Assessment of doses and environmental contamination from decommissioning of the nuclear facilities at Risø

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Published in:
Baltic-Danish cooperation on radiation protection

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

Assessment of doses and environmental contamination from decommissioning of the nuclear facilities at Risø

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Abstract When a nuclear installation is to be dismantled in a Member State of the European Union the government should submit a document to satisfy the requirements in Article 37 of the Euratom Treaty on assessed contamination levels close to the site and in the nearest neighbouring country, and individual doses to the critical group and to individuals in the nearest neighbouring country. The contamination levels and individual doses should be assessed from both routine and accidental releases. Almost all of the expected discharges of radioactive materials to the atmosphere from future decommissioning activities will come from operations inside the reactor vessel of DR 3 and during the cleaning operations in the concrete cells at the Hot Cell facility. The physico-chemical form of the discharges from DR 3 would be as tritiated water and as very small particles (of the construction parts) containing activation products. The expected discharges from the Hot Cell facility would be as very small particles of irradiated fuel and contaminated dust. Only minor discharges of activity are expected to occur during the decommissioning operations at the reactors DR 1 and DR 2 and, if so, such discharges would be as very small particles of the reactor components. The calculated doses to the critical group from both routine and accidental releases during decommissioning - and from both atmospheric and aquatic exposure – as presented in this paper appear to be only a very small fraction of the individual doses from the naturally occurring background radiation.

1 Introduction

When a nuclear installation is to be dismantled in a Member State of the European Union the government of the country should submit a document to satisfy the requirement of Article 37 of the Euratom Treaty as recommended by the Commission of the European Communities (Annex 2 of Commission Recommendation 1999/829/Euratom of 6 December 1999). These recommendations include the dismantling and nuclear reactors and reprocessing plants in the list of operations to which Article 37 applies. Under paragraph 5.1 of the Recommendation, a submission of general data in respect of such dismantling operations is only necessary when the proposed authorised limits and other requirements are less restrictive than those in force when the plant was operational. However, in the case of the nuclear installations at Risø National Laboratory, no previous submission of general data has been made under Article 37 and no Opinion given by the Commission on a plan for the disposal of radioactive waste. For this reason, general data including the impact on neighbouring countries has to be submitted in respect of the proposed dismantling operations, even though no change to a less restrictive authorisation is envisaged at this time. The models used to calculate any impact on the environment during the decommissioning of the nuclear facilities at Risø and the assessed consequences on the environment are described below.

2 Models for assessing doses and environmental contamination

When radionuclides are discharged into the atmosphere they will be dispersed in the downwind direction and can be deposited on the ground leading to contamination of the soil and foodstuffs grown at the soil. When radionuclides are discharged into an aquatic environment they are likely to be transported by tides and currents while dispersing within the water body. Some of the activity might be

transferred to suspended sediments, and hence to sediments layers, and some taken up by aquatic organisms like fish.

2.1 Atmospheric dispersion and dose models

The average concentration from material being released to the atmosphere can be calculated from the gaussian plume model. This model describes the concentration in the atmosphere, C, as a function of the coordinates (x, y, z) in a xyz-coordinate system with origo at the point of release. Figure 2.1 shows the calculated relative concentration as a function of downwind distance for the Pasquill stability category D, which is the domination stability class in Denmark.

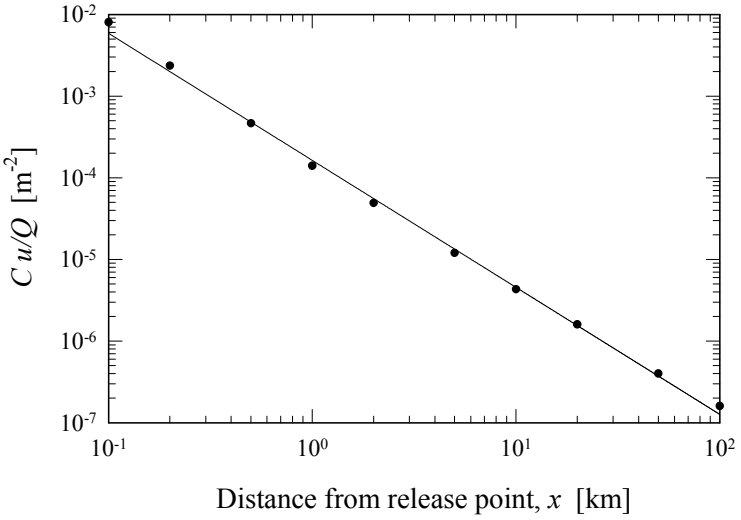

Figure 2.1. Relative concentration, $C \cdot u/Q$, in air at ground level from a short-term ground level release as a function of downwind distance during Pasquill category D. The concentration is normalised to the wind velocity, u, and the release rate, Q.

The average concentration, C_{av}, for a continuous release over a year at distances 1 km (critical group) and 63 km (nearest inhabitants in Sweden) from the release point as well as for a short-term release under the most frequent meteorological conditions (Pasquill category D and a wind speed of 5 m/s) has been calculated as shown in Table 2.1.

