

Radioecological consequences of a potential accident during transport of radioactive materials along the Norwegian coastline



Reference:

Iosjpe M., Reistad O., Amundsen I. Radioecological consequences of a potential accident during transport of radioactive materials along the Norwegian coastline StrålevernRapport 2007:3. Østerås: Norwegian Radiation Protection Authority, 2007.

Key words:

Radioactivity, transport, accident, consequences, concentration, doses, marine, biota

Abstract:

This report presents results detailing possible consequences of an accident occurring while spent nuclear fuel (SNF) is being transported along the Norwegian coastline. The findings are based on modelling of hypothetical releases of radionuclides, radionuclide transport and uptake in the marine environment. Modelling work has been done using a revised box model developed at NRPA. Results from the calculation of concentrations of radionuclides in marine organisms as well as doses to man and biota are discussed.

Referanse:

Iosjpe M., Reistad O., Amundsen I. Radioecological consequences of a potential accident during transport of radioactive materials along the Norwegian coastline StrålevernRapport 2007:3. Østerås: Statens strålevern, 2007. Språk: engelsk.

Emneord:

Radioaktivitet, transport, ulykke, konsekvenser, konsentrasjon, doser, marint, biota

Resymé:

Rapporten inneholder beregninger av mulige konsekvenser dersom et transportskip med kjernebrensel forliser langs norskekysten. Resultatene er basert på modellering av hypotetiske utslipp av radionuklider, transport av radionuklider og akkumulering i det marine miljø. Modelleringsarbeid er utført med bruk av Statens strålevern modifiserte modell. Beregninger av konsentrasjoner av radionuklider i marint organismer og stråledoser til befolkning og biota er diskutert.

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Approved:



Per Strand, Director, Department for Emergency Preparedness and Environmental Radioactivity

15 pages.

Published 2007-03-10.

Printed number 150 (07-03).

Cover design: LoboMedia AS.

Printed by LoboMedia AS, Oslo.

Coverphoto: Contribution from the Norwegian Maritime Directorate photo competition: Knut Revne.

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Telephone +47 67 16 25 00, fax + 47 67 14 74 07.

www.nrpa.no

ISSN 0804-4910

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Østerås, 2007

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1 Introduction

In 2002 the Russian Federation supplemented the Federation Law “Concerning Use of Atomic Energy” from 1995 with an article concerning the possibility of importing spent nuclear fuel (SNF) to Russia (RF, 2002). In Norway, public concerns have been raised about Russian plans for importing SNF for reprocessing and storage at Mayak facilities as it is likely to result in sea transport of SNF along the Norwegian coastline. Concern has also been raised about the possible opening of a new transport route along the northern coast of Russia for SNF e.g. from European reprocessing facilities to Japan. The Russian plans caused much publicity and debate in Norway, where large economical interests are connected to the export of marine food products. Past experiences have shown that only rumours of radioactive contamination in seafood can lead to economical consequences for producers. This report evaluates the consequences of a potential accident during transport of radioactive material along the Norwegian coastline. The study is financed by the Norwegian Ministry of Foreign Affairs through the Action Plan for Nuclear Safety.

In 1995, the IAEA initiated a coordinated research project considering the severity of accidents during marine transport of radioactive materials. The project, which was completed in 1999, came to the following overall conclusion:

“Consequently, since the probabilities of severe ship collisions and severe fires are small and since individual radiation doses that might result in the event of such collisions or fires are smaller than normal background doses, the risk posed by maritime transport of highly radioactive material such as irradiated nuclear fuel, vitrified high level waste and

mixed oxide fuel in Type B packages are very small.”

While the IAEA conclusion is of general interest, this report describes possible consequences for a similar transport accident occurring along the Norwegian coastline, based on modelling of hypothetical releases of radionuclides, transport and uptake in the marine environment. Modelling work has been done using a revised box model developed at NRPA.

2 Theory and methodology

2.1 Source terms

The main focus of this project has been to develop credible source terms together with the application of the box model developed at NRPA, which uses geographical areas relevant for the proposed transport route for radioactive materials.

The source term describes the release of radioactive materials from a specific source. In this work we have described the source term as an inventory of radionuclides, released as a function of time and release point. The release inventory has developed using the ORIGEN programme with calculations undertaken at the Institute of Energy (IFE), based on Sanders *et al.*, (1992).

For the potential accidents, a standard fuel assembly has been chosen, using relatively low enrichment (3,2 %) and two different burn-up values (standard 38 169/ extended 53 068 MWd/ tHM), with average cooling times i.e., 5 years. This was chosen on the basis of that future transport of SNF along the

Norwegian coast probably be fuel from recently designed reactors, therefore lower enrichments and higher burn-up values are particularly relevant.

