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Estimation of the Years Of Lost Life (YOLL) as a consequence of the nuclear fuel cycle

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2001-03-06

1 Introduction

Production of energy by nuclear power gives rise to releases of radionuclides to air and water during the different steps in the nuclear chain. This report will give an overview of the consequences from such production taking releases from the different steps into account. The main objective is to show years of life lost (YOLL) due to radioactive releases generated in the nuclear energy production. In contrast to many other pollutants the radionuclides affect only man's radiation environment. The amounts are very low if looking on masses so radionuclides do not e g influence chemical conditions (except for releases of coolant water which may change the temperature of the recipient). One advantage is on the other hand that their effects are additive, so independent of radionuclide or external or internal exposure their resulting effect to man can easily be quantified.

In order to estimate the releases of radioactive nuclides to different ecological systems in the whole nuclear cycle one has to consider all steps taken from the production of the fuel, burning up of the same and finally the deposition of the generated waste. In the following report the releases and corresponding dose consequences are outlined for some of the steps. The most comprehensive publications in the field can be found in Refs 1 and 2.

2 Radionuclides in the nuclear fuel cycle

Important steps included in the nuclear fuel cycle with corresponding releases of radionuclides are presented in Table 1 reproduced from Ref 1.

Table 1
Radioactive releases from the nuclear fuel cycle.

Mining and milling	
- gaseous:	Rn-222, U-234, U-235, U-238
- liquid:	U-234, U-235, U-238
Conversion, enrichment, fuel fabrication	
- gaseous:	U-234, U-235, U-238
- liquid:	U-234, U-235, U-238
Reactor normal operation	
- gaseous:	H-3, C-14, Co-58, Co-60, Kr-85, I-131, I-133, Xe-133, Cs-134, Cs-137
- liquid:	H-3, Mn-54, Co-58, Co-60, Ag-110m, Sb-124, I-131, Cs-134, Cs-137
Reprocessing	
- gaseous:	H-3, C-14, Kr-85, I-129, I-131, I-133, Pu-238, Pu-239
- liquid:	H-3, C-14, Co-60, Sr-90, Ru-106, I-129, Sb-125, Cs134, Cs-137, U-238, Pu-238, Pu-239, Am-241, Cm244
Low level waste disposal	
- solid:	H-3, C-14, Co-60, Ni-59, Ni-63, Sr-90, Zr-93, Nb-94, Mo-93, Tc-99, Pd-107, I-129, Cs-135, Cs-137, U-234, U-238, Pu-239, Pu-241, Am-241, Np-237
High level waste disposal	
- solid:	Se-79, Zr-93, Tc-99, Pd-107, Cs-135, Th-229, U-233, Np-237, Am-241

The radionuclides can be grouped in different classes due to their origin and behaviour in the biosphere. The releases of radionuclides vary also considerable between different facilities.

Noble gases dominate the releases from normal operation of nuclear power plants. They are all relatively short-lived and give only rise to external exposure. The stack height and dispersion conditions determine the concentrations in air from which doses are calculated. Other radionuclides like fission and activation products are also related to normal operation of NPPs but also to the waste.

2.1 Exposure calculations

The exposure to man due to radioactive irradiation from a nuclear facility may be divided into two different categories. Firstly, doses to workers in the facility (a mine or a NNP) mainly due to body-external exposure and secondly, doses to the public due to air- and waterborne releases of radionuclides from the facility. Public exposure may also be due to a leakage of radionuclides from a repository for radioactive waste.

Doses to workers due to external irradiation within a facility are continuously monitored and registered. Doses to the public may be calculated from measured air- and waterborne releases of radionuclides or from estimates of releases from a repository. The turnover of radionuclides in the biosphere after a release is illustrated in Figure 1.

