Journal of Radioanalytical and Nuclear Chemistry, Vol. 222, Nos 1–2 (1997) 209–213

Dispersion model of cesium-137 in surface oceanic waters

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(Received January 2, 1997)

The ^{137}Cs radionuclide dispersion in the marine environment through the compartmental model is reported. The model simulates the surface water contamination caused by routine or accidental radionuclide releases. For the simulation the OCEAN program was applied in the North Sea, near to Sellafield and adjacent areas, based on published transfer coefficient data. The results are in good agreement with the literature and the model developed can be applied to the brazilian coastal regions.

Introduction

The study of radionuclide oceanic dispersion model is very important to evaluate the behavior of the radionuclides in the marine environment as well as the assessment of collective dose. The contamination of the oceans by radionuclides can occur by means of nuclear reactor accidents, nuclear tests, fallout and radioactive effluents from reactors and reprocessing facilities. The radionuclides are distributed over the world by maritime or atmospheric currents.[1,2]

The behavior of radionuclides in the ocean depends on the radionuclide dispersion, the radionuclide interaction with the bottom sediments and the suspended matter and radionuclide removal due to outflow process. The radionuclide dispersion phenomenon in superficial waters is in general studied by mathematical models.

In this context, a mathematical program for the simulation of ^{137}Cs radionuclide in superficial oceanic waters was developed (OCEAN). From the environmental impact point of view ^{137}Cs is a very important radionuclide due to its nuclear and chemical characteristics. A number of data relative to the ^{137}Cs concentration as well as transfer coefficients in the North Sea are available in the literature.

The OCEAN program presents as principal structure a compartmental model. The region is divided in compartments, which exchange radionuclides through their boundaries. The transfer of the material from one compartment to the other is given by constant transfer coefficients. The model calculates the amount of ^{137}Cs entering and leaving each compartment.

The program was applied to ^{137}Cs dispersion in the North Sea and adjacent areas, where an extensive set of information is available. The results were compared to the values published by Hallstadius.[3] The computer program developed by Hallstadius calculates the transfer coefficients, which were here employed to simulate the ^{137}Cs dispersion in the North Sea.

Mathematical model

In the compartment model,[4] the time evolution of the number of atoms of the radionuclide of a compartment is given by;

$$\frac{dN_i}{dt} = \Sigma(K_{ji} N_j - K_{ij} N_i) - \lambda N_i + Q_i(t) \qquad (1)$$

where

- λ – radioactive decay rate,
- N_i – number of atoms of a given radionuclide in the compartment i,
- N_j – number of atoms of a given radionuclide in the compartment j,
- K_{ij} – transfer coefficients from compartment i to j,
- K_{ji} – transfer coefficients from compartment j to i,
- $Q_i(t)$ – source term in compartment i,
- $K_{ji} \cdot N_j$ – inputs to neighbouring compartments,
- $K_{ij} \cdot N_i$ – losses to neighbouring compartments.

Equation (1) shows in and out flows of the material in the compartment i. The summation extends over of the compartments j, in contact with compartments i. The resolution of the matricial equation was performed applying a method considering time-dependent coefficients.[5–7] Considering that the ^{137}Cs amount scavenged by suspended particles is insignificant (low K_D), K_{ij} represents the advection and diffusion of the radionuclide between the different compartments. The horizontal transfer of the radionuclide from i to j is given by:

$$\frac{N_i}{t} = \frac{K}{DV_j} \cdot N_j \left(\frac{\mu A}{V_i} + \frac{K}{D \cdot V_i} \right) \cdot N_i - \lambda N_i + Q_i \qquad (2)$$

where

- K – eddy mixing coefficient ($m^2 \cdot s^{-1}$),
- D – suitable distance over which to evaluate the gradient,
- μ – flow from i to j ($m \cdot s^{-1}$),
- A – interface area (m^2),
- V_i – volume of the compartment