The source term has been divided into two possibilities: (i) an instantaneous release of radionuclides; often referred to as the Instant Release Fraction and (ii) a slow long-term contribution corresponding to the dissolution of the uranium oxide matrix. Considering (i), this consists of 10% release of the total inventory immediately after the ship sinking, due to the accident, followed by annual releases of 0,09 % of the inventory over the course of following 1000 years. This is a conservative estimate, in particular for the transuranium elements; further studies will consider a more differential approach for different groups of radionuclides. However, this initial study adds important knowledge to sensitivity considerations related to variations in the source term. One scenario was constructed based on the releases from one waste cask. Further scenarios corresponded to releases from 10 and 100 waste casks, also based on the standard fuel assembly, in order to discuss the sensitivity of the final results. The total available release inventory of radioactivity for a standard fuel assembly, at the time of the ship sinking, was assumed to be 30,1 PBq.

About eight hundred radionuclides (fission products and actinides) were considered in this project. Most of the potentially released radionuclides had a negligible influence for the potential accident consequences due to short half-lives and/or small activities. However, in each scenario, 25-30 radionuclides that could potentially affect the surroundings were studied in the modelling work.

Additional considerations such as the causes and potential frequency of such accidents have not been made part of this work.

2.1.1 Accident location

The location chosen for the potential accident was based on the evaluation of radiological sensitivity of the relevant marine areas. The radiological sensitivity analysis was based on the definition of the radiological sensitivity index $RS^{(M)}$ (Iosjpe *et al.*, 2003):

$$RS^{(M)} = \frac{\Delta D}{S \Delta T},$$

where ΔD is a variation in the collective dose to man during time ΔT (a collective dose-rate) and S is the surface area of the relevant marine region.

Radiological sensitivity analysis of marine regions shows that the Norwegian coastline and the Barents Sea are the most sensitive areas in the Arctic region when considering the effects of radioactive contamination. Figure 1 illustrates this conclusion with calculations of the collective dose-rate (milli-manSv per year) variation per 1 m² after uniform atmospheric deposition of 1 kBq/m² on to the Arctic, North Atlantic and European coastal waters. Calculated doses presented in Figure 1 correspond to the most significant value of the dose-rate calculated after deposition.

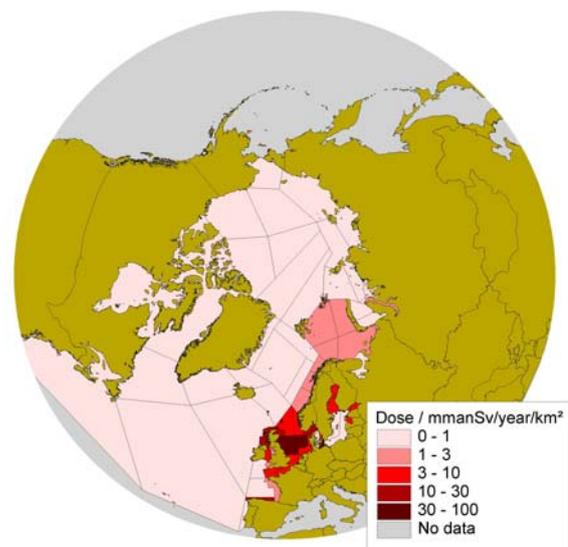


Figure 1. Sensitivity of marine regions in the Arctic Ocean.

Experimental data (AMAP, 1998) and calculations of the dispersion of radionuclides from the Sellafield region (Karcher *et al.*, 2005) show that radionuclides entering southern Norwegian coastal waters become part of the Norwegian current moving northwards along the coastline in the direction of the Barents Sea and Svalbard Current

Therefore, considering results of sensitivity analysis, potential ship paths and radionuclide traces, the accident location was chosen in the south part of the Norwegian Current with purpose to achieve the maximal effect of potential contamination to man and environment (Figure 2).

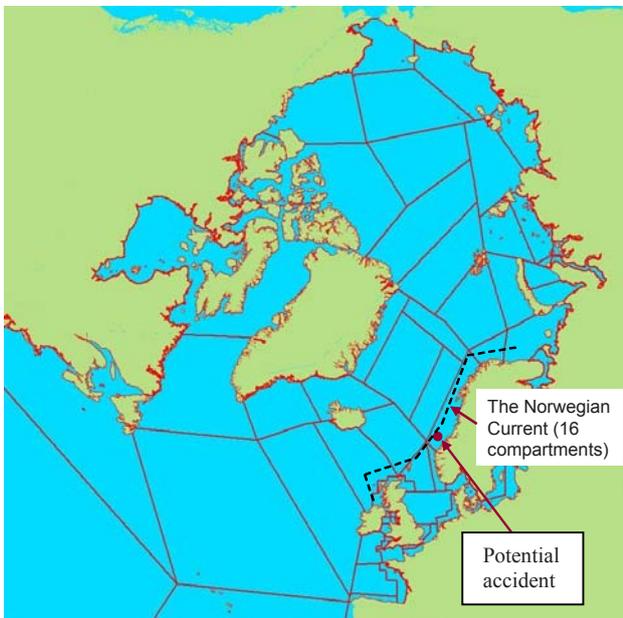


Figure 2. A potential ship trace and the potential accident location.