Table 2.1. Relative activity concentration in Denmark and Sweden from short-term and continuous releases of activity from the nuclear installations at Risø.

Downwind distance (km)	Relative concentration, C/Q (Bq·s·m^{-3}/Bq)	
	Short-term	Continuous
1	$28 \cdot 10^{-6}$	$10 \cdot 10^{-6}$
63	$45 \cdot 10^{-9}$	$16 \cdot 10^{-9}$

A person being submerged in a concentration, C, will per unit time inhale an activity, q, given as the product of concentration and inhalation rate, I ($\approx 2 \cdot 10^{-4}$ m^3/s):

$$q = I \cdot C$$

The committed effective dose per unit time, $\dot{E}(50)$, from inhalation of the activity, q, per unit time of the given radionuclide is calculated as the product of q and the committed effective dose per unit intake, $e_{inh}(50)$ as:

$$\dot{E}(50) = I \cdot C \cdot e_{inh}(50)$$

The transfer of deposited activity on ground surfaces to a specified foodstuff, *e.g.* milk, can be calculated from the transfer factor, *TF*, which for a given element gives the ratio of equilibrium foodstuff concentration, C_∞, and the amount of activity added to the surface per unit time and area, q. The ingestion doses can be calculated from the food consumption rate, M, and the nuclide-specific dose conversion factor, $e_{ing}(50)$. It is here assumed that the critical group consumes a fraction, f, of their local grown foodstuffs. In these assessments the value of f is conservatively taken to be 10%. The annual committed effective dose is given as:

$$\dot{E}(50) = f \cdot C_\infty \cdot M \cdot e_{ing}(50) = f \cdot TF \cdot q \cdot M \cdot e_{ing}(50)$$

2.2 Aquatic dispersion and dose models

The aquatic dispersion of radioactive materials being released to Roskilde Fjord is calculated from a compartment model, which is shown in Figure 2.2 (reference Sven P. Nielsen, Risø). A release of radioactive materials to Roskilde Fjord will result in a contamination of the different regions with the largest concentrations in Roskilde Fjord and Isefjorden. Concentrations in the different compartments can be calculated for a short-term release or from a continuous release.

Region	*Area (m²)*	*Depth (m)*	*Volume (m³)*
Roskilde Fjord	1.0E+08	4	4.0E+08
Isefjord	2.5E+08	9	2.3E+09
Kattgat, deep	2.0E+09	100	2.0E+11
Kattegat, surface	1.6E+10	20	3.2E+11
Skagerrak	3.2E+10	210	6.8E+12
Belt Sea, deep	4.7E+09	30	1.4E+11
Belt Sea, surface	1.1E+10	14	1.5E+11

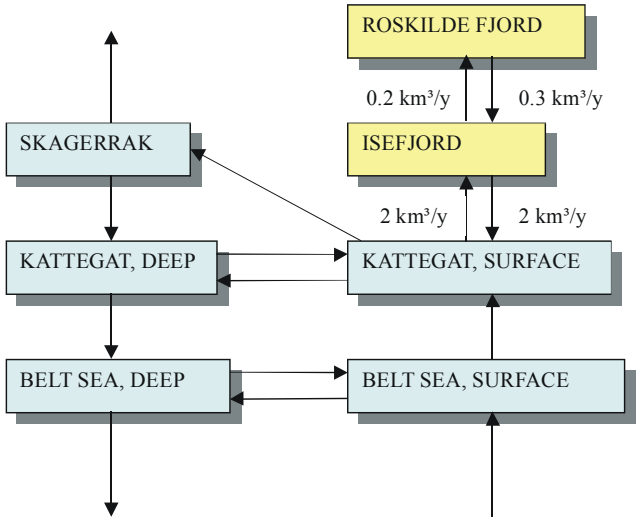

Figure 2.2. Compartment model of Roskilde Fjord and the surrounding Danish seas.

A *short-term* release of 1 TBq of tritium to the Fjord will result in the following *maximum* concentrations, C_{max}, in the Fjord (at Risø) and in the Kattegat surface waters:

- Roskilde Fjord: 2,000 Bq/m^3 (mean residence time ≈ 1.3 year)
- Kattegat surface waters: 0.1 Bq/m^3 (mean residence time ≈ 1.3 year)

The calculated concentration of tritium in Roskilde Fjord from a single release has been compared to measured concentrations from an accidental release of tritium to the Fjord of about 30 TBq as shown

in Figure 2.3 (normalised to 1 TBq). It appears from Fig. 2.3 that the observed and the calculated concentrations are in good agreement and that the observed mean residence time is slightly less than the calculated value.