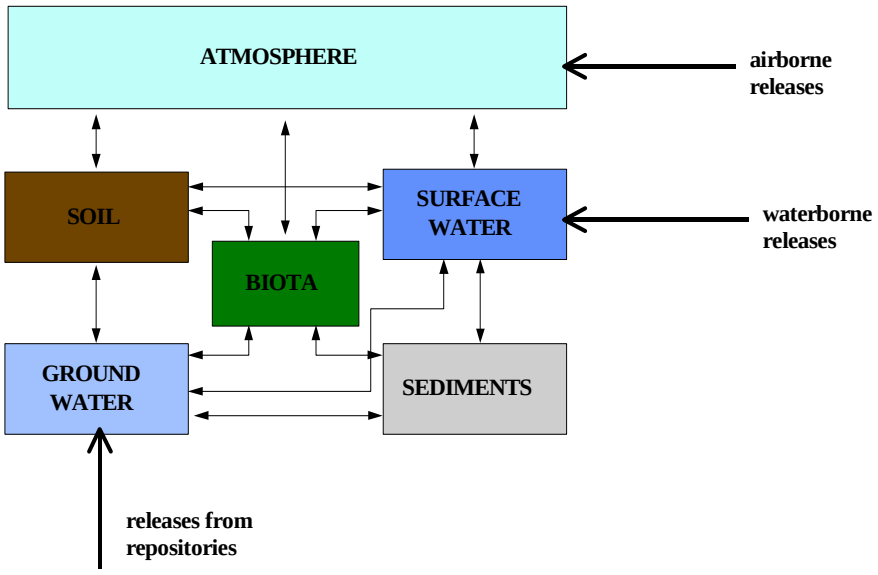

Figure 1
The turnover of radionuclides in the biosphere after a release, illustrated with compartments for the different media of the biosphere.

Once the radionuclides have been released into the biosphere and started to circulate within it, the turnover pathways and processes may be seen as principally the same, independent on into which medium the primary release occurs. Man may be exposed to the released radionuclides via external irradiation, intake of food and water or inhalation. For a more detailed description of turnover of radionuclides in the biosphere and exposure pathways see, Bergström & Cedervall, 1999, Bergström *et al*, 1999, BIOMOVS 1, 1997.

3 Estimation of Years Of Lost Lives (YOLL)

In order to calculate Years Of Lost Lives shortly called YOLL it is necessary to estimate the number of deaths due to radiation by some method. Normally the collective dose is used as basis. In Table 2, reproduced from Ref 1, Page 56, the risk factors to get fatal cancers are given. If a linear and not a threshold model is used to calculate the number of fatal cancers, overestimated values are obtained.

Table 2

	Occurrence (per manSv)		
Population	**Fatal cancers**	**Non-fatal* cancers**	**Severe hereditary effects**
Public	0.05	0.12	0.01
Workers	0.04	0.12	0.006

* Rounded values.

It is necessary to point out that it is still not clear how the dose-health effect relation looks like in the low dose region. If the dose obtained from the natural sources don't give any statistical fatal cancers, then no cancers would be the follow of releases of activity from nuclear power plants in normal operation.

3.1 YOLL attributed to natural irradiation

Among the Swedish population would if a linear model is used, annually, $0.05 \cdot 8.9 \cdot 10^{6} \cdot 2.4 \cdot 10^{-3} = 1068$ individuals in average obtain fatal cancers attributed to natural sources, see Table 3, which in turn will cause annually $1068 \cdot 24 = 25632$ YOLL, during 50 years $1.2816 \cdot 10^{6}$ YOLL and $2.5632 \cdot 10^{8}$ YOLL! estimated over 10000 years assuming constant population. The figure 24 means that for each cancer death 24 years of life are lost (see Ref 2, page 152).

Table 3
Annual effective doses to adults from natural sources.
(Reproduced from Ref.3, Table 7, Page18)

Source of exposure	Annual effective dose (mSv)	
	Typical	Elevated[a]
Cosmic rays	0.39	2.0
Terrestrial gamma rays	0.46	4.3
Radionuclides in the body (except radon)	0.23	0.6
Radon and its decay products	1.3	10
Total (rounded)	2.4	-

[a] The elevated values are representative of large regions. Even higher values occur locally

4 Mining and milling

Mining is carried out by two general methods.

a Open-pit mining, in which the top layer of overburden is removed and the extraction operation occurs in a huge open air pit

b Underground mining, where tunnels are dug for the pro extraction process to occur underground.

Milling is the process of converting the uranium (U) ore to a concentrated form of the U called ”yellow cake”, which contains 70 - 75 % U. The amount of ore processed depends naturally on the natural U concentration in the ore. Milling is usually carried out near the mine sites to avoid the need for transporting large amounts of material. It may be worth to mention that normally 22 tonnes of mineral U are needed to produce 1 TWh in a 900 MWe Pressurised Water Reactor (PWR).

4.1 Source term attributed to mining and milling

Radon is the most important radionuclide released from Uranium mines. The production-weighted average of the normalised radon release is 300 GBq/tonne of Uranium Oxide. Since 250 tonnes Uranium Oxide (Table 4, reproduced from Ref.1, Table 16) are required to produce 1 GWa of electrical energy the average radon release normalised to the generation of electrical energy is approximately 75 TBq/GWa or 8.5 MBq/GWh (Table 5, reproduced from Ref 3, Table 4.2).