2.2 Model description

The box model developed at NRPA uses a modified approach for compartmental modelling (Iosjpe *et al.*, 2002) which includes dispersion of radionuclides during time (non-instantaneous mixing in oceanic space).

The boxes structure for surface, mid-depth and deep waters is developed with regards to improved description of polar, Atlantic and deep waters in the Arctic Ocean and the Northern Seas and site-specific information for description

of the boxes (Karcher & Harms, 2000; Karcher, 2006¹) on the basis of the 3D hydrodynamic model NAOSIM. The volume of the water layers in each box has been calculated by using a detailed bathymetry using GIS.

The model includes the processes of advection of radioactivity between compartments, sedimentation, diffusivity of radioactivity through pore water in sediments, resuspension, mixing due to bioturbation and particle mixing and a burial process of activity in deep sediment layers. Radioactive decay is included in all compartments.

Contamination of biota is calculated by the model from the radionuclide concentrations in filtered seawater in the different water regions.

Doses to man are calculated on the basis of data for the catch of seafood and assumptions about human diet. Doses to biota are calculated on the basis of radionuclide concentrations in marine organisms, water and sediment and dose conversion factors (Iosjpe, 2006; Brown, 2006²).

It is necessary to note that the concentration factors used for calculating doses to biota (Brown, 2006) can differ significantly from IAEA recommendations (IAEA, 2004). This is largely because concentration factors given in Brown (2006) were evaluated for the whole organism, whereas IAEA concentration factors are often defined only for edible parts of biota, that which has a potential consequence for dose assessments to man.

¹ Karcher M.J. (2006). Estimation of water fluxes in the Arctic Ocean on the basis of the NOSIM model, personal communications

² Brown J. (2006). CF and DCF for biota. Present statement of the ERICA project, personal communications

3 Results and discussion

Evaluation of the radioecological consequences of potential accidents during the transport of SNF along Norway's coastline has been made on the basis of calculated collective dose rates to man, doses to critical groups, concentrations of radionuclides in biota, with regards to seafood, and doses to marine organisms.

3.1 Release Scenario

In this report, results of simulations will be discussed with regard to a worst case scenario: 100 fuel packages lost from a sunken transport ship off the southern Norwegian coastline.

Total releases and individual releases of the ten radionuclides that had the most significant effect on the release rate during the initial and final time of releases are shown in Figure 3. As would be expected, the maximal release corresponds to the initial period after the sinking of the ship. ¹³⁷Cs and ²⁴¹Pu are most significant radionuclides for the total release during this time, while ²⁴¹Am dominates in the final period of calculated radionuclide releases. It is necessary to note that release of ²⁴¹Am increases significantly during initial phase, due to the large amounts of ²⁴¹Pu in releases.

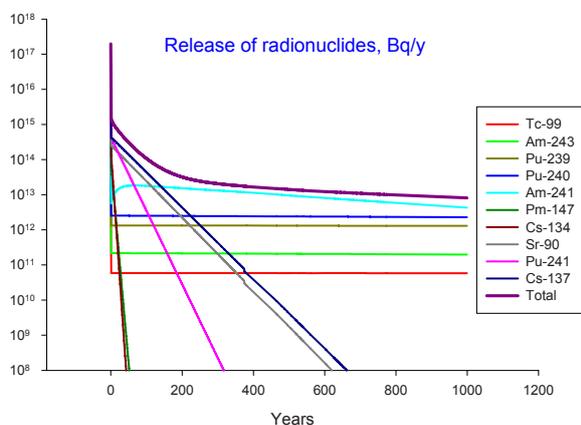
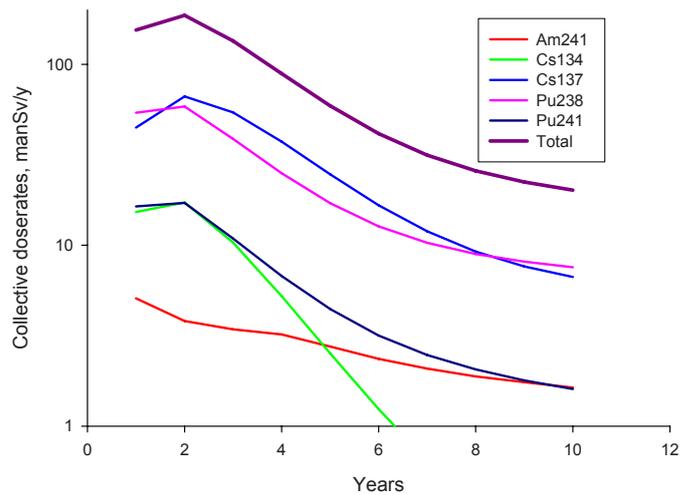


Figure 3. The worst case release scenario.