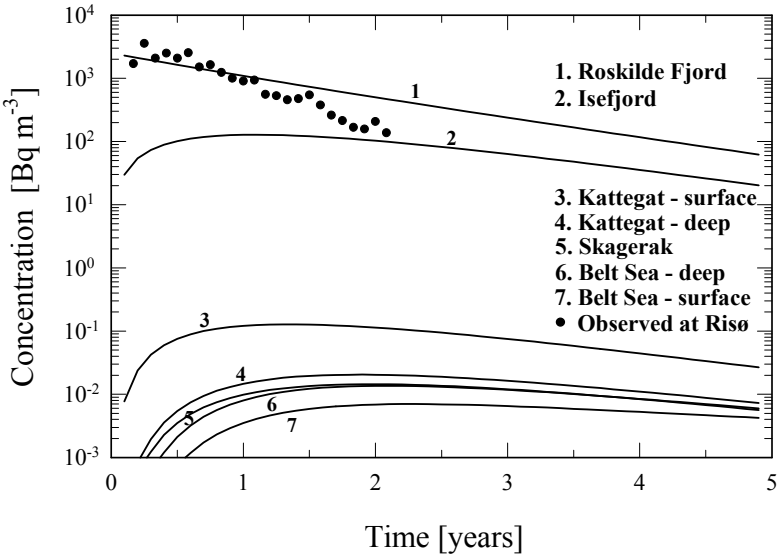

Figure 2.3. Calculated concentrations of tritium in Danish seas following a short-term release of 1 TBq of tritium to Roskilde Fjord.

The concentrations of tritium from a continuous release have been calculated from the response to a short-term release shown in Fig. 2.3. The results are shown in Fig. 2.4 for Roskilde Fjord and Kattegat surface waters.

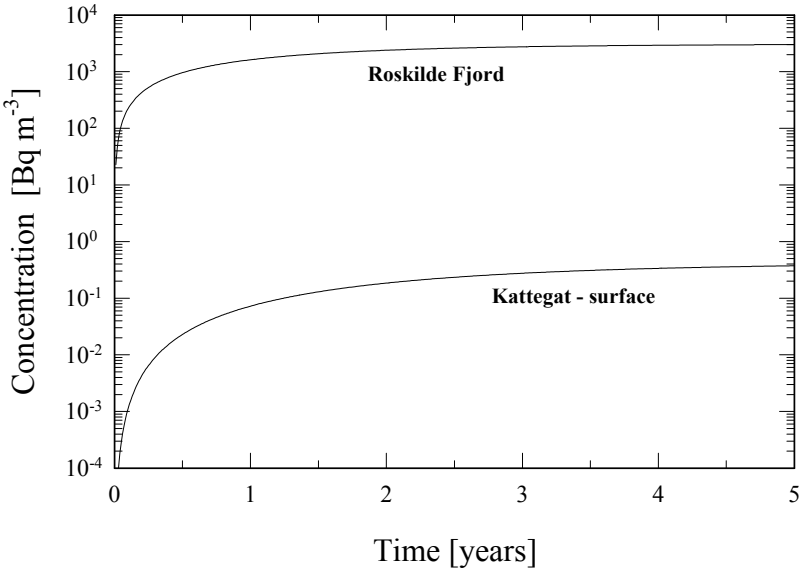

Figure 2.4. Calculated concentrations of tritium in Roskilde Fjord and Kattegat surface waters following a continuous release of 1 TBq per year of tritium to Roskilde Fjord.

A *continuous* release of 1 TBq/year of tritium to the Fjord will result in the following *equilibrium* concentrations, C_{equil}, in the Fjord and in the Kattegat surface waters:

- Roskilde Fjord: 3,000 Bq/m^3
- Kattegat surface waters: 0.4 Bq/m^3

Individual radiation doses from fish consumption rates, V_{fish}, can be calculated from the water concentrations and transfer factors of radionuclides from water to fish, $TF_{water\text{-}fish}$:

$$\dot{E}(50) = C \cdot TF_{water-fish} \cdot V_{fish} \cdot e_{ing}(50)$$

3 Individual doses from routine releases

Any operational release of radionuclides during decommissioning of the nuclear facilities is expected to be small. For the reactor DR 3 and the Waste Treatment Plant the foreseen releases would be significantly less than during the operation of DR 3 and the dominating activity will be tritium. Almost all of the expected discharges of radioactive materials to the atmosphere from future decommissioning activities will come from operations inside the reactor vessel of DR 3 and during the cleaning operations in the concrete cells at the Hot Cell facility. The physico-chemical form of the discharges from DR 3 would be as tritiated water and as very small particles (of the construction parts) containing activation products. The expected discharges from the Hot Cell facility would be as very small particles of irradiated fuel and contaminated dust. Only minor discharges of activity are expected to occur during the decommissioning operations at the reactors DR 1 and DR 2 and, if so, such discharges would be as very small particles of the reactor components.

3.1 Individual doses from atmospheric releases

Releases of the radionuclides present in the components of the nuclear facilities during their decommissioning are difficult to estimate. The major part of the activity in the reactor components is fixed within the components as activation products, and it is therefore assumed that an annual fractional release rate of 0.1% of the inventory per year is rather conservative. Due to filtration through HEPA filters a maximum of 1% of this fractional release rate is assumed to penetrate the filters. For the Hot Cell facility, the activity within the cells is found as dust and small particles, and therefore, a fractional release rate during decommissioning of the cells of about 0.1% might be more likely than during decommissioning of the reactors, but still a very conservative estimate. Also the fractional release from the Hot Cell facility is assumed to be filtered through HEPA filters with a maximum penetration of 1%.