Table 4
Estimated uranium and fuel requirements to generate 1 GWa of electrical energy.

Reactor type	Amount required for 1 GW year or GW_a)			
	Natural uranium (t)	Uranium oxide[a] (t)	Enrichment (SWU)[b]	Fuel (t)
LWR[c]	220	260	130000	37
HWR[d]	180	210	-	180
Magnox[e]	330	390	-	330
AGR[f]	220	260	130000	38

a Derived from the amounts of natural uranium using a U_3O_8 heavy metal ratio of 1:18.
b Separative work units.
c Assuming average fuel irradiation of 30 GWd/tU (thermal energy), thermal efficiency of 33 % and an average fuel enrichment of 3 % with 0.25 % tails.
d Assuming a fuel irradiation of 7.3 GWd/tU (thermal energy) and a thermal efficiency of 30 %.
e Assuming a fuel irradiation of 4.5 GWd/tU (thermal energy) and a thermal efficiency of 26 %.
f Assuming an average fuel irradiation of 24 GWd/tU (thermal energy) a thermal efficiency of 40 % and average enrichment of 2.7 % and tails of 0.25 %.

Table 5
UNSCEAR source term for mining and milling.

Radionuclide	Mine	Mill	Mill tailings	Total	Total
	(MBq/TWh)	(MBq/TWh)	(MBq/TWh)	(MBq/TWh)	(MBq/year)
Rn-222	$8.5 \cdot 10^6$	$3.4 \cdot 10^5$	$2.3 \cdot 10^6$	$1.1 \cdot 10^7$	$5.1 \cdot 10^8$
U-234	-	-	-	$4.5 \cdot 10^1$	$2.1 \cdot 10^3$
U-235*	-	-	-	1.9	$8.9 \cdot 10^1$
U-238	-	-	-	$4.5 \cdot 10^1$	$2.1 \cdot 10^3$

* Estimated from the amount of U-234.

During mining and milling operations, there are atmospheric (particles and radioactive gases released from the ore), and also liquid releases. Additional liquid radioactive releases result from the water that runs-off of the stock-piled solid ore wastes. Unlike other stages of the fuel cycle, the releases from this stage do not occur from a concise monitored point source, and therefore it is difficult to define a source term. The mines are spread over a large area and the dusts and gases are released from stacks used to vent the underground tunnels. A lot of the dust is generated from the various above ground activities and movement of material on the site. Liquid is pumped from different locations underground. The vicinity around mines is area of high natural background due to the uranium in the ore. For this reason, it is difficult to separate the exposures due to the mining activities from natural background.

For the calculation required by the assessment, a more precise source term is needed. Because there is often no measure point of gaseous releases from a site, the assessment for this stage relies on the average source term proposed by the UNSCEAR 1993 report (Ref 3).

4.2 Dose estimates for mining and milling

According to the model used in the UNSCEAR report from 1988 (Ref 4) the total collective effective dose per unit electrical energy generated for a reference mine and mill site plus abandoned tailing piles is estimated to be 1.5 manSv/GWa (Ref 3, Page 106). In the model is assumed a population density of 3/km^2 out to 100 km and 25/km^2 at (100-2000) km. The dose is mainly attributed to radon release. Contributions from other nuclides are presented in Table 6, reproduced from Ref 3, Table 22, Page 137.

Table 6
Normalised releases of radionuclides in airborne effluents and collective doses to the public and workers, from a model uranium mine and mill[a].

Radio-nuclide	Normalised release [GBq (GW a)$^{-1}$)]				Collective dose per unit release (man Sv TBq^{-1})	Normalised collective effective dose [man Sv (GW a)$^{-1}$]			
	Mine	Mill	Mill tailings			Mine	Mill	Mill tailings	
			In operation	Abandoned				In operation	Abandoned
Pb-210		0.02			1		0.00002		
Po-210		0.02			1		0.00002		
Rn-222	75000 (250-500000)	3000	20000 (200-86000)	1000[b] (7-6700)	0.015	1.1 (0.0037 -7.3)	0.045	0.3[c] (0.003-1.3)	150[d] (1-1000)
Ra-226		0.02			0.6		0.00001		
Th-230		0.02			30		0.0006		
U-234		0.4			8		0.003		
U-238		0.4			7		0.003		

a Normalised emissions in liquid effluents (0.01 for Po-210, Pb-210 and Th-230; 0.02 for Ra-226; 0.3 for U-234 and U-238) contribute negligibly to the collective dose.

b Annual activity released; the rate of activity is assumed to remain constant over more than 10000 years.

c Dose commitment corresponding to a five-year release.

d Dose commitment corresponding to a 10000-year release.