3.2 Collective dose-rates to man

Dose rates to man were calculated using the following assumptions for edible fractions of marine produce in the human diet: 50 % for fish, 35 % for crustaceans and 15 % for molluscs. More than 30 radionuclides were considered. Figure 4 shows five radionuclides that have the most significant impact on doses to man during the initial time of releases. Results of calculations presented in Figure 4 show that maximum dose rates in the studied scenario, for the global population, occur during the second year after radioactivity is released.

Collective Doserates to Scenario 1:
 maximum doserate according to the present scenario is 200 manSv per year (the guideline level for Norwegian population is 4000 manSv per year)



The maximum dose rate is 200 manSv per year, approximately. Cesium-137 and ²³⁸Pu were the nuclides that had the most impact on total dose rates. It is necessary to stress that the guideline level for dose rate for the Norwegian population alone can be estimated as 4000 manSv per year (1 mSv · 4·10⁶ persons = 4000 manSv) i.e., significantly higher dose rates than of the modelling estimates for the accident scenario.

3.3 Concentration of radionuclides in biota / seafoods

The calculated concentrations of radionuclides in biota (fish, molluscs and crustaceans) was evaluated with regards to international guideline levels (CAC, 2006). According to CAC (2006), radionuclides can be separated into four groups (examples of some typical radionuclides are shown in Table 1.

Table 1. Examples of international guideline levels for radionuclides in food.

Radionuclides in Foods		Guideline Level (Bq/kg)	
		Infant Foods	Other Foods
Group 1	^{238}Pu , ^{239}Pu , ^{241}Am	1	10
Group 2	^{90}Sr , ^{106}Ru , ^{129}I	100	100
Group 3	^{60}Co , ^{134}Cs , ^{137}Cs	1000	1000
Group 4	^3H , ^{14}C , ^{99}Tc	1000	10000

The model calculations indicated that concentrations of radionuclides in biota remain below acceptable guideline levels for the radionuclides in CAC groups 3 and 4. The concentrations of radionuclides in biota / seafoods for group 1 and 2 radionuclides did, in

certain instances, become higher than guideline values. Results for radionuclides in groups 1 and 2 are shown in Figures 5 – 7.

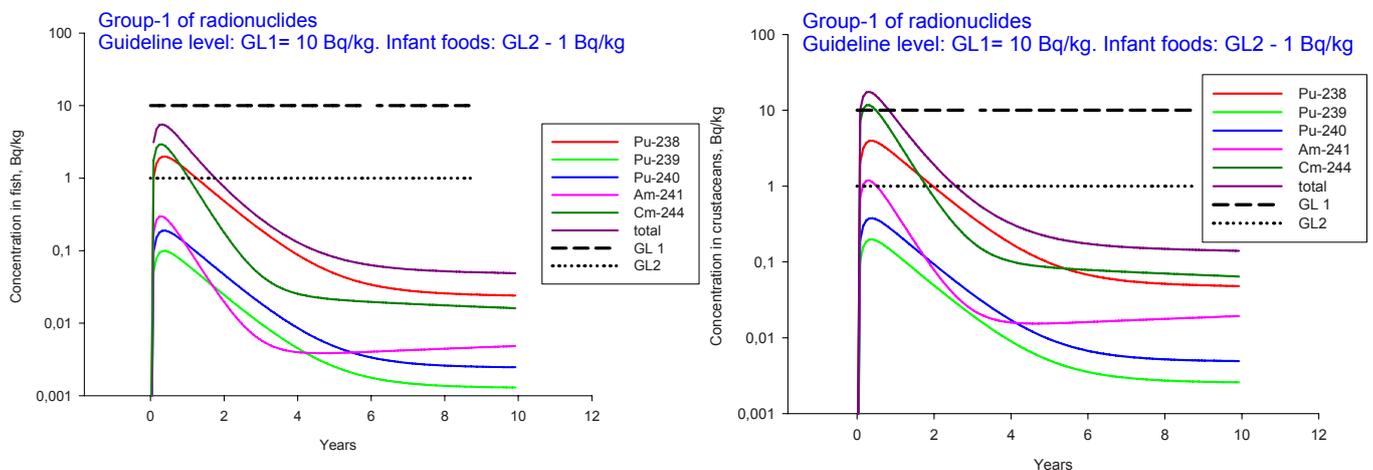


Figure 5. Comparison of radionuclides levels in fish and crustaceans with international recommendations to group 1