Concentrations and individual doses have been calculated for two sets of annual releases. The first set includes the maximum value of the expected nuclide-specific atmospheric releases from each of the nuclear facilities. These values are therefore acting as a generic annual release rate for the Risø-site, irrespective of the facility. The second set includes the release limits envisaged to be specified by the Nuclear Regulatory Authorities. Both set of release rates are given in Table 3.1.

Table 3.1. Atmospheric release rates used in the calculations of exposures and doses to the critical groups in Denmark and Sweden. The first column gives the selected maximum values and the values in the second column are the annual discharge limits.

Radionuclide	Expected maximum annual discharges (GBq/a)	Annual discharge limits (GBq/a)
^{3}H	1,000	1,000,000
^{14}C	0.002	1,000
^{60}Co	1	1,000
^{90}Sr	0.01	200
^{137}Cs	0.02	700
$^{152+154}Eu$	0.02	700
Actinides	0.001	1

The individual doses from the exposure to activity released during decommissioning will be dominated by inhalation and ingestion pathways. The inhalation and ingestion doses would be dominating compared to external doses. Therefore, only doses from ingestion of contaminated foodstuffs and inhalation doses have been calculated.

The transfer factors for four major Danish foodstuffs are given in Table 3.2 and the annual average food consumption rate for these foodstuffs are given in Table 3.3.

Table 3.2. Transfer factors for major foodstuffs in the Danish food basket[1].

Radionuclide	Transfer factors [Bq·year·kg^{-1}/Bq·m^{-2}]			
	Milk	Meat	Grain	Vegetables
^{3}H	-	-	-	-
^{14}C	-	-	-	-
^{60}Co	$2.3\cdot10^{-3}$	$9.3\cdot10^{-4}$	$2.2\cdot10^{-3}$	$1.6\cdot10^{-4}$
^{90}Sr	$3.9\cdot10^{-3}$	$1.4\cdot10^{-3}$	$3.0\cdot10^{-2}$	$3.0\cdot10^{-3}$
^{137}Cs	$5.7\cdot10^{-3}$	$2.7\cdot10^{-2}$	$3.5\cdot10^{-2}$	$4.0\cdot10^{-3}$
$^{152+154}$Eu	$2.1\cdot10^{-5}$	$1.3\cdot10^{-3}$	$2.8\cdot10^{-4}$	$1.1\cdot10^{-4}$
Actinides	$2.6\cdot10^{-6}$	$1.4\cdot10^{-4}$	$1.8\cdot10^{-4}$	$1.6\cdot10^{-5}$

Table 3.3. Annual average food consumption (kg/year) in Denmark as a function of age for some major foodstuffs[2].

Age group	Milk	Grain products	Vegetables	Meat
1 – 6 years	186	61	45	18
7 – 14 years	202	78	73	36
15 – 80 years	128	77	84	42

For ^{3}H the dose assessments are based on the assumption that all intake of water via inhalation, uptake through skin, water intake and food intake has the same ^{3}H-concentration and that the total annual intake for adults is 930 kg/a. The water intake by inhalation and absorption through skin contributes with about 10% (99 kg) and the remaining through food and drinking water.

With the assumption that 1 m^3 of air contains 8.1 g of water, a steady state concentration of 1 Bq/m^3 in air will cause a total annual ^{3}H-uptake of 0.12 MBq[3]. As the liquid and solid food intake for children is about 46% of that for adults[3], the corresponding ^{3}H-uptake will be 0.056 MBq.

For ^{14}C the dose assessments are based on an air concentration of 300 ppm of CO_2 and equilibrium of ^{14}C in foodstuffs and air. For a steady state air concentration of 1 Bq/m^3 of ^{14}C in air the annual intake of ^{14}C with food will be 0.91 MBq[4] for adults and 0.83 MBq for children based upon the annual food consumption (incl. milk) for adults and children.

Furthermore, it has been assumed in the calculations that the transfer factors and food habits in Denmark and in Sweden are similar. To account for indoor/outdoor occupancy, the annual outdoor inhalation doses have been reduced by a factor of 2 due to the filtering effect of buildings.

The dose conversion factors for calculating inhalation and ingestion doses for adults and children (1 - 2 years) are shown in Table 3.4.

[1] Based on the model Farmland in the NRPB developed software PC CREAM and many years studies of ^{90}Sr and ^{137}Cs in Denmark.

[2] Cost habits in Denmark 1995 (In Danish). Publication No. 235, Ministry of Health (1996).

[3] *Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment.* European Commission, Radiation Protection 72, EUR 15760 EN.

Table 3.4. Inhalation and ingestion dose conversion factors for radionuclides expected to be released during decommissioning (ICRP Publication 72).