The collective effective dose per unit electrical energy generated attributed to releases of radon from abandoned tailings piles is estimated to be delivered at a rate of 0.015 manSv/GWa per year due to 1 TBq annual release. The rate of release as a function of time is assumed to be constant, and given the very long radioactive half-lives of the radon precursors, the normalised collective effective dose committed is proportional to the assumed duration of the release. Taking this period to be 10000 years for the sake of illustration, the result is an estimated 150 manSv/GWa. This figure is naturally highly dependent on future management practices; it's estimated range is from 1 to 1000 manSv/GWa.

4.3 YOLL for mining and milling

According to the discussion in the section before the annually YOLL/GWa from mining and milling would be $0.015 \cdot 0.05 \cdot 24 = 0.018$ and taken over 10000 years it will be 180 YOLL.

5 Uranium fuel Fabrication

For PWRs (Pressurized Water Reactors) and BWRs (Boiling Water Reactors) the uranium ore concentrate produced at the mills need further to be processed through three steps: Conversion, Enrichment and Fabrication. During these processes some effluents of activity appear. It is mainly emissions of long-lived radionuclides such as U-isotopes like U-234, U-235 and U-238 along with Th-234 and Pa-234m, which are the short-lived decay products of U-238. The long half-life of Th-230 prevents the activity build-up of any other radionuclide of the U-238 series. The solid wastes arising during uranium fuel fabrication are trivial in quantity by comparison with those from the uranium mines and mills.

The normalised effluent discharges from model fuel conversion, enrichment and fabrication facilities, is presented in Table 7, reproduced from UNSCEAR, 1993 (Ref 3, Table 24, Page 138).

Table 7
Normalised releases of radionuclides from model fuel conversion, enrichment and fabrication facility.

Radio-nuclide	Atmospheric discharges [MBq (GW a)$^{-1}$) from]			Aquatic discharges [MBq (GW a)$^{-1}$) from]		
	Conversion	Enrichment	Fabrication	Conversion	Enrichment	Fabrication
Ra-226				0.11		
Th-228	0.022					
Th-230	0.4					
Th-232	0.022					
Th-234	130	1.3	0.34			170
U-234	130	1.3	0.34	94	10	170
U-235	6.1	0.06	0.0014	4.3	0.5	1.4
U-238	130	1.3	0.34	94	10	170

5.1 Dose estimates for fuel fabrication

Collective doses resulting from the airborne releases were estimated for the model facility specified in the UNSCEAR 1988 report (Ref 3), with a constant population density of 25/km^2 out to 2000 km. The normalised collective effective dose is estimated to be 0.0028 manSv/GWa with

inhalation as the most important pathway of exposure. The collective doses due to liquid discharges are much less than those from airborne discharges, as was assessed in the UNSCEAR 1982 report (Ref 5) for the same relative releases.

5.2 YOLL attributed to Uranium fuel fabrication

Since the annually estimated normalised collective dose due to fuel fabrication is $2.8 \cdot 10^{-3}$ manSv/GWa, the YOLL/GWa would be $2.8 \cdot 10^{-3} \cdot 24 \cdot 0.05 = 3.36 \cdot 10^{-3}$ and taken over the assuming life time of a nuclear plant of 50 years 0.168 YOLL are obtained.

6 Reactor operation

In the UNSCEAR report, 1993 comprehensive tables of data are compiled concerning releases of radioactive nuclides from all reactors in the world. Using a dispersion model adapted and fitted to European situation the total collective effective dose from all reactors in the world up to 1990 has been estimated to about 3665 manSv (Table 8, reproduced from Ref 3, Page 192). This result should be compared with the annual effective dose to adults due to exposition from the natural sources, 2.4 mSv (Table 3, reproduced from Ref 3, Page 18). If this value is multiplied with the average number of the world population during the last 20 years, $5.0 \cdot 10^9$ a value of $2.4 \cdot 10^8$ manSv is obtained. This means that the figure 3665 manSv given above is negligible compared to $2.4 \cdot 10^8$ manSv.

Table 8
Collective effective dose from radionuclides released from reactors worldwide.