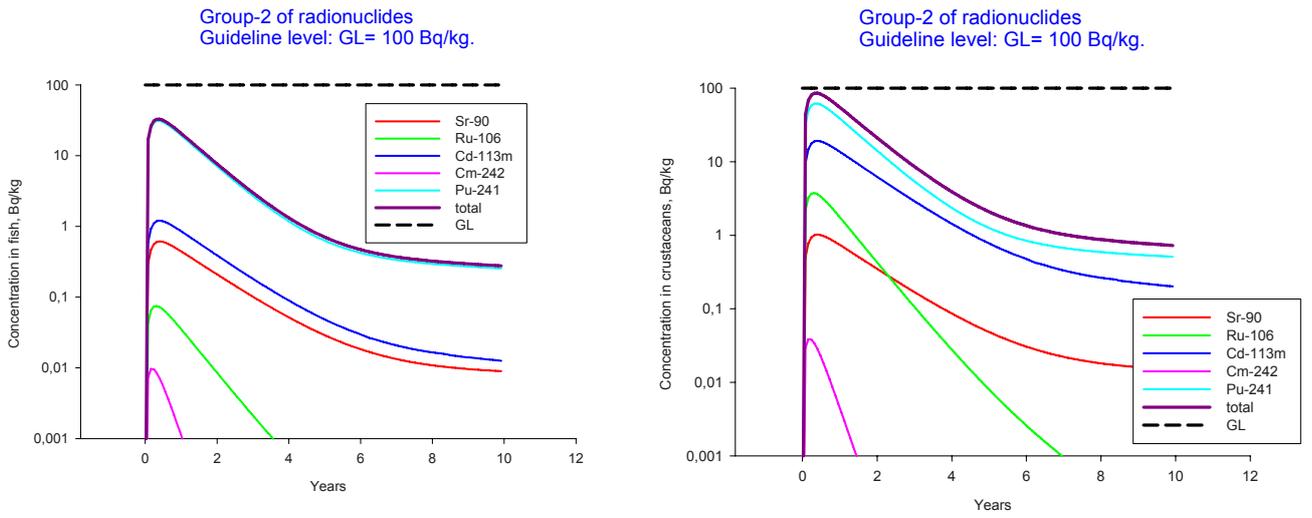


Figure 6. Comparison of radionuclides levels in fish and crustaceans with international recommendations to group 2.

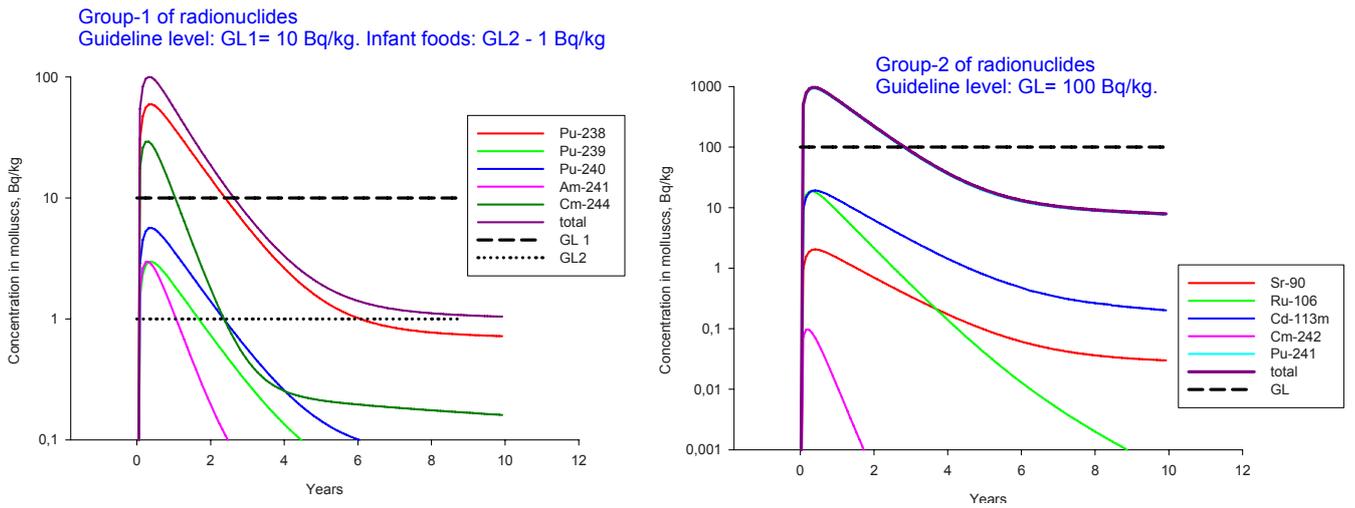


Figure 7. Comparison of radionuclides levels in molluscs with international recommendations to groups 1 and 2.