Radionuclide	$e_{inh}(50)$ [Sv/Bq]		$e_{ing}(50)$ [Sv/Bq]	
	Children	Adults	Children	Adults
^{3}H	$2.0\cdot10^{-11}$	$6.2\cdot10^{-12}$	$4.8\cdot10^{-11}$	$1.8\cdot10^{-11}$
^{14}C	$6.7\cdot10^{-10}$	$2.0\cdot10^{-10}$	$1.6\cdot10^{-9}$	$5.8\cdot10^{-10}$
^{60}Co	$3.4\cdot10^{-8}$	$1.0\cdot10^{-8}$	$2.7\cdot10^{-8}$	$3.4\cdot10^{-9}$
^{63}Ni	$1.9\cdot10^{-9}$	$4.8\cdot10^{-10}$	$8.4\cdot10^{-10}$	$1.5\cdot10^{-10}$
^{90}Sr	$1.1\cdot10^{-7}$	$3.6\cdot10^{-8}$	$7.3\cdot10^{-8}$	$2.8\cdot10^{-8}$
^{133}Ba	$1.0\cdot10^{-8}$	$3.1\cdot10^{-9}$	$6.2\cdot10^{-9}$	$1.5\cdot10^{-9}$
^{137}Cs	$5.4\cdot10^{-9}$	$4.6\cdot10^{-9}$	$1.2\cdot10^{-8}$	$1.3\cdot10^{-8}$
$^{152+154}Eu$	$1.3\cdot10^{-7}$	$4.7\cdot10^{-8}$	$1.2\cdot10^{-8}$	$2.0\cdot10^{-9}$
Actinides	$7.7\cdot10^{-5}$	$5.0\cdot10^{-5}$	$4.2\cdot10^{-7}$	$2.5\cdot10^{-7}$

As both the dose conversion factors and breathing rate are different for children compared to adults the doses to young people might be different. For selected radionuclides the product of the age-specific breathing rate and the age-specific inhalation dose conversion factor has thus been investigated. This product is proportional to the committed effective inhalation dose from a given time-integrated concentration, and it appeared that the inhalation doses are largest for adults for *e.g.* tritium and ^{137}Cs. For ^{60}Co the inhalation doses are slightly larger for the age groups 7 - 12 years and 12 - 17 years. Therefore, it would normally be conservative to use adults as the critical group for inhalation dose calculations. The same investigation was made for ingestion doses from food consumption and it appeared that ingestion doses normally would be larger for the younger age groups, most predominantly for milk. Therefore, in contrast to the inhalation pathway, it would be conservative to use children as the critical group for ingestion dose calculations. The calculated individual doses for children and adults are given in Table 3.5.

Table 3.5. Annual doses to children and adults in Denmark (1 km) and Sweden (63 km) from the release rates specified in Table 3.1.

Radionuclide	Expected maximum annual discharges				Annual discharge limits			
	Denmark (μSv/a)		Sweden (μSv/a)		Denmark (μSv/a)		Sweden (μSv/a)	
	Children	Adults	Children	Adults	Children	Adults	Children	Adults
^{3}H	$2\cdot10^{-2}$	$4\cdot10^{-2}$	$4\cdot10^{-5}$	$6\cdot10^{-5}$	$5\cdot10^{1}$	$3\cdot10^{1}$	$8\cdot10^{-2}$	$5\cdot10^{-2}$
^{14}C	$8\cdot10^{-5}$	$3\cdot10^{-5}$	$1\cdot10^{-7}$	$5\cdot10^{-8}$	$5\cdot10^{1}$	$2\cdot10^{1}$	$8\cdot10^{-2}$	$3\cdot10^{-2}$
^{60}Co	$3\cdot10^{-2}$	$1\cdot10^{-2}$	$5\cdot10^{-5}$	$2\cdot10^{-5}$	$5\cdot10^{1}$	$2\cdot10^{1}$	$8\cdot10^{-2}$	$3\cdot10^{-2}$
^{90}Sr	$3\cdot10^{-3}$	$1\cdot10^{-3}$	$4\cdot10^{-6}$	$2\cdot10^{-6}$	$5\cdot10^{1}$	$2\cdot10^{1}$	$8\cdot10^{-2}$	$4\cdot10^{-2}$
^{137}Cs	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$2\cdot10^{-6}$	$2\cdot10^{-6}$	$4\cdot10^{1}$	$5\cdot10^{1}$	$6\cdot10^{-2}$	$8\cdot10^{-2}$
$^{152+154}Eu$	$1\cdot10^{-3}$	$9\cdot10^{-4}$	$2\cdot10^{-6}$	$2\cdot10^{-6}$	$5\cdot10^{1}$	$3\cdot10^{1}$	$8\cdot10^{-2}$	$5\cdot10^{-2}$
Actinides	$4\cdot10^{-2}$	$5\cdot10^{-2}$	$7\cdot10^{-5}$	$8\cdot10^{-5}$	$4\cdot10^{1}$	$5\cdot10^{1}$	$7\cdot10^{-2}$	$8\cdot10^{-2}$

3.2 Individual doses from aquatic releases

Releases of tritiated heavy water to Roskilde Fjord have in recent years been around some hundred GBq/y from DR 3. From the Waste Treatment Plant the tritium release has been around a few TBq/y. The release of dissolved gross β-/γ-activity from the Waste Treatment Plant is less than 0.2 GBq/y of which about half is the naturally occurring ^{40}K. The remaining part is a mixture of several nuclides; for illustrative purposes the activity is conservatively considered to be ^{137}Cs.

