TRANSPORT OF RADIONUCLIDES ALONG MARINE FOODCHAIN*

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ABSTRACT

A compartment model is employed to calculate the radionuclide concentrations in the ocean currents for a nuclear accient scenario where the long-lived ^{137}Cs is totally discharged into the sea. The radionuclide concentrations in both the waters of Daya Bay and the adjacent South China Sea are considered. Using the concentration factors for the marine organisms: fish, crustacea and mollusca, their radionuclide concentrations are also estimated. In this way, the whole body radiation doses received by an individual due to ingestion of marine organisms from the Daya Bay and the South China Sea are calculated.

Keywords Marine foodchain, Nuclear power plant, ^{137}Cs, Whole body radiation dose, Ingestion, Hong Kong

1 INTRODUCTION

In this paper, the discharge of the long-lived ^{137}Cs to the seawater in the Daya Bay in the event of a nuclear accident is considered. A compartment model DAYAQUA is used to estimate the concentrations of radionuclides in the sea compartments by taking into account the exchange of water masses between the sea compartments, adsorption of radionuclides on the seabed sediments and the physical radioactive decay of the radionuclides. By multiplying the radionuclide concentration in the sea compartments by the concentration factors for the marine fauna, the mean body burden of radionuclides in the marine fauna can be estimated. For the marine fauna, the 3 groups of fish, crustacea and mollusca will be considered as they are the main seafood consumed by the population. The individual body dose as well as collective dose for the population due to ingestion of contaminated seafood can then be calculated.

2 DAYAQUA MODEL

2.1 General description

The DAYAQUA model is a one-dimensional marine dispersion model which calcualtes the radionuclide concentrations in both the seawater and the seabed sediments when radionuclides are discharged into the sea. This kind of model has been used by several authors in calculating the radionuclide concentrations in the Baltic Sea and Irish Sea[1,2]. Transports of radionuclides among the compartments are assumed to take place

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instantaneously and uniformly. The time-evolution of the amount of radionuclides in a compartment i is given by

$$\mathrm{d}N_i/\mathrm{d}t = \Sigma_{j=1}^{n}(k_{ji}N_j - k_{ij}N_i) - (k_{i,s} + \lambda)N_i + Q_i(t) \tag{1}$$

where the summation includes all the compartments j with contents N_j and in physical contact with the compartment i and N_i = the number of atoms of a given radionuclide in compartment i at time t, k_{ij} = the transfer coefficient from compartment i to compartment j in d^{-1}, $k_{i,s}$ = the rate of loss of radionuclides from compartment i by sedimentation in d^{-1}, λ = the radioactive decay constant of the radionuclide in compartment i in d^{-1}, $Q_i(t)$ = the rate of discharge of radionuclides into compartment i in d^{-1}, n = the number of compartments in the system.

The transfer coefficients $K_{i,s}$ are given by Evans[2] as

$$k_{i,s} = K_\mathrm{d}S/[h_\mathrm{m}(1 + K_\mathrm{d}SS)] \quad \text{in d}^{-1} \tag{2}$$

where K_d = distribution coefficient (g/g or cm^{-3}/g), S = the sedimentation rate ($\mathrm{g{\cdot}m^{-2}{\cdot}d^{-1}}$), h_m = the mean water depth (m), SS = the amount of suspended materials in the water column ($\mathrm{g{\cdot}L^{-1}}$).

The transfer coefficients k_{ij} are found out using the exchange rate of water masses between the seawater compartments, which are obtained from Hsu *et al*[3].

2.2 Particular modelling

The Daya Bay, with an area of approximately 600 km^2 and a mean depth of 11 m, is situated at the northern part of the South China Sea between 22°30′ — 22°50′N, 114°30′ — 114°50′W, about 50 km from the populated areas of Hong Kong. Ocean currents flow into and out of the Bay in a clockwise direction normally.

In the DAYAQUA model, we consider two seawater regional compartments consisting of the Daya Bay and the adjacent South China Sea surrounding all the Hong Kong boundary and part of the China coast. The seabed sediments should also be represented by another two compartments within the ecosystems. There should be transfers of the radionuclides from the upper level of the sediment back to the seawater and to the bottom of the seabed, the latter being due to the resettling of the sediments. Therefore, a portion of the materials adsorbed to the sediment initially will be transferred to the bottom. In this preliminary investigation, we have presumed that the transfer from the upper level of the sediment back into the seawater is negligible (see Fig.1).

