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2046 Estimation of the radiation dose equivalent for the hypothetical submergence of a sea-transport package of radioactive materials by the state-of-the-arts oceanic dispersion model

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Abstract

The requirement for a 200 m water submersion test for irradiated fuel packages was originally added to the 1985 edition of the Regulations to reduce the radiological impact by the submergence accident based on the impact assessment study on the hypothetical submergence of spent fuel package. After that, CRIEPI has carried out assessments of the dose to the public from a hypothetical release of radioactive materials from a submerged irradiated nuclear fuel packages, such as spent fuel, high level wastes and fresh mixed-oxide fuel to gain the public acceptance for sea transport even if the probability of the accident is estimated to be extremely low.

The method of impact assessment for both near shore and deep sea areas consists of estimation of the release rate, simulation of the radionuclide concentration by the oceanic dispersion model and estimation of the dose by ingestion of sea foods to the public. We have employed the state-of-the-arts oceanic dispersion model which has been making rapid progress due to the rapid progress of super-computing.

We applied oceanic dispersion models to simulate the concentration of radioactive materials due to the Fukushima Daiichi Nuclear Power Plant accident. Release amounts of radioactive materials were estimated by comparison with measured data and simulated result by oceanic dispersion model. Validations of the model was carried out in comparison with measured data after the accident to improve the model. Improved model reasonably represented measured data and helped understanding ocean-ic contamination due to the accident.

We carried out impact assessment of submergence accident of a radioisotope package near shore by the improved oceanic dispersion model. The estimated dose equivalents were extremely lower than the ICRP recommendation (1 mSv year^{-1}). The results of tracer studies by the improved model indicated that the results of dose assessment by previous model are also reasonable. Improved model can predict the affected area reasonably because the model can represent the realistic oceanic condition, such as current and stratification. This is an advantage to employ to make the emergency plan for the submergence accident.

Introduction

Assessments of the dose to the public from a hypothetical release into the sea of spent fuel from a submerged irradiated nuclear fuel package were first carried out by Battelle Pacific Northwest Labs in 1977 (Heaberlin *et al.*, 1977) and Central Research Institute of Electric Power Industry (CRIEPI) in 1978 (Nagakura *et al.*, 1978). Based on the results of these studies, the IAEA included the following passage in advisory material for the IAEA Regulations for the safe transport of radioactive material (IAEA, 2008): "Various risk assessments consider the possibility of a ship carrying packages of radioactive material sinking at various locations. In general, it was found that most situations would lead to negligible harm to the environment and minimal radiation exposure to persons if the packages were not recovered following the accident. In the interest of keeping the radiological impacts as low as reasonably achievable should such an accident occur, the requirement for a 200 m water submersion test for irradiated fuel packages containing more than 37 PBq of activity was originally added to the 1985 edition of the Regulations. Recovery of a package from this depth would be possible and often would be desirable."

Assessments of the dose to the public from a hypothetical release of radioactive materials related to the nuclear power from a submerged irradiated nuclear fuel package into the sea have been carried out by CRIEPI mainly for spent fuel (SF) (Nagakura *et al.*, 1978), high level waste (HLW) (Watabe *et al.*, 1996) and mixed oxide (MOX) fuel (Tsumune *et al.*, 2000a). Later, CRIEPI summarised its findings regarding the radiological impact of the submergence of Type B packages (SF, PuO_2 powder, HLW and MOX fuel) in coastal areas in IAEA TECDOC 1231 (IAEA, 2000) and a journal article (Tsumune *et al.*, 2000b). The evaluated results of the dose equivalent for all these materials were far below the dose equivalent limit of the ICRP recommendation (1 mSv year^{-1}). The methods used to simulate the concentration of radionuclides in the ocean were improved by employing an ocean general circulation model (Tsumune *et al.*, 2007). In previous study, an ocean general circulation model was driven by the climatologic forcing data to estimate the averaged distribution of radioactive materials in the ocean. More realistic regional ocean circulation model was required to estimate the distribution of radioactive materials released by the Fukushima Daiichi Nuclear Power Plant accident (Tsumune et al., 2012; 2013). The regional ocean model driven by the realistic forcing data can represent the realistic temporal change of radioactive material concentration.

In this study, we carried out assessments of the dose to the public from a hypothetical release of radioisotope (C-188 Cobalt-60 Sealed source) packages near shore around Japan by the state-of-the-arts regional ocean model. In addition to the radioactive material related to nuclear power, radioisotope was broadly transported by sea from US coast to Japan and other countries.