Internal exposures are calculated from consumption of fish that have taken up tritium and ^{137}Cs from contaminated water bodies and consumption of contaminated water. Annual individual doses and average water concentrations is determined for aquatic releases of tritium and ^{137}Cs to Roskilde Fjord from the Waste Treatment Plant at two specific locations:

- A critical group located near the site (*i.e.* consuming fish caught in Roskilde Fjord and consuming water from Roskilde Fjord).
- The nearest population group in another Member State (*e.g*. Sweden) consuming fish caught in Kattegat.

Concentrations and individual doses have been calculated for two sets of annual releases. The first set includes the maximum value of the expected nuclide-specific aquatic releases from the Waste Treatment Plant; the second set includes the release limits envisaged to be specified by the Nuclear Regulatory Authorities. The Waste Treatment Plant is the only nuclear facility from which aquatic releases can be expected during decommissioning of the other facilities. Both sets of release rates are given in Table 3.6.

Table 3.6. Aquatic release rates used in the calculations of exposures and doses to the critical groups in Denmark and Sweden. The first column gives the expected maximum releases and the values in the second column are the annual discharge limits.

Radionuclide	Expected maximum annual discharges (GBq/a)	Annual discharge limits (GBq/a)
^{3}H	$2 \cdot 10^{3}$	$1 \cdot 10^{6}$
^{137}Cs	$3 \cdot 10^{-1}$	$4 \cdot 10^{2}$

The individual doses have been calculated to the critical group living around the Fjord and to people in Sweden. The assumed exposure pathway is consumption of fish exclusively from Roskilde fjord or Kattegat and consumption of water exclusively from Roskilde Fjord.

The average consumption of fish and water (and other liquid intakes) varies with age as shown in Table 3.7.

Table 3.7. Annual average food consumption (kg/year) in Denmark as a function of age for fish and liquids (excl. milk and fruit juice)[4].

Age group	Fish	Liquids
1 – 6 years	4.8	204
7 – 14 years	6.2	305
15 – 80 years	8.8	779

The transfer factor from water to fish for tritium is 1 Bq/kg per Bq/l and for caesium 100 Bq/kg per Bq/l. The dose conversion factors for a conservative fish consumption rate of 25 kg/year for adults and a water consumption also for adults of 2.2 litres per day directly from the Fjord have been calculated as shown in Table 3.8. The corresponding doses to children have been calculated from lower values of consumption rates. It should be emphasized that the calculated doses from fish are rather conservative due to the high consumption rate assumed for fish (nearly a factor of three higher compared to the average consumption rate of fish in Denmark).

[4] Cost habits in Denmark 1995 (in Danish). Publication No. 235, Ministry of Health (1996).

Table 3.8. Ingestion doses from consumption of liquids (2.2 litres per day for adults) and fish (25 kg per year for adults) from Roskilde Fjord per unit release rate of tritium and ^{137}Cs expected to be released from the nuclear facilities during decommissioning.

Radionuclide	Children		Adults	
	Individual dose [μSv·a^{-1}/GBq·a^{-1}]		Individual dose [μSv·a^{-1}/GBq·a^{-1}]	
	Liquids	Fish	Liquids	Fish
^{3}H	$3.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-5}$	$1.4 \cdot 10^{-6}$
^{137}Cs	$7.0 \cdot 10^{-3}$	$5.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$

The results of the dose calculations are given in Table 3.9 and Table 3.10 for the expected maximum annual releases and the release limits, respectively.

Table 3.9. Annual doses to children and adults in Denmark and Sweden from expected releases of tritium and ^{137}Cs to Roskilde Fjord.

Radionuclide	Individual doses in Denmark (μSv/a)				Individual doses in Sweden (μSv/a)	
	Water		Fish		Fish	
	Child	Adult	Child	Adult	Child	Adult
Tritium	$6 \cdot 10^{-2}$	$8 \cdot 10^{-2}$	$4 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$5 \cdot 10^{-7}$	$4 \cdot 10^{-7}$
^{137}Cs	$2 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	$2 \cdot 10^{-6}$	$4 \cdot 10^{-6}$

Table 3.10. Annual doses to children and adults in Denmark and Sweden from releases of tritium and ^{137}Cs to Roskilde Fjord equal to the release limits.