The differential equations that describe the transport of ^{137}Cs in the compartments after a spiked pulse of the radionuclide is discharged into the sea water are given by (see Fig.2).

Daya Bay (compartment 1):

$$\mathrm{d}N_1/\mathrm{d}t = k_{2,1}N_2 - (k_{1,2} + k_{1,s} + \lambda)N_1, \quad N_1(0) = Q(0) \tag{3}$$

South China Sea (compartment 2):

$$\mathrm{d}N_2/\mathrm{d}t = k_{1,2}N_1 - (k_{2,1} + k_{2,s} + \lambda)N_2, \quad N_2(0) = 0 \tag{4}$$

Daya Bay seabed sediment (compartment 3):

$$dN_3/dt = k_{1,s}N_1 - \lambda N_3, \quad N_3(0) = 0 \tag{5}$$

South China Sea seabed sediment (compartment 4):

$$dN_4/dt = k_{2,s}N_2 - \lambda N_4, \quad N_4(0) = 0 \tag{6}$$

Consequently, we have radiation doses to an individual through an ingestion of seafood as

$$RD_i = DF \times C_i \times R_i \tag{7}$$

where DF is dose conversion factor, C_i radionuclide concentration in the seafood i, R_i consumption rate of the seafood i.

Collective doses to the population are given by

$$CD_i = POP \times RD_i \tag{8}$$

where POP=Population size.

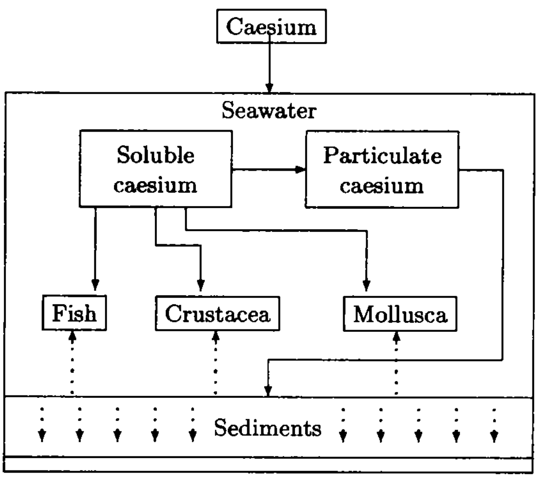

Fig.1 Schematic representation of the transport of ^{137}Cs in the marine pathways

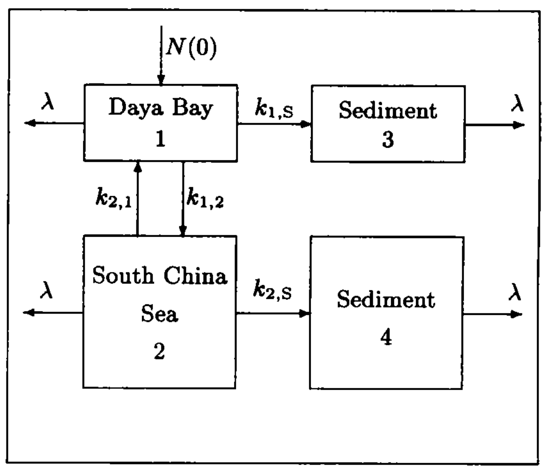

Fig.2 Compartment scheme of the DAYAQUA model

Since we have insufficient information about the rate of transfer of ^{137}Cs from the marine environment (water plus sediment) to the marine fauna in the Daya Bay or vice versa, we utilize the concept of concentration factors for calculating the concentration of the given radionuclide ^{137}Cs in the body of the marine fauna. The concentration factor is defined as

$$\text{Concentration Factor} = \frac{\text{Radioactivity in the marine organism per unit mass}}{\text{Radioactivity in the water per unit volume or mass}} \tag{9}$$

When using the concentration factors, we have assumed that equilibrium is reached at a particular time. In general, the concentration factors depend on the feeding habit of the marine fauna, the salinity in the water, the biological half life related to the excretion rate and the physical radioactive decay of the radionuclide in the marine fauna[4]. We further presume the concentration factors to be valid for a geographical location rather than a specific site, so only one concentration factor for each kind of marine fauna is used for ^{137}Cs, without taking into account the differences in species and feeding habits. In this way, the calculated ^{137}Cs concentration should only be considered as mean values in the marine fauna. Other authors have discussed the formulation of a time dependent model for the concentration of radionuclides in the marine fauna in more details[5].