Year	Collective effective dose (man Sv)							
	Noble gases	Tritium	C-14	I-131	Particulates	Tritium (liquid)	Other (liquid)	**Total**
Before 1970	38	5.7	19	0.30	1.4	0.28	5.3	**70**
1970	18	2.0	6.3	0.13	0.61	0.08	1.3	**28**
1971	41	5.1	13	0.29	1.2	0.16	2.1	**63**
1972	62	7.4	19	0.44	1.7	0.23	3.0	**94**
1973	78	15	34	0.57	2.3	0.40	3.3	**133**
1974	96	17	40	0.70	3.0	0.48	4.0	**161**
1975	25	15	45	2.3	3.3	1.3	1.6	**94**
1976	33	18	57	3.0	4.3	1.5	1.8	**119**
1977	36	21	65	3.2	4.6	1.9	2.0	**133**
1978	47	28	85	4.2	6.1	2.3	2.2	**175**
1979	53	33	99	4.7	6.7	2.5	2.3	**201**
1980	16	41	107	0.32	6.4	2.5	1.5	**176**
1981	18	45	123	0.39	7.2	2.8	1.6	**198**
1982	20	44	127	0.43	7.9	3.0	1.7	**205**
1983	22	57	155	0.53	8.5	3.6	1.9	**249**
1984	26	64	177	0.57	10	4.1	2.1	**283**
1985	6.9	52	156	0.15	3.7	5.3	0.62	**225**
1986	6.6	59	164	0.14	3.7	5.8	0.62	**240**
1987	7.5	64	182	0.16	4.1	6.3	0.65	**264**
1988	7.9	67	192	0.17	4.4	6.8	0.71	**279**
1989	8.0	65	190	0.17	4.5	6.8	0.72	**275**
Total	**668**	**724**	**2055**	**23**	**95**	**58**	**41**	**3665**

Table 9
Installed and net electrical power effect in Swedish NPPs.

Power of the NPPs in Sweden	Type	Capacity (MW)	Net electrical power (MWe)	Sum of each NPP (MWe)
Barsebäck 2	BWR	615	500	0.500
Ringhals 1	BWR	860	835	0.835
Ringhals 2	PWR	917	875	2.705
Ringhals 3	PWR	960	915	
Ringhals 4	PWR	960	915	
Oskarshamn 1	BWR	465	360	1.76
Oskarshamn 2	BWR	630	480	
Oskarshamn 3	BWR	1200	920	
Forsmark 1	BWR	1006	968	3.095
Forsmark 2	BWR	1006	969	
Forsmark 3	BWR	1200	1158	
Total PWR		**2837**	**2705**	
Total BWR		**6982**	**6190**	

6.1 Occupational exposure at Swedish NPPs

in Ref 6 the collective dose at Ringhals and Forsmark is estimated at $2.5 \cdot 10^{-4}$ and $1.4 \cdot 10^{-4}$ manSv/GWh, respectively. The total electrical effect in the Swedish NPPs is summarised in Table 9. The average annual collective dose measured and estimated for workers in the Swedish NPPs is summarised in Table A.2 in Appendix A.

The results presented there show that the average annual collective dose to workers is 14.33 manSv. During 50 years it means about 716 manSv. This in turn means $716 \cdot 0.05 \cdot 24 = 859$ YOLL during 50 years.

6.2 Dose estimates for the public around Swedish NPPs

In Sweden there are four sites for nuclear power stations, Barsebäck(1), Oskarshamn(3), Forsmark(3) and Ringhals(4). There are 3 PWR at Ringhals and the other are of BWR type.

The average annual individual doses estimated at Ringhals 1 (BWR) attributed to airborne releases are $1.4 \cdot 10^{-5}$ Sv and for the three PWR stations $1.1 \cdot 10^{-7}$ Sv. At Forsmark the result is $3.9 \cdot 10^{-7}$ Sv. The committed annual effective dose as a consequence of water borne releases at Ringhals is $2.5 \cdot 10^{-7}$ Sv. The corresponding figure for Forsmark is $8.4 \cdot 10^{-8}$ Sv. These results are taken from Ref 6. Similar results are obtained for Oskarshamn and Barsebäck (Ref 7). These values should be compared to the annual individual dose attributed to natural sources, $2.4 \cdot 10^{-3}$ Sv mentioned above (see Table 3).

In practise most of the source terms, i.e. releases to air and water are continuously monitored except for some specific radionuclides like C-14. After release the radionuclides are dispersed in air and water while they are taken up in the food web leading to exposure to man, see Figure 1. It is important to point out that the consequences from radioactive releases are more or less based on models or assumptions, because of the low levels, which are hard to detect.