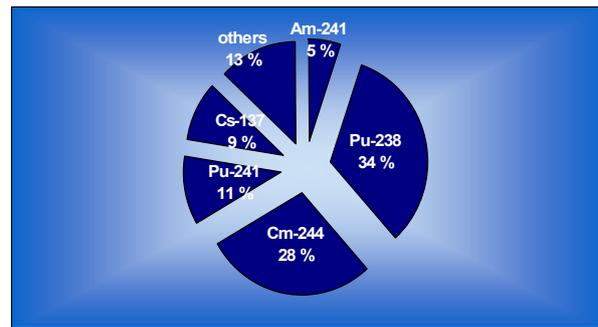
Calculated concentrations of group 2 radionuclides in fish and crustaceans were lower than guideline levels (Figure 6). However concentrations in molluscs were calculated to be higher than guideline levels during the first three years after the accident. Concentration of radionuclides for group 1 are higher than guideline levels for all reference biota. The most significant concentrations were found in molluscs (Figure 7). Figure 7 indicates that concentrations of radionuclides in molluscs were higher than guideline levels during the first four years after releases and for more than ten years when considering guidelines for infant foods.

The maximal differences between evaluated concentrations of radionuclides and international recommendations are up to a factor ten for general foods and factor 100 for infant foods, during the initial period after release. The most significant impact to concentration levels for group 1 of radionuclides corresponds to ^{238}Pu and ^{244}Cm . It is necessary to note that concentrations of radionuclides in biota in excess of international guidelines will not lead to the high dose-rates calculated for man presented in section 3.2 of the present report.

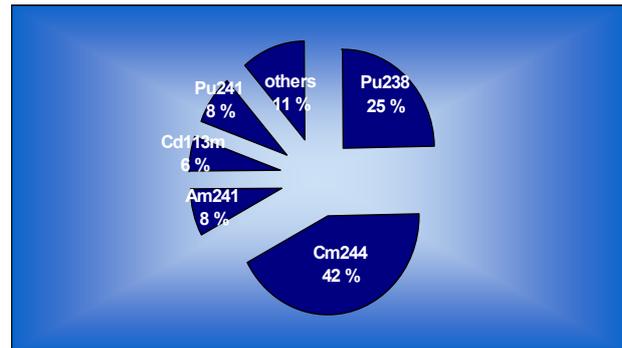
3.4 Doses to critical group

Doses have been calculated for the critical group according to an investigation of consumption patterns for different population groups living on the coast and in the inland of Norway (Bergsten, 2003). Maximal consumption for seafood was reported as 200g per day for fish, 40g per day for crustaceans and 4g per day for molluscs.

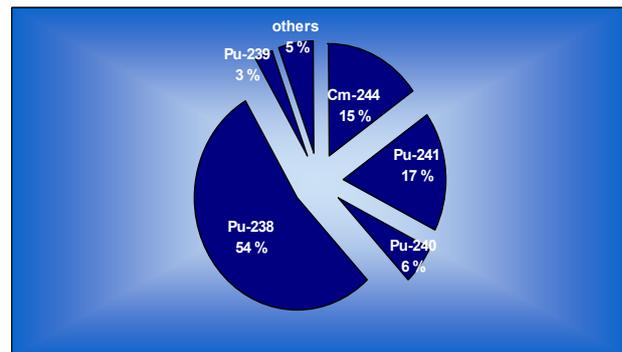
The proportions of the total calculated dose attributable to different seafoods are presented in Figures 8 and 9. Model calculations showed that maximal impacts to total dose from fish, crustacean and molluscs are were 0.3, 0.2 and 0.1 mSv per year, respectively.



(a)



(b)



(c)

Figure 8. Dose impact to critical group from biota: (a) fish, (b) crustaceans and (c) molluscs