0236–5731/97/USD 17.00

Elsevier Science B.V., Amsterdam
Akadémiai Kiadó, Budapest

$$K_{ij} = \left(\frac{\mu A}{V_i} + \frac{K}{DV_i} \right) \quad \text{and} \quad K_{ji} = \frac{K}{DV_j}$$

Considering the compartment i to evaluate the behavior of the radionuclide with time, the program took into account: (1) the source term; (2) the transfer coefficients;

Table 1. Estimations of ^{137}Cs releases from Sellafield

Year	TBq · y^{-1}	Year	TBq · y^{-1}	Year	TBq · y^{-1}	Year	TBq · y^{-1}
1957	150	1964	160	1971	1450	1978	4100
1958	250	1965	170	1972	1420	1979	2600
1959	100	1966	250	1973	750	1980	3000
1960	90	1967	220	1974	4100	1981	2450
1961	100	1968	450	1975	5350	1982	2100
1962	100	1969	470	1976	4250	1983	1250
1963	0	1970	1250	1977	4500	1984	500

Table 2. Estimations of ^{137}Cs releases from Cap la Hague

Year	TBq · y^{-1}	Year	TBq · $^{-1}$	Year	TBq · y^{-1}	Year	TBq · y^{-1}
1966	10	1971	240	1976	35	1981	40
1967	20	1972	25	1977	50	1982	50
1968	25	1973	70	1978	40		
1969	20	1974	60	1979	25		
1970	90	1975	35	1980	30		