Concerning the dose estimates attributed to releases of activity in normal operation it is necessary to pay attention to four special nuclides:

H-3, C-14, Kr-85 and I-129. The reason to this is that these nuclides are globally dispersed. Furthermore two of them have very long half-lives. This means that one has to estimate the collective dose for a very long time in the future. Four special global models have been used for that purpose and are described in Ref 1.

Tables 10a and 10b present a summary of doses estimated for a time period of 100000 years due to a unit release of 1 MBq per year.

Table 10a
Collective effective dose (manSv/MBq) for the release of 1 MBq of H-3 and Kr-85.

	H-3		Kr-85
Time after release	Ocean	Air	Air
10	$2.86 \cdot 10^{-11}$	$9.40 \cdot 10^{-9}$	$4.83 \cdot 10^{-11}$
20	$3.96 \cdot 10^{-11}$	$9.41 \cdot 10^{-9}$	$6.63 \cdot 10^{-11}$
30	$4.26 \cdot 10^{-11}$	$9.42 \cdot 10^{-9}$	$8.13 \cdot 10^{-11}$
100	$4.46 \cdot 10^{-11}$	$9.42 \cdot 10^{-9}$	$9.3 \cdot 10^{-11}$
100000	$4.46 \cdot 10^{-11}$	$9.42 \cdot 10^{-9}$	$9.3 \cdot 10^{-11}$

Table 10b
Collective effective dose (manSv/MBq) for the release of 1 MBq of I-129 and C-14.

	I-129		C-14
Time after release	Ocean	Air	Air
10	$2.3 \cdot 10^{-7}$	$8.7 \cdot 10^{-5}$	$5.7 \cdot 10^{-6}$
100	$3.3 \cdot 10^{-7}$	$1.2 \cdot 10^{-4}$	$1.26 \cdot 10^{-5}$
1000	$6.3 \cdot 10^{-7}$	$2.0 \cdot 10^{-4}$	$3.26 \cdot 10^{-5}$
10000	-	-	$9.26 \cdot 10^{-5}$
100000	$6.6 \cdot 10^{-5}$	$5.5 \cdot 10^{-4}$	$1.42 \cdot 10^{-4}$
∞	$1.7 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$	-

The calculated collective dose attributed to releases of radionuclides from Swedish NPPs is presented for the years 1995 – 1998 (Refs 7 - 9) see Appendix A, Table A.2.

It is, as mentioned above, necessary to distinguish between C-14 and other nuclides.

Appendix A, Table A.1, is a summary of results reproduced from Refs 7 - 9.

It is observed that the collective dose contribution comes to 99.9 % from C-14. This conclusion is further emphasized by the results presented in Table 11 (reproduced from Ref 3, Table 51, p 199).

Table 11
Normalized collective effective dose from globally dispersed radionuclides for a time period of 10 000 years.

Radionuclide	Normalized activity released [TBq (GW a)$^{-1}$]			Collective dose per unit release (manSv TBq^{-1})	Normalized collective dose [manSv (GW a)$^{-1}$]
	Reactors[a]	Reprocessing plant[b]	Total[c]		
H-3	71	684[d]	98	0.0012[e, f]	0.09
C-14	0.52	2.54	0.62	85[g]	53
Kr-85		12300	490	0.0002[f]	0.1
I-129		0.038	0.0015	4[g]	0.006
Total					**53**

a Normalization for total energy generated.
b Normalization for fuel reprocessed.
c Normalization for total energy generated; the contribution from reprocessing is weighted according to the fraction of fuel reprocessed (0.04).
d Release to sea: 643 TBq (GW a)$^{-1}$ remainder released to air.
e For release to air or fresh water; less by a factor of 10 for release to sea.
f For world population of $5 \cdot 10^9$ at time of release.
g For world population of 10^{10}.

The collective effective dose commitment at Ringhals, due to releases of activities, except for C-14, is calculated to be $4.8 \cdot 10^{-6}$ manSv per GWh and for Forsmark $1.5 \cdot 10^{-5}$ manSv per GWh. (Ref 6). The corresponding collective doses for C-14 integrated over 500 years are $5.2 \cdot 10^{-4}$ and $6.8 \cdot 10^{-4}$ manSv/GWh at Ringhals and Forsmark, respectively (Ref 6).

If the same method is used to estimate the number of cancer deaths due to releases at Ringhals and Forsmark we obtain 0.007 and 0.02 cancer deaths annually respectively. Over 50 years this means only 1 case of fatal cancer as a follow of releases from the two power stations.

6.3 YOLL attributed to normal releases of activities from Swedish NPPs

According to Ref 6 it is estimated that the normalised collective dose attributed to airborne releases from Ringhals and Forsmarks NPPs are $4.8 \cdot 10^{-6}$ manSv/GWeh and $1.5 \cdot 10^{-5}$ manSv/GWeh, respectively.