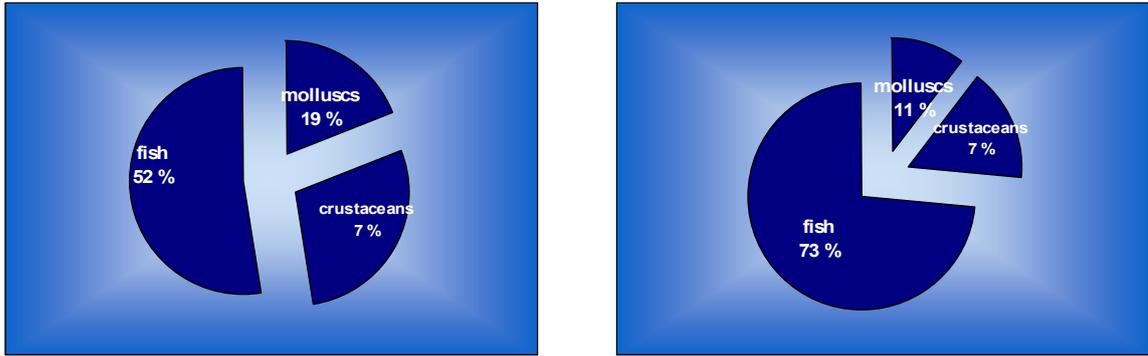


Figure 9. Distribution of total doses to critical groups according to (Bergsten, 2003) – left, (IASAP, 2003) – right.

The maximum total dose-rate for the critical group is 0.6 mSv per year. For the studied scenario, radionuclides ^{238}Pu and ^{244}Cm have had the most significant contribution to doses. In the EU funded project IASAP (IASAP, 2003) maximal consumption for fish was evaluated as 500g per day. If the same consumption rate is used in this scenario (over twice the recorded consumption), maximum total doses per year are 1.1 mSv. Results of calculations have demonstrated that the doses to the critical group are most likely to be below the international personal guideline level of 1 mSv per year.

3.5 Doses to marine organisms

Doses were also calculated for reference marine organisms (fish, crustaceans and molluscs). A preliminary agreement exists that dose rates of $10 \mu\text{Gy}$ per hour are non-dangerous levels for biota (Brown, 2006). Results of model calculations are shown in Figure 10.

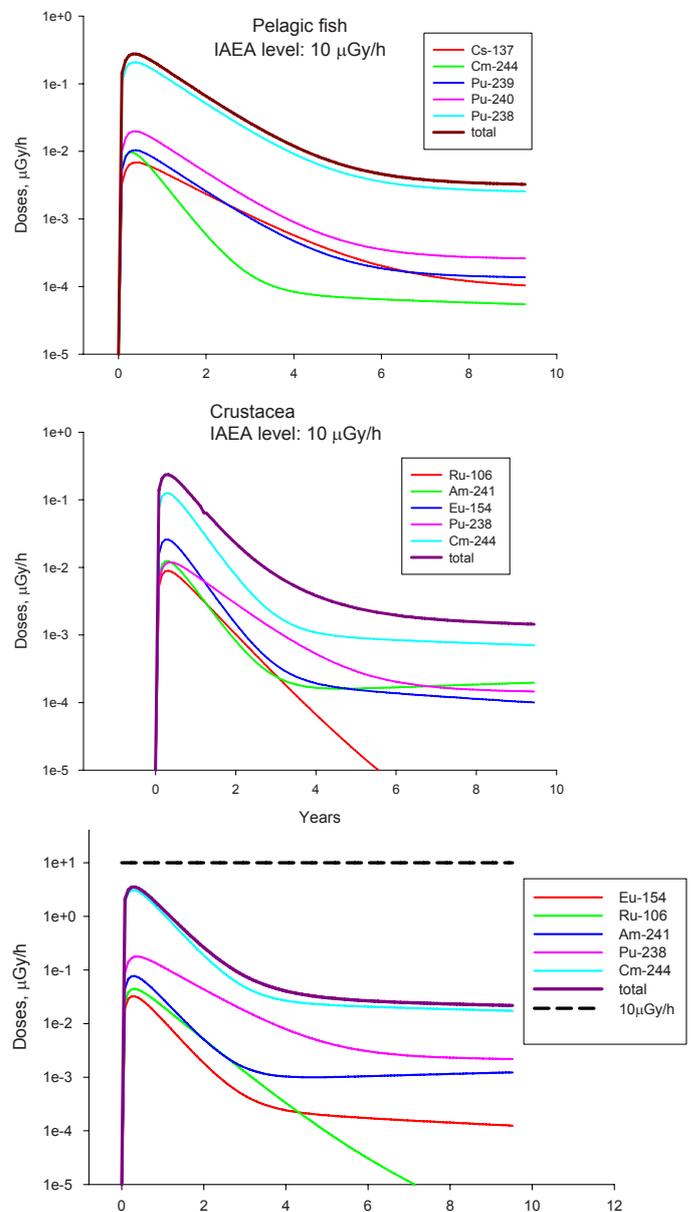


Figure 10. Doses to biota in comparison with screening dose of $10 \mu\text{Gy/h}$

Comparing results of dose calculations to the considered reference organisms with screening dose of 10 μGy per hour indicates that maximal doses to biota are generally below this recommended level. It is necessary to note that evaluation of the doses to marine organisms is not a trivial problem; it is now under discussion in the course of the EU funded project ERICA.