Methods

The method of impact assessment for both near shore and deep sea areas consists of estimation of the release rate, simulation of the radionuclide concentration and estimation of the dose to the public.
According to IAEA transport regulations, a package submerged to a depth of 200 m should not rupture.

It would therefore be possible to salvage the package, so a conservative depth of 200 m was assumed for the assessment in the case of submergence near shore. Submergence point is set to be at the depth of 200m off Fukushima coast as a case study.

Radionuclide release scenario

The barrier effect model (Watabe et al., 1996; Tsumune et al., 2000a), in which the presence of packaging material reduces the release rate of nuclides to the ocean, is employed to estimate the release rate of radionuclides from a package submerged near shore. We use an analytical solution method in this study. Accordingly, the following conservative scenario is assumed:

(a) The package is submerged on the seabed at a depth of 200 m.

(b) After submergence, sealability is immediately lost by the failure of an O-ring.

(c) Seawater enters into the cavity of the package.

(d) Radioactive materials are exposed to the seawater.

(e) Nuclides leach into the seawater in the cavity of the package.

(f) The solution of nuclides is released to the ocean through the seal gap.

Transport package

Special designed package is used for sea transport. Total amount of radioactivity of ^{60}Co is 7.4 PBq in a package.The inner diameter of the package is set to be 0.162 m. The length of the flow channel is set to be 0.04 m, which is the thickness of the package wall. It is assumed that seawater enters the package through the lower part of the gap and goes out through the upper part of the gap. The width of the gap is conservatively assumed to be 0.01 mm, taking into account the degree of surface finish (3–6 μ m) of the lid and body (Tsumune *et al.*, 2000a). The volume of the cavity in the package is set to be 0.01 m^3.

Ocean circulation model

We employed the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005). The ROMS is a three-dimensional Boussinesq free-surface ocean circulation model formulated using terrain-following coordinates. The model domain in this study covered the oceanic area off Fukushima (35° 54′ N-40° 00′ N, 139° 54′ E-147° 00′ E). The horizontal resolution was 1 km in both zonal and meridional directions. The vertical resolution of the σ coordinate was 30 layers. The ocean bottom was set at a depth of 1000 m to reduce the computer resources needed for the simulation. The actual ocean depth reaches much more than 1500 m in this region.

The model was forced at the sea surface by wind stress and heat and freshwater fluxes, the values of which were acquired by a real-time nested simulation system (NuWFAS, Hashimoto et al., 2010) of the WRF, a global spectral model used for numerical weather prediction by the Japan Meteorological Agency (JMA). The horizontal resolution of the system was 5 km in both the zonal and meridional directions. The time step of the output from the real-time simulation system was 1 h, and the duration of the simulation was 1 year. During the simulation, horizontal currents, temperature, salinity, and sea surface height along the open boundary were restored to the JCOPE2 reanalysis data (JCOPE2, Japan Coastal Ocean Prediction Experiment 2, Miyazawa et al., 2009). Horizontal resolution of JCOPE2 is 1/10°. Temperature and salinity were nudged to the JCOPE2 reanalysis results to represent mesoscale eddies during the simulation period in the ROMS with higher resolution (1km x 1km). The nudging parameter was 1 d^{-1}. The initial conditions of temperature, salinity, horizontal current velocities, and sea surface height were set by the JCOPE2 reanalysis output.

The basic three-dimensional diffusion equation with the decay of radionuclides is used to describe the concentration of radionuclides.

Assessment of the dose to the public

The internal dose from ingestion of seafood in the area of calculation is calculated according to ICRP Pub. 72 (ICRP, 1995), as in previous studies (Tsumune *et al.*, 2000a). The external dose equivalent by marine operations was ignored in this study because it is much smaller than the internal one.

The internal exposure route was taken from guidelines for the calculation model for evaluating the dose equivalent around a nuclear power station during normal operation. Internal exposure is evaluated for a maximally exposed reference person by considering daily averaged seafood ingestion. The numerical model and the values for ingested seafood, in which the radionuclides are concentrated, were obtained from the guidelines (Nuclear Safety Committee, 1989a, 1989b).