Since the net electrical powers at Ringhals NPPs are 2.705 GWe (PWR) and 0.835 (BWR) and at Forsmark 3.095 GWe it is possible to roughly estimate the YOLL for these sites.

Ringhals

$0.05 \cdot 3.54 \cdot 4.8 \cdot 10^{-6} \cdot 24 \cdot 8760 = 0.16$(8 during 50 years)

Forsmark

$0.05 \cdot 3.095 \cdot 1.5 \cdot 10^{-5} \cdot 24 \cdot 8760 = 0.48802$ (24.4 during 50 years)

The total collective dose due to releases of C-14 is roughly estimated at 40 manSv integrated over 500 years, which corresponds to YOLL of $40 \cdot 0.05 \cdot 24 = 48$ (integrated over 500 years), and 4.8 integrated over 50 years).

7 Decommissioning and waste disposal

For high level waste the releases are considered negligible and for intermediate and low level waste YOLL/GWa are found in Table 12. Concerning YOLL attributed to decommissioning there are not enough data to estimate this value.

Concerning low level waste some collective dose calculations were carried out for SFR (Ref 10). In this report two situations are treated

1 Transport and emptying of containers: $7.5 \cdot 10^{-3}$ manSv/year

2 Driving of terminal vehicle: $7.5 \cdot 10^{-3}$ manSv/year

Furthermore, it is assumed that further activities give $1.0 \cdot 10^{-3}$ manSv/year.

In total it means $1.51 \cdot 10^{-2}$ manSv/year.

This collective dose during 50 years corresponds to

$$0.0151 \cdot 24 \cdot 0.05 \cdot 50 = 0.91 \text{ YOLL}$$

8 Conclusions

From the results obtained in this study it can be concluded that the Years of Lost Lives (YOLL) attributed to the processes in the nuclear fuel cycle are negligible to the corresponding effects caused by the natural irradiation.

The most important sources to the YOLL in the nuclear fuel cycle are the global dispersion of C-14 released from nuclear power plants and reprocessing plants during normal operation and the long-term releases of radon from abandoned mine and mill tailings.

9 Summary of YOLL in the nuclear fuel cycle

Table 12

Normalized collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle and corresponding YOLL (Years Of Lost Lifes). (Reproduced from Ref 3, Table 53, Page 200.)

Source	Normalized collective effective dose [man Sv $(GWa)^{-1}$]	YOLL/GWa	YOLL (Total during 50 years)
Local and regional component			
Mining Radon	1.1 (0.004-7.3)	1.3 (0.0048 – 8.8)	65(0.24-440)
Milling Radon	0.05	0.054	2.7
Mine and mill tailings (releases over 5 years) Radon	0.3 (0.003-1.3)	0.36 (0.0036-1.56)	18 (0.18-78)
Fuel fabrication	0.0028	0.0034	0.17
Reactor operation Atmospheric Aquatic Swedish NPPs 9.819 GWa see Table 9	 1.3 0.04	 1.56 0.048 15.8 (YOLL/year)	 78 2.4 790
Occupational exposure Swedish NPPs 9.819 GWa see Table 9	1.46	1.75 17.2 (YOLL/year)	87 860
Reprocessing (Not actual in Sweden) Atmospheric Aquatic	 0.05 0.2	 0.06 0.24	 3 12
Transportation	0.1	0.12	6
Total (Average and rounded)	3		272

Table 12 (cont'd)

Solid wate disposal and global component	Normalized collective effective dose [man Sv $(GWa)^{-1}$]	YOLL/GWa*	
Mine and mill tailings (releases of radon over 10000 years)	150 (1-1000)	180 (1.2-1200)	
Reactor operation Low-level waste disposal Intermediate-level waste disposal	 0.00005 0.5	 $6 \cdot 10^{-5}$ 0.6	
Reprocessing solid waste disposal	0.05	0.06	
Globally dispersed radionuclides (truncated to 10000 years)	50	60	
Total (Average and rounded)	200	240	

* These values are obtained by multiplication of the collective effective dose values by $0.05 \cdot 24$.

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2003-05-15

Table A.1
Collective doses to the personnel at Swedish NPPs (man Sv).