An example of when doses exceed recommended levels for this scenario is provided by the dose to the *Polychaete Worm* which exceeds the screening dose (10 μGy) by up to one order of magnitude during a long time period for many generations of marine organisms (Figure 11). This result can be explained by the habitat of *Polychaete Worm*, which lives in sediments that generally have high distribution coefficients regarding radionuclides held in the sediment/seawater. It is, however, important to note that the doses to the *Polychaete Worm* exceeding the screening dose 10 μGy would not automatically mean damage to organism colony. It may however merit that the situation would have to be taken under special consideration.

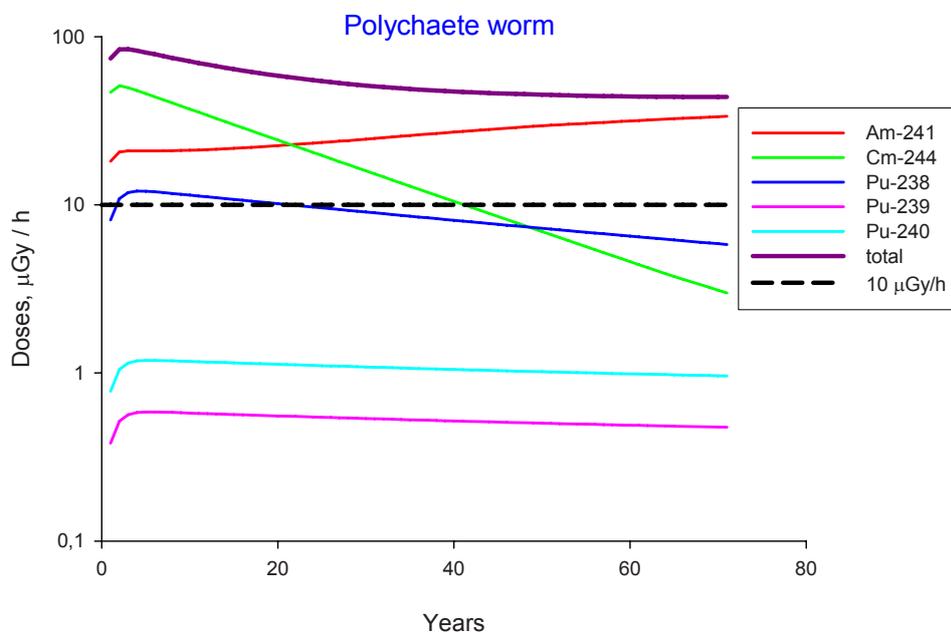


Figure 11. Doses to *Polychaete Worm* in comparison with screening dose of 10 $\mu\text{Gy/h}$

4 Uncertainties

The choice of the scenario is a crucial factor for evaluation of radioecological consequences after releases of radionuclides into marine environment. Therefore, the conservative scenario, used in the present report, has to “cover” other potential uncertainties of model simulations.

Furthermore, accuracy of calculations can be improved by refinements of concentration factors and sediment distributions coefficients, which are now defined with a precision of up to one order of magnitude (IAEA, 2004).

It is, also, necessary to improve knowledge about water-sediment interaction with regards to sedimentation and remobilisation processes for radionuclides. This is especially important because remobilisation effects for radionuclides from group 1 have been documented and are therefore very significant for the evaluation of consequences after discharge of radionuclides into marine environment.

5 Conclusions

In spite of the very conservative scenario, the collective dose rates to man and to the critical group are not higher than 1,1 mSv per year.

Results did indicate, however, that concentrations of radionuclides for some marine organisms exceeded guideline levels after the radioactive releases. Elevated levels of radionuclides in marine food products may lead to economical consequences in a market which is very sensitive to reports of contamination. However, health consequences due to the elevated radiation doses in humans were shown to be of minor concern.

Comparing dose calculations for biota with screening dose limits agreed within the ERICA project (Brown, 2006) indicates that doses to the majority of marine organisms are far below the level where adverse effects are expected (screening dose of 10 μ Gy per hour). At the same time doses to some marine organisms can be much higher (up to one order of magnitude) than screening dose of 10 μ Gy/h over long periods, which means that statistically significant effects could be expected for these organisms (Real *et al.*, 2004).

Moreover, extensive additional monitoring of marine environment as well as assessment of levels of contamination in the environment and doses to man and biota are expected in the event of this accident scenario ever occurring, where a ship carrying SNF sinks off the Norwegian coastline.

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StrålevernRapport 2007:1

Virksomhetsplan 2007

StrålevernRapport 2007:2

Representative doser i Helse Øst. Representative doser for røntgendiagnostikk rapportert fra virksomheter i Helse Øst høsten 2006