Radionuclide	Individual doses in Denmark (μSv/a)				Individual doses in Sweden (μSv/a)	
	Water		Fish		Fish	
	Child	Adult	Child	Adult	Child	Adult
Tritium	$3 \cdot 10^{1}$	$4 \cdot 10^{1}$	$2 \cdot 10^{0}$	$1 \cdot 10^{0}$	$3 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
^{137}Cs	$3 \cdot 10^{0}$	$1 \cdot 10^{1}$	$2 \cdot 10^{1}$	$4 \cdot 10^{1}$	$3 \cdot 10^{-3}$	$5 \cdot 10^{-3}$

4 Individual doses from accidents

After closure of reactor DR3 the potential consequences of accidents at this facility is greatly reduced. Here - and also at the other installations - inherent driving forces supporting release such as heat generation or high pressures will be absent. Ordinary working accidents such as drop of heavy components or machinery may still occur. Spillage of contaminated solutions or dispersion of contaminated dust must be taken into account, but will normally be local phenomena involving only a minor fraction of the activity in the installations. Fire would probably constitute the greatest risk. Suitable precautions will therefore be taken to limit the possibility of fires by removal of burnable materials, good working practices etc. Accidents of external origin have a very small probability and such accidents have not occurred at the nuclear facilities at the Risø site during the last forty years.

4.1 Individual doses from atmospheric releases

After all the nuclear facilities have been closed 'reference accidents' have been defined as described in Table 4.1. These scenarios are considered to be very unlikely and the activity releases to the environment to be at the upper end of the possible release scale.

Table 4.1. Unplanned releases of radioactive materials to the environment from 'reference accidents' during decommissioning of the nuclear facilities at Risø.

Nuclear facility	Decommissioning operation
Research reactor DR 1	Release of ^{137}Cs from recombiner due to a fire in the graphite moderator
Research reactor DR 2	Leakage of tritiated heavy water from steel drums to Roskilde Fjord via the Waste Management Plant
Research reactor DR 3	Release of ^{60}Co after drop of the top shield during a crane operation through open containment
Hot Cell facility	Release of ^{90}Sr, ^{137}Cs and actinides after failure of the ventilation system during 'shot-blast' cell cleaning

The reference accidents shown in Table 4.1 are further discussed below. In addition to these accidents during decommissioning, an additional accident has been considered for the Waste Treatment Plant. A small plane crash in the storage facility for low-active waste drums causes an explosion in which about 1% of the activity content in the drums are being released to the atmosphere. The atmospheric stability during the release is assumed to be Pasquill D and the duration of the release is assumed to be a few hours. Only dry deposition is considered.

Reactor DR 1

The oxygen and hydrogen produced by radiation of the water in the core solution of reactor DR 1 were recombined by a gas handling system. The recombiner contains a platinized aluminium oxide catalyst, which was maintained at a temperature of approximately 100 °C during operation of the reactor. The hydrogen and oxygen were catalytically recombined by the platinum. The water vapour formed was condensed on a cooling coil in the recombiner, and the water drained by gravity back to the core. Fission gases like ^{137}Xe also entered the recombiner and fission gas decay products like ^{137}Cs were trapped in the catalyst.

During dismantling of the graphite it is assumed that a fire breaks out in the graphite and due to high temperatures, all the trapped ^{137}Cs in the recombiner platinum will be released to the reactor building. Furthermore, it is assumed that about 10% of the ^{137}Cs-activity, *i.e.* 2 - 3 GBq will be released to the atmosphere from a damaged reactor building.

Reactor DR 3

The major residual activity in DR 3 will be found in the reactor aluminium tank, the graphite reflector, the reactor steel tank, the top shield, the annular shield, and the biological shield. During a crane operation where the top shield is being lifted by an external crane through an open reactor-building roof, it is assumed that the top shield accidentally is dropped to the top of the reactor block and partly crushed. As the activity is concentrated in only a small part in the bottom of the top shield it is assumed that a rather large fraction, about 1% of the activity content, *i.e.* about 300 GBq of ^{60}Co, is released to the atmosphere through the open roof as small particles.

Hot Cell facility

The major part of the activity, *i.e.* more than 90% of the total activity is found in the concrete cells 1 - 3. During decontamination of the inner surfaces of concrete cell 3 using shot-blasting techniques it is assumed that the filter in the ventilation system fails and that a few per cent of the content in cell 3 is released continuously to the atmosphere over a working day, *i.e.* about 20 GBq of ^{137}Cs, about 15 GBq of ^{90}Sr and about 1 GBq of actinides before the failure is discovered. (Shot blasting is a tech-

nique where a large number of small metal fragments are shot against a surface at high pressure thereby releasing a few millimetres of the surface).

Waste Treatment Plant

During passage of the Risø-site a small aeroplane experiences problems with the engines and subsequently crashes into the storage facility for low-active waste. In the explosion and fire following the crash 1% of the activity content in the drums is assumed to escape to the atmosphere, *i.e.* 10 GBq of ^{60}Co, 30 GBq of ^{90}Sr, 50 GBq of ^{137}Cs and 0.1 GBq of actinides. This accident can also be considered as representative for the storage facility for high-radiation waste drums. As the number of drums and their inventory here is less than in the low-active waste facility, a larger fraction of the inventory should be released for the same total release. The releases during the accidents described above are summarised in Table 4.2.

Table 4.2. Releases of radionuclides from the nuclear facilities at Risø during the reference accidents.

