit. Laboratory discharges from Seinäjoki.

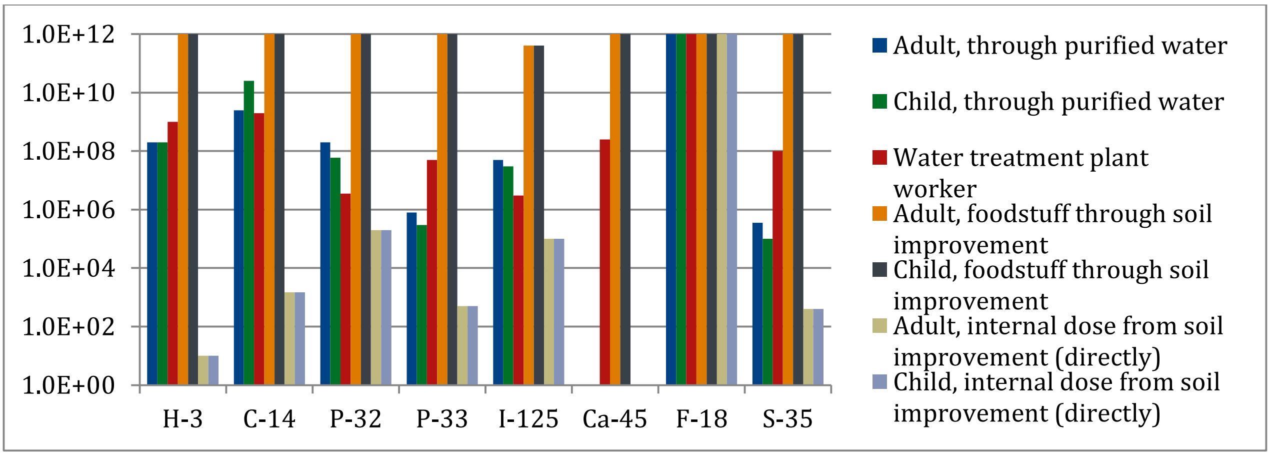

Figure 5. The ratio between a discharge that causes 10 microSv annual dose and annual discharge of the exemption limit. Laboratory discharges from Tampere

Conclusions

In this study the doses to public resulting from the use of radionuclides in laboratories and hospitals in Finland was studied. The specific aim of the study was to achieve a “Bq to Sv” calculation ant to get a basis for regulation renewal. The dose calculation was done as realistically as possible, for example taking dilution into account from the beginning. When insufficient data was unavailable, a conservative approach was selected. For example the effect of decay was in some cases ignored. The results presented in this do not cover the entire study, the entire results will be published by STUK in 2012.

The results presented in figures 2, 3, 4 and 5 show that there are large nuclide specific differences between a 10 microSv discharge and exemption limit discharge with direct internal doses from soil improvement giving the smallest ratio. Generally, the ratio is above 1000. Given the conservative assumptions made and e.g. the fact that the flow of H-3 and C-14 in ecosystems is a highly complex issue, it can be said that the use exemption limit as a basis of discharge regulations is justified.

The doses caused by hospital discharges are not regulated. It can be seen from tables 4, 5 and 6 that the doses are, however, well within the 10 microSv per year limit with some exceptions. The biggest doses are generally caused by I-131 and P-32. Given the conservative nature of the dose scenarios, the real doses are much smaller.

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