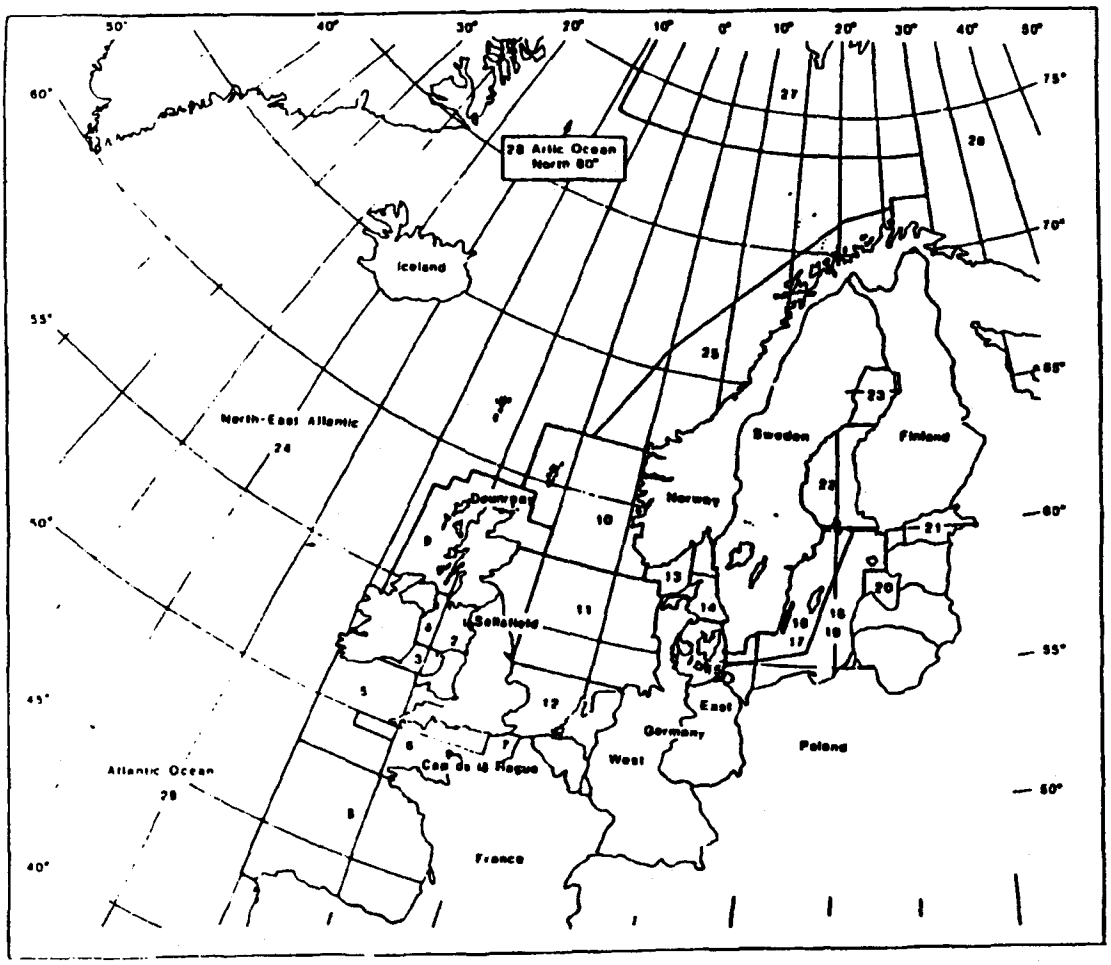

Fig. 1. Map of the region studied showing the compartments of the model[3]

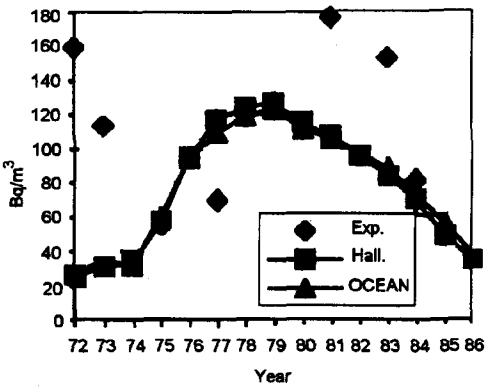

Fig. 2. Compartment 9 – Scottish Waters

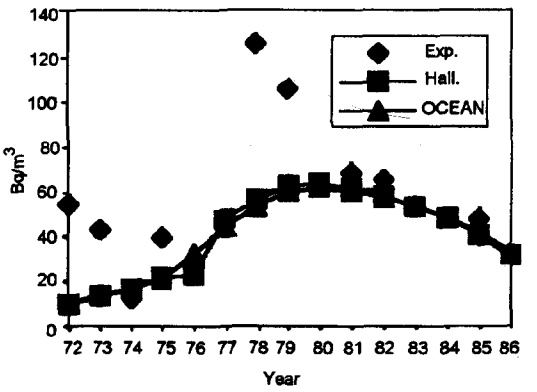

Fig. 3. Compartment 10 – North Sea

(3) the inflow of the radionuclide in the compartment *i* from the adjacent compartments, by means of transfer coefficients between the compartments; (4) the radionuclide quantity present in the compartment *i* was considered as the sum of the inicial compartment contents more the quantity that was transferred between the adjacent compartments; (5) the integral of the quantity of radionuclides in the compartment *i* at the time interval; (6) the sediment interactions were not considered; (7) the direct deposition of radionuclide onto surface water and (8) the radioactive decay.

Table 3. Estimations of ^{137}Cs releases from Dounreay

Year	$TBq \cdot y^{-1}$
1976	13
1977	6
1978	3
1979	8.5
1980	22

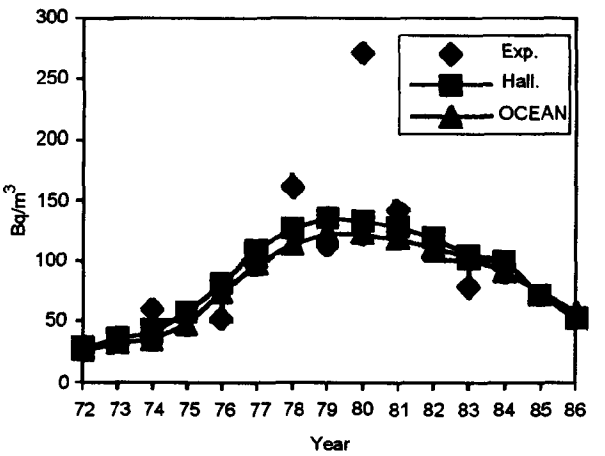

Fig. 4. Compartment 11 – Central (North Sea)