The equivalent dose to the public is estimated by the radionuclide concentration in the ocean by using the following equation:

[Equivalent dose to the public (Bq $year^{-1}$)] = [Radionuclide concentration in the ocean (Bq m^{-3})] × [Dose factor (Sv Bq^{-1})] × [Concentration factor ((Bq g^{-1})/(Bq cm^{-3}))] × [Ingestion rate (g day^{-1})]

Results and discussion

Release rate

The release rates of radionuclides from the radioisotope packages were estimated by the barrier effect model. Fig.1 show the release rates with and without the barrier effect of ^{60}Co from one radioisotope package. The release rates increased with time until the radionuclide concentration saturated. After that, the release rates decreased with time from decay. The release rate with barrier effect is four order of magnitude smaller than the one without barrier effect one year after release.

Tracer concentration in the ocean

Three-dimensional distribution of tracer concentration is simulated with unit release (1 unit/year) by the regional ocean model from January 2013 to December 2013. Fig. 2 shows the distribution of tracer concentration in the surface layer (0-100m) one year after release. “x” shows the release point at the depth of 200m. Released tracer upwelled along the Fukushima coast. Tracer in the surface layer advected to east along the Kuroshio. The distribution varies with time due to the change of oceanic current field. Maximum and year averaged tracer concentration in the surface layer (0-100m) for one year are estimated to be 5.1 x 10^{-13} unit/m^3 and 1.2 x 10^{-13} unit/m^3, respectively. Averaged tracer concentration is similar to the one by previous regional ocean model (horizontal distribution; 10km) driven by the climatological forcing data (Tsumune et al., submitted). This shows that the previous estimation is also reasonable for dose estimation. The reginal ocean model with realistic forcing has an advantage to make the emergency response plan.

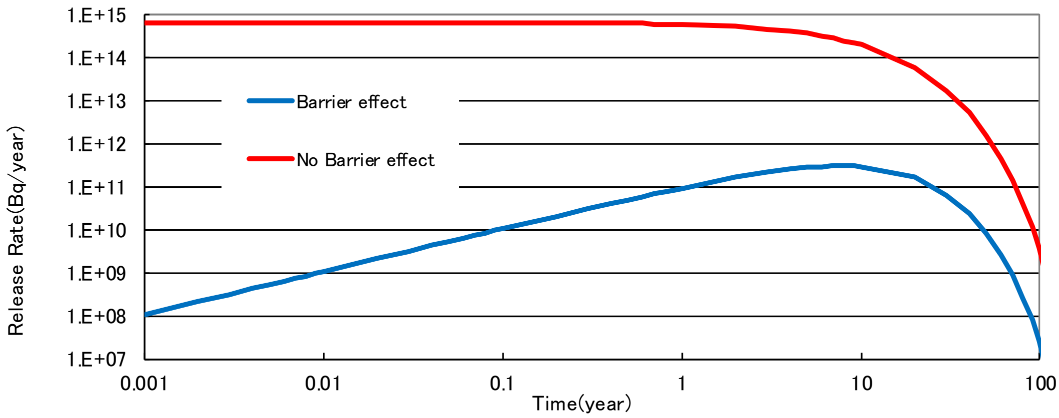

Figure 1 Release rate of ^{60}Co from one radioisotope package. Blue line shows the results with barrier effect. Red line shows the results without

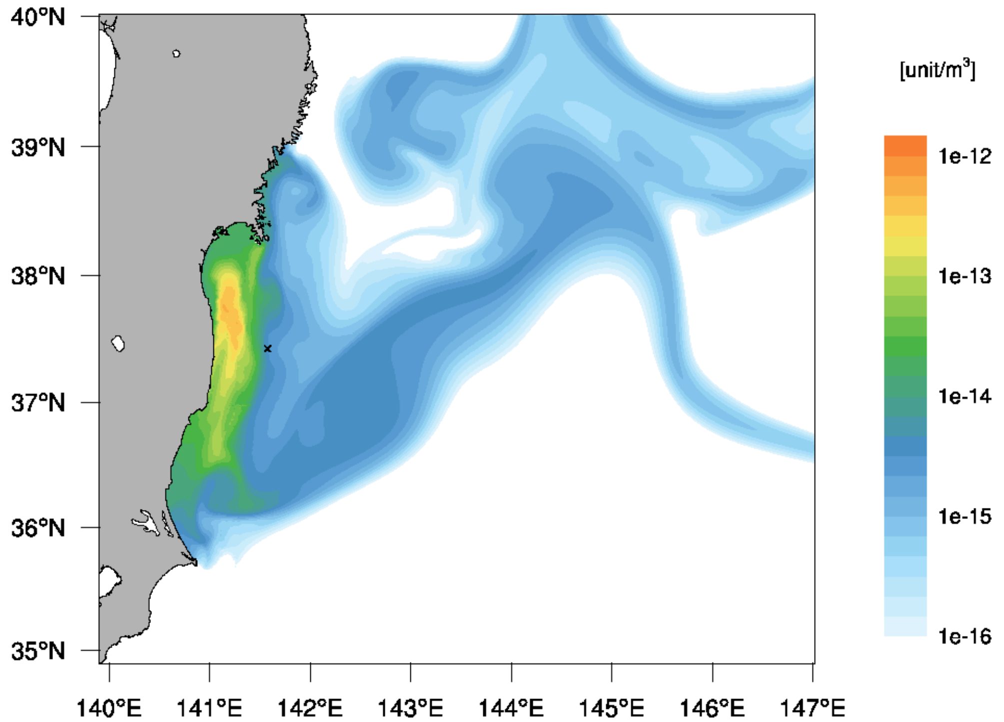

Figure 2 Distribution of tracer concentration with unit release one year after release. " x" shows the release point.

^{60}Co concentration in the ocean

Radionuclide concentrations in the ocean (Bq m^{-3}) for each release rate of radionuclides (Bq year^{-1}) were estimated from the tracer concentrations (unit m^{-3}) with a unit release of tracer (1 unit year^{-1}). The spatiotemporal maximum tracer concentration was 2.3×10^{-13} Bq m^{-3} off Fukushima in the surface layer (0–100 m) with unit release. The spatiotemporal maximum radionuclide concentrations from the radioisotope packages are 9.3×10^{-2} Bq m^{-3}. Measured ^{60}Co concentration was 1.2 Bq m^{-3} at Yokosuka port when the Nuclear submarine, Honolulu called in on 14 September 2006 http://www.mext.go.jp/a_menu/anzenkakuho/news/siryou/environ01/20061211_02g.pdf(in Japanese)). This concentration is quite smaller than the guidance level for ^{60}Co in drinking water by the World Health Organization, which is 100,000 Bq m^{-3} (WHO, 2011). There is no guideline for sea water. The estimated concentration of ^{60}Co in this study is quite smaller than both concentration.

Equivalent dose to the Puclic

We estimated the equivalent dose to the public from the radionuclide concentrations in the ocean due to the hypothetical submergence of a radioisotope package. The total dose equivalents from the radioisotope packages were 8.1×10^{-5} mSv year^{-1}. The dose equivalent by fallout was estimated to be 2.4×10^{-3} mSv year^{-1} in the 1960s and 2.3×10^{-4} mSv year^{-1} in the 1990s from the averaged background concentrations of ^{137}Cs, ^{90}Sr and ^{239,240}Pu. The estimated dose equivalents in this study are much smaller than those due to global fallout and natural sources. The estimated dose equivalents are also much smaller than the ICRP recommendation (1 mSv year^{-1}).

Conclusions

The estimated dose equivalents from the hypothetical submergence of a radioisotope package is summarised in Table 1 with the results for spent fuel, high level waste and MOX fuel packages. The estimated dose equivalents from a radioisotope package was 8.1×10^{-5} mSv year^{-1} for the near shore case. These dose is similar to that from one of the Type B packages (spent fuel, high level waste and MOX fuel) for the near shore case. The estimated dose equivalents are smaller than those from fallout in the ocean due to the atmospheric nuclear weapons test from 1960s. The estimated dose equivalents are much smaller than past exposures and the ICRP recommendation.

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Table 1 Summary of estimated dose equivalent for one package.

	Transport Package	Main Nuclide	Dose equivalent （mSv/year）
Near shore	Spent Fuel	^{244}Cm	5.0×10^{-4}
	High level waste	^{244}Cm	5.0×10^{-4}
	MOX fuel	^{238}Pu	5.0×10^{-6}
	Radioisotope	^{60}Co	8.1×10^{-5}
Deep sea	High level waste	^{244}Cm	1.0×10^{-5}
	MOX fuel	^{238}Pu	1.0×10^{-9}
Fallout in the ocean	1960s	^{137}Cs, ^{90}Sr, $^{239,240}Pu$	2.4×10^{-3}
	1990s		2.3×10^{-4}
ICRP recommendation			1.0×10^{0}

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