Reference accident		Accidental release (GBq)
Reactor DR 1	^{137}Cs	$3.0 \cdot 10^{0}$
Reactor DR 3	^{60}Co	$3.0 \cdot 10^{2}$
Hot Cell plant	^{90}Sr	$1.3 \cdot 10^{1}$
	^{137}Cs	$2.0 \cdot 10^{1}$
	Actinides	$1 \cdot 10^{0}$
Waste Treatment Plant	^{60}Co	$1 \cdot 10^{1}$
	^{90}Sr	$3 \cdot 10^{1}$
	^{137}Cs	$5 \cdot 10^{1}$
	Actinides	$1 \cdot 10^{-1}$

Individual doses to critical groups in Denmark and Sweden from the reference accident releases to the atmosphere are shown in Table 4.3. The doses are the sum of inhalation doses and ingestion doses from major foodstuff consumption, assuming that 10% of the annual foodstuff consumption is contaminated to the calculated levels. Furthermore, it has been assumed in the calculations that the transfer factors and food habits in Denmark and in Sweden are similar. The ingestion doses are those accumulated by the critical groups from all future consumption of foodstuffs produced in areas with an initial surface contamination density equal to the surface contamination density immediately after the accident.

Table 4.3. Individual doses to members of critical groups close to Risø and in Sweden from atmospheric releases during reference accidents at the reactors DR 1 and DR 3 and the Hot Cell plant.

Reference accident	Individual doses in Denmark (μSv)		Individual doses in Sweden (μSv)	
	Children	Adults	Children	Adults
Reactor DR 1	$4.1 \cdot 10^{-1}$	$5.7 \cdot 10^{-1}$	$6.6 \cdot 10^{-4}$	$9.1 \cdot 10^{-4}$
Reactor DR 3	$2.8 \cdot 10^{1}$	$9.9 \cdot 10^{0}$	$4.5 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$
Hot Cell plant	$1.3 \cdot 10^{2}$	$1.5 \cdot 10^{2}$	$2.1 \cdot 10^{-1}$	$2.4 \cdot 10^{-1}$
Waste Treatment Plant	$4.1 \cdot 10^{1}$	$3.4 \cdot 10^{1}$	$6.6 \cdot 10^{-2}$	$5.4 \cdot 10^{-2}$

The assumption that 10% of the annual foodstuffs consumed are contaminated is extremely conservative being equivalent to a situation where the critical groups grow 10% of their annual consumption locally in the contaminated areas.

4.2 Individual doses from aquatic releases

In the experimental cellar at the research reactor DR 2 approximately 10,000 litres of heavy water are stored in stainless steel drums. A reference accident has therefore been defined for an aquatic release of tritiated heavy water to Roskilde Fjord.

The heavy water from the primary cooling system at reactor DR 3 has been exposed to neutrons during the operation of the reactor. The concentration of tritium in the heavy water is about 300 GBq per litre. The heavy water has been drained into stainless steel drums each with a volume of about 200 litres. In total, about 10,000 litres of heavy water with a content of about 3,000 TBq of tritium is placed in the experimental cellar at the DR 2 reactor. During handling of the drums it is assumed that the content of one drum (60,000 GBq) leaks and the water is transferred into the tank collection system for contaminated water and ends in the steam recompression plant at the Waste Treatment Plant. This system does not remove tritiated water, which will be released into Roskilde Fjord.

A release of radioactive materials to Roskilde Fjord will result in a contamination of the different regions with the largest concentrations in Roskilde Fjord and the Isefjorden. Concentrations in the different compartments have been calculated for a short-term release of 60,000 GBq of tritium to Roskilde Fjord. Based on these concentrations individual doses have been calculated and shown in Table 4.4. The individual doses are those accumulated by critical groups in Denmark from all future consumption of 2.2 litres of water per day from Roskilde Fjord (adults) and from 25 kg fish per year (adults) caught in Roskilde Fjord and Kattegat, respectively. It has conservatively been assumed that the consumption of fish and water by children is 14 kg per year and 0.6 litres per day, respectively.

Table 4.4. Individual doses to members of critical groups close to Risø and in Sweden from accidental aquatic releases of tritium to Roskilde Fjord from reactor DR 2.

Reference accident	Doses in Denmark (μSv)				Doses in Sweden (μSv)	
	Water		Fish		Fish	
	Children	Adults	Children	Adults	Children	Adults
Reactor DR 2	$1 \cdot 10^{0}$	$2 \cdot 10^{0}$	$8 \cdot 10^{-2}$	$5 \cdot 10^{-2}$	$4 \cdot 10^{-6}$	$3 \cdot 10^{-6}$

5 Conclusions

Assessments of potential doses to the surrounding population from atmospheric releases of radioactive materials during decommissioning, both from normal operation and from accidents, require analyses that would be extremely costly. An alternative and deterministic approach has been used relating a fractional release of the activity inventory from each nuclear plant to individual radiation doses to members of the critical group in the surrounding population and the nearest population in the neighbouring country Sweden. The calculated doses to the critical group from both routine and accidental releases during decommissioning - and from both atmospheric and aquatic exposure - appear to be only a very small fraction of the individual doses from the naturally occurring background radiation.