Table 4. Concentrations of ^{137}Cs in the compartment 9 (Scottish Waters)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	160	26.2	28.4
73	114.3	30.9	34.6
74	n.d.	33.3	32.1
75	54.8	57.1	60.0
76	n.d.	95.2	94.4
77	69	116.7	109.0
78	n.d.	123.8	119.2
79	n.d.	126.1	123.0
80	n.d.	114.3	111.3
81	176.2	107.1	105.3
82	n.d.	95.2	96.9
83	152.3	83.3	87.4
84	80.9	69	72.8
85	n.d.	48	55.1
86	n.d.	33.3	37.7

n.d. – not determined.

Table 5. Concentrations of ^{137}Cs in the compartment 10 (North Sea)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	54.8	9.5	10.1
73	42.9	13.1	14.3
74	11.9	16.2	16.5
75	39.3	21.5	20.9
76	23.8	22.6	31.9
77	n.d.	47.6	44.0
78	126.2	56	53.1
79	106	61.9	59.4
80	n.d.	63.1	61.3
81	67.9	60.7	59.6
82	64.3	57.2	56.7
83	52.4	52.4	52.8
84	47.6	47.6	47.6
85	46.4	39.3	40.5
86	n.d.	29.8	32.1

n.d. – not determined.

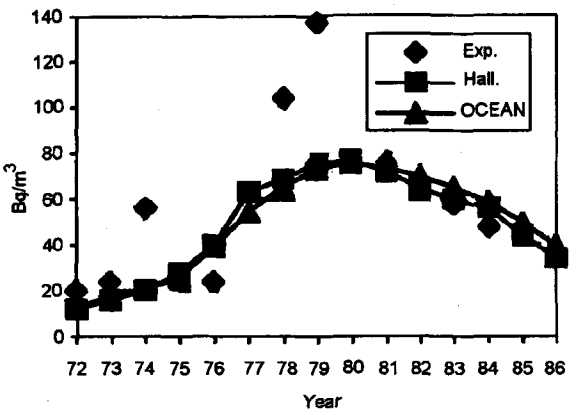

Fig. 5. Compartment 13 – Skagerak

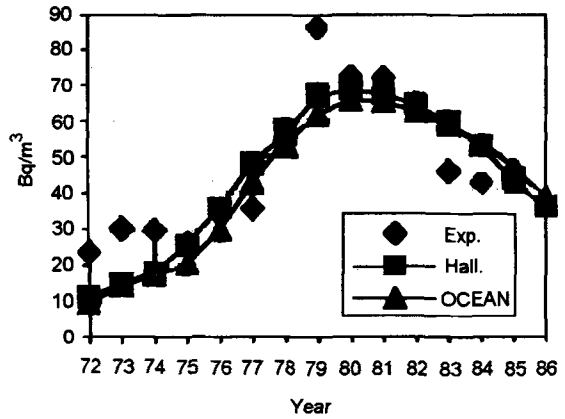

Fig. 6. Compartment 14 – Kattegat

Table 6. Concentrations of ^{137}Cs in the compartment 11 (Central-North Sea)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	28.6	28.6	25.8
73	35.7	35.7	32.3
74	59.5	40.5	34.8
75	57.1	57.1	47.7
76	52.4	80.9	73.6
77	95.2	109.5	96.6
78	161.9	126.2	112.0
79	111.9	135.7	123.0
80	271.4	133.3	122.5
81	142.8	128.5	117.5
82	119	119	110.8
83	78.6	104.8	102.4
84	95.2	100	90.2
85	71.4	71.4	74.5
86	52.3	52.3	57.1

Table 7. Concentration of ^{137}Cs in the compartment 13 (Skagerak)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	20	12	13.1
73	24	16	18.0
74	56	20	20.6
75	28	28	25.8
76	24	40	39.3
77	63	63	54.5
78	104	69	65.7
79	137	76	73.5
80	n.d.	77	75.8
81	76	72	73.6
82	65	65	70.0
83	58	60	65.2
84	48	56	58.7
85	n.d.	44	49.8
86	n.d.	34	39.5

n.d. – not determined.