2.3 Accident scenario

Twelve possible nuclear scenarios have been discussed and listed in the risk assessment report[6] produced by the UK Atomic Energy Agency for the Hong Kong Government. We choose the GD7 release category among the scenarios as it is the most probable accident (annual probability of 4.8×10^{-5}) and has a high release fraction of ^{137}Cs among the radionuclide inventory (0.15). For calculation purposes, we consider that after an instantaneous release of the radionuclides, they all discharge into the Daya Bay, which is indeed the most pessimistic situation. For a realistic situation in which only a portion of the radionuclides is released to the environment, the true results can be obtained simply by scaling.

2.4 Pathways of exposure to marine fauna

Since ^{137}Cs has a long life-time (half life=30.2 a) and has a high solubility in seawater, it may pose a potential long term hazard to the marine organisms. Generally speaking, the marine fauna have different feeding habits and they can be classified into sediment-inhabiters, filter-feeders, grazers, herbivores and carnivores, which can cause complications to the actual pathway of ingestion of radionuclides. For simplicity, however, we only use the recommended values of concentration factor for the marine fauna, but for a more detailed assessment, more refined data should be used.

3 RESULTS AND DISCUSSION

The system of differential equations given in the proceeding section is solved numerically using the Birchall-James (BJ) computer algorithm[7] with parameter values listed in Table 1, which have been selected either to best represent the specific site or case when possible, or based on best estimation or mean values.

3.1 ^{137}Cs concentration in the compartments and in marine fauna

In general, the radionuclide concentrations in the compartments depend on the transfer coefficients. Their detailed results are shown in Figs.3,4.

We only consider fish, crustacea and mollusca in our calculations as they constitute the three main seafood consumed by the Hong Kong population. Other marine organisms such as the algae, seaweed, etc., have not been taken into consideration because of the comparatively lower consumption rate. The results are listed in Table 2. We have assumed here that the marine fauna intake radionuclides from the water alone and not from other pathways such as the uptake from the seabed sediments. In reality, some

Table 1

Parameter values in the DAYAQUA model

	Daya Bay	Ref	South China Sea	Ref
Initial ^{137}Cs fallout activity /Bq				
Sea water	2.934×10^{16}	6	0	—
Sea-bed sediment	0	—	0	—
Marine fauna	0	—	0	—
Spatial data:				
A: surface area/m^2	6×10^8	3	4×10^{11}	6
V: Volume/m^3	6×10^9	3	4×10^{13}	6
h_m: Mean water depth/m	11	3	20	9
Sedimentation data:				
S: Total suspended solids in sea water/$g\cdot cm^{-3}$	9.8×10^{-6}	3	24.4×10^{-6}	3
K_d: Distribution coefficient/$cm^3\cdot g^{-1}$	5×10^3	8	5×10^3	8
ρ: Bulk density of the sediment/$g\cdot cm^{-3}$	1.0	—	1.0	—
Sediment active zone thickness/m	1.0	—	1.0	—
Sedimentation rate/$cm\cdot a^{-1}$	9.0×10^{-1}	3	4.0×10^{-1}	9
Rate coefficients/d	Values			
Daya Bay→South China Sea: $k_{1,2}$	1.01×10^{-1}	—	—	—
Daya Bay→Sea-bed sediment: $k_{1,S}$	1.12×10^{-5}	—	—	—
South China Sea→Daya Bay: $k_{2,1}$	4.70×10^{-1}	—	—	—
South China Sea→Sea-bed sediment: $k_{2,S}$	2.74×10^{-5}	—	—	—
Physical decay constant: λ	6.29×10^{-5}	—	—	—
Concentration factor /$kg\cdot kg^{-1}$				
Fish	100	8	—	—
Crustacea	20	10	—	—
Mollusca	20	10	—	—
^{137}Cs				
Ingestion dose per unit intake /$Sv\cdot Bq^{-1}$	1.3×10^{-8}	11	—	—

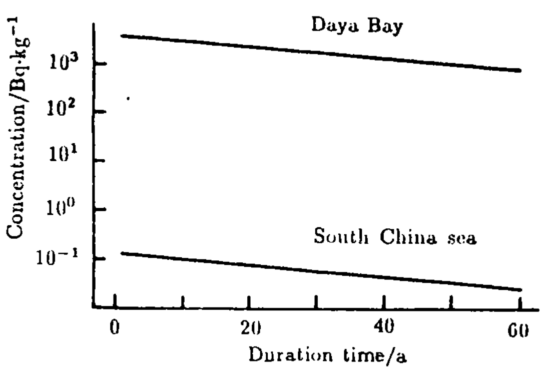

Fig.3 Concentration of ^{137}Cs in seawater compartments

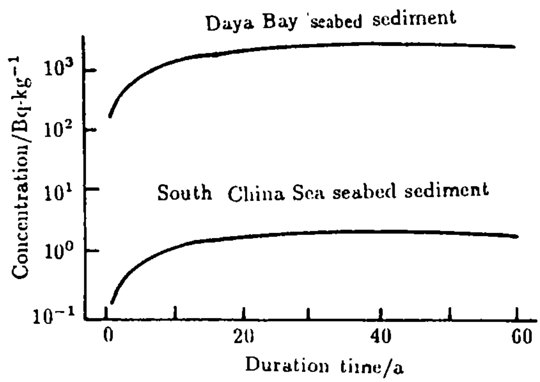

Fig.4 Concentration of ^{137}Cs in seabed sediments

marine demersal fish may accumulate more radionuclides since they ingest more seabed sediments which may not be excreted from the body totally[12].

3.2 Individual radiation dose and collective dose

As stated in the RPAG report 1[13], the whole population of Hong Kong is taken as the critical group because of the high degree of homogeneity of the population of Hong Kong. Thus, using the annual total consumption rate of marine fauna for the Hong Kong population, the consumption rate for an individual can be estimated and each individual is assumed to consume the same amount of seafood annually. For the first case, we consider all the marine fauna are caught from either one of the sea compartments alone (see Tables 3,4). For the second case, we can estimate the fraction of the ingestion radiation dose due to the contaminated marine fauna caught in the Daya Bay using the amount of annual marine fauna production in the Daya Bay (see Table 5). For a comparison, the total average annual effective dose equivalent from natural background for a Hong Kong citizen is about 3.24 mSv[15]. For the first case, the radiation dose due to the ingestion of marine fish is the most important, while for the second case, the ingested radiation dose due to mollusca is the most important.

Table 2

Predicted ^{137}Cs concentration in marine fauna

Bq/kg

Marine fauna	Duration/a	Daya Bay	South China Sea
Fish	1	3.82×10^5	1.23×10^1
	5	3.41×10^5	1.10×10^1
	15	2.58×10^5	8.30×10^1
	25	1.95×10^5	6.27×10^1
	35	1.47×10^5	4.74×10^1
	45	1.11×10^5	3.58×10^1
	55	8.38×10^4	2.70×10^1
Crustacea	1	7.64×10^4	2.46×10^1
	5	6.83×10^4	2.20×10^1
	15	5.15×10^4	1.66×10^1
	25	3.89×10^4	1.26×10^1
	35	2.94×10^4	9.50×10^{-1}
	45	2.22×10^4	7.20×10^{-1}
	55	1.68×10^4	5.40×10^{-1}
Mollusca	1	7.64×10^4	2.46×10^1
	5	6.83×10^4	2.20×10^1
	15	5.15×10^4	1.66×10^1
	25	3.89×10^4	1.26×10^1
	35	2.94×10^4	9.50×10^{-1}
	45	2.22×10^4	7.20×10^{-1}
	55	1.68×10^4	5.40×10^{-1}

Table 3

Quantities of marine foodstuffs landed yearly and effective consumption for Hong Kong population[14]

Marine Foodstuff	$/kg\cdot a^{-1}$	Edible fraction	Effective consumption $/kg\cdot a^{-1}$
Fish	1.45×10^8	0.5	7.25×10^7
Crustacea	1.45×10^7	0.4	5.80×10^6
Mollusca	1.26×10^7	0.7	8.82×10^6

Table 4

Estimated whole body radiation dose rates from ingestion of contaminated marine fauna caught in either compartments for the same consumption rate in the first year

$mSv\cdot a^{-1}$

Marine Fauna	Consumption rate $/kg\cdot a^{-1}$	Daya Bay	South China Sea
Fish	12.08	60.0	1.93×10^{-3}
Crustacea	0.97	0.96	3.10×10^{-5}
Mollusca	1.47	1.46	4.70×10^{-5}
Total	—	62.4	2.00×10^{-3}

In future, we may consider the possibility of treating the fishermen as a critical group since they consume a great deal of marine fauna. The calculated ingestion radiation dose rates to an individual tabulated in Tables 4 and 5 allow us to control the import of contaminated marine fauna to Hong Kong by calculating the "Derived Intervention Levels" for the contaminated marine fauna[13].

Table 5

Estimated whole body radiation dose rates from ingestion of contaminated marine fauna caught in both compartments in the first year $mSv{\cdot}a^{-1}$

Marine fauna	Consumption rate /$kg{\cdot}a^{-1}$		Radiation dose /$mSv{\cdot}a^{-1}$	
	Daya Bay	South China Sea	Daya Bay	South China Sea
Fish	3.00×10^{-3}	12.08	1.50×10^{-2}	1.93×10^{-3}
Crustacea	2.62×10^{-2}	9.40×10^{-1}	2.60×10^{-2}	3.00×10^{-5}
Mollusca	1.28	1.86×10^{-1}	1.27	5.95×10^{-6}
Total	—	—	1.31	1.97×10^{-3}

Table 6

Estimated collective dose rates for the Hong Kong population from the results of Tables 4,5 $mSv{\cdot}a^{-1}$

Marine fauna	Daya Bay		South China Sea	
	From Table 3	From Table 4	From Table 3	From Table 4
Fish	3.60×10^{5}	9.00×10^{1}	1.16×10^{1}	1.16×10^{1}
Crustacea	5.76×10^{3}	1.56×10^{2}	1.86×10^{-1}	1.80×10^{-1}
Mollusca	8.76×10^{3}	7.62×10^{3}	2.82×10^{-1}	3.57×10^{-2}
Total	3.75×10^{5}	7.87×10^{3}	1.21×10^{1}	1.18×10^{1}

For the first and second cases, the collective dose rates are given in Table 6. In the risk assessment report of Cook *et al*[6], a model has been proposed by considering several sea compartments including the compartment 2 discussed in the present paper and the collective dose due to the marine pathways of exposure for the release category GD7 is estimated to be 6.9×10^{1} man·Sv. The discrepancy is that only large areas of the sea have been considered, and the effects coming from a smaller area like the Daya Bay in which plenty of seafood is obtained has not been considered. For a comparison, the terrestrial foodchain pathway of exposure for the GD7 release category gives a collective dose of 1.4×10^{4} man Sv from the terrestrial foodchain pathway[6] which is comparable to our results obtained for the collective dose due to consumption of marine fauna caught in the Daya Bay solely. Therefore, the marine foodchain pathway of exposure is definitely deserving our attention. More refined results can be obtained in the future when we develop a more detailed version of the DAYAQUA model and obtain more site-specific parameters.

4 CONCLUSIONS

This paper describes the compartment model DAYAQUA for the simulation of the transport of ^{137}Cs along a marine foodchain. The transport processes are assumed to take place uniformly and instantaneously among the compartments. Although the actual transport of ^{137}Cs may vary at different sites, we can still have a preliminary description of the processes that take place. In the whole, we have found that the contamination of the marine seafood may increase the ingestion radiation dose to the population. In future, a sensitivity study of the model is needed to assess the relative sensitivity of the results to different parameter values. This will enable us to concentrate on the "sensitive" parameters that affect the results significantly. A more realistic validation of the model using site-specific values can then be performed.

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