Year	O1	O2	O3	Oskarshamn	R1	R2	R3	R4	Ringhals	F1	F2	F3	Forsmark	B1	B2	Barsebäck	Total
1972	0.080			0.080					0.000				0.000				0.080
1973	0.214			0.214					0.000				0.000				0.214
1974	1.365			1.365					0.000				0.000				1.365
1975	0.630	0.170		0.800	0.827	0.823			1.650				0.000			0.098	2.458
1976	2.180	1.047		3.227	1.612	0.413			2.025				0.000			0.858	6.110
1977	1.670	1.263		2.933	3.888	2.771			6.659				0.000			1.022	10.614
1978	0.700	1.010		1.710	3.549	1.995			5.544				0.000			0.976	8.230
1979	1.450	0.896		2.346	4.287	2.469			6.756				0.000			1.026	10.128
1980	1.580	0.527		2.107	3.324	3.158	0.015		6.497	0.137			0.137			1.303	10.044
1981	1.310	0.752		2.062	4.621	3.409	0.384		8.414	1.200			1.200			1.467	13.142
1982	1.350	0.477		1.827	2.080	3.157	0.425	0.021	5.683	1.327			1.327			0.831	9.668
1983	1.790	0.921		2.711	4.272	3.540	1.168	0.097	9.077	0.407	0.518		0.925			2.210	14.923
1984	1.640	0.379		2.019	2.550	2.638	0.584	0.462	6.234	0.550	0.818	0.001	1.368			1.970	11.591
1985	1.603	1.064	0.065	2.732	2.660	2.245	0.827	0.308	6.040	0.613	0.457	0.133	1.203			1.055	11.030
1986	2.846	0.970	0.308	4.124	3.129	3.053	2.001	0.936	9.118	0.501	0.505	0.522	1.527			2.316	17.085
1987	2.820	1.076	0.434	4.331	2.660	1.999	1.662	0.730	7.051	0.548	1.014	0.415	1.977			1.525	14.883
1988	2.629	1.542	1.222	5.393	3.238	1.929	1.491	0.931	7.589	0.701	0.589	0.660	1.950			1.930	16.861
1989	1.830	1.278	0.585	3.693	1.667	4.099	1.209	0.607	7.582	0.408	0.863	0.984	2.255			1.826	15.355
1990	2.635	1.354	1.087	5.076	2.120	1.221	1.337	0.587	5.264	0.460	1.163	0.672	2.295			1.416	14.052
1991	2.391	1.744	0.480	4.614	1.944	0.973	1.017	0.542	4.475	0.490	0.877	0.833	2.199			1.483	12.772
1992	3.826	2.012	0.960	6.798	4.496	1.607	1.080	0.672	7.855	0.912	1.129	1.349	3.390			2.407	20.450
1993	6.024	4.158	0.557	10.739	3.677	1.417	0.645	0.494	6.233	1.141	2.226	0.872	4.239			6.223	27.434
1994	4.636	1.712	0.638	6.986	3.310	0.752	0.650	0.507	5.219	0.898	1.013	0.893	2.804	0.953	1.303	2.256	17.265
1995	3.400	2.100	0.600	6.100	3.020	0.675	1.876	0.383	5.954	0.939	1.160	0.979	3.078	1.478	1.554	3.032	18.164
1996	1.916	5.467	1.731	9.114	2.811	0.993	0.436	0.552	4.792	1.086	1.562	1.207	3.855	1.950	2.455	4.405	22.166
1997	0.798	1.648	0.607	3.053	13.805	0.777	0.438	0.695	15.715	1.922	2.355	1.120	5.397	1.849	1.856	3.705	27.870
1998	3.350	1.849	0.555	5.754	1.965	0.883	0.509	0.269	3.626	0.992	0.868	0.860	2.720	1.924	1.422	3.346	15.446
1999	0.567	0.953	1.211	2.731	2.301	0.515	0.450	0.334	3.600	0.278	0.925	0.789	1.992	1.525	0.941	2.466	10.789

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Table A.2
Collective doses from releases during 1995 – 1998 from Swedish NPPs.

Plant	1995		1996		1997		1998	
	All other nuclides	C-14	All other nuclides	C-14	All other nuclides	C-14	All other nuclides	C-14
Barsebäck	0.0046	7.4	0.0062	7.4	0.0022	7.4	0.0021	7.4
Forsmark	0.0047	19.3	0.0055	19.3	0.0074	19.3	0.0020	19.3
Oskarshamn	0.0075	11.0	0.0098	13.8	0.0104	13.8	0.0067	13.8
Ringhals	0.30	10.6	0.16	10.6	0.0481	10.6	0.0612	10.6
Total	0.3168	48.3	0.1815	51.1	0.0681	51.1	0.0720	51.1