Model simulation

The OCEAN program was applied in the North Sea and adjacent areas. Discharges of ^{137}Cs from Sellafield, Cap la Hague and Dounreay were employed as source term. The estimations of ^{137}Cs releases are shown in Tables 1 to 3.

The transfer coefficients were taken from HALLSTADIUS.[3] Figure 1 shows the map of the North Sea and adjacent regions divided in compartments.

Results and discussion

Tables 4 to 9 and Figs 2 to 7 present the variation of ^{137}Cs concentration in the period of 1972 to 1986, for some compartments obtained by both OCEAN and HALLSTADIUS programs.

The analysis of the data shows good agreement of ^{137}Cs concentration obtained by OCEAN and HALLSTADIUS program.

Simulated values and experimental data can be also compared in Figs 2 to 7. For the great majority of the points, there is a good agreement between the values. However, the OCEAN program is representative for both

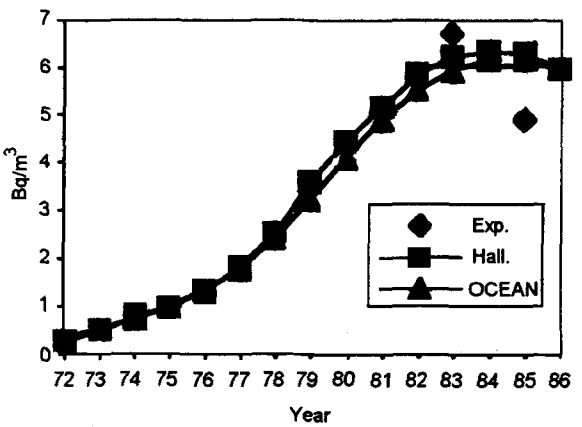

Fig. 7. Compartment 27 – Spitsbergen Waters

Table 8. Concentrations of ^{137}Cs in the compartment 14 (Kategat)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	23.8	11.3	9.7
73	30.4	14.9	14.2
74	29.8	17.9	17.3
75	26.2	25.7	20.3
76	34	36	29.8
77	36	48	43.0
78	55	56	53.8
79	86.3	66.7	61.7
80	72.6	68.4	65.7
81	72	67.2	64.9
82	64.9	64.3	62.4
83	45.8	59.5	58.7
84	42.9	52.4	53.8
85	n.d.	43.4	46.9
86	n.d.	35.7	38.4

n.d. – not determined.

Table 9. Concentrations of ^{137}Cs in the compartment 27 (Spitsbergen Waters)

Time, y	Experimental, $Bq \cdot m^{-3}$	HALLSTADIUS, $Bq \cdot m^{-3}$	OCEAN, $Bq \cdot m^{-3}$
72	n.d.	0.26	0.36
73	n.d.	0.48	0.51
74	n.d.	0.71	0.73
75	n.d.	0.95	0.99
76	n.d.	1.31	1.31
77	n.d.	1.78	1.75
78	n.d.	2.5	2.45
79	n.d.	3.57	3.21
80	n.d.	4.4	4.07
81	n.d.	5.12	4.87
82	n.d.	5.83	5.50
83	6.67	6.19	5.92
84	6.13	6.3	6.12
85	4.88	6.25	6.13
86	n.d.	5.95	5.93

n.d. – not determined.

large area and large time interval, usually annual average values, while experimental values correspond to "instantaneous" distribution, which can be affected by changes in normal or accidental releases, characteristics of the water body, values of current speed, direction as a function of time.

In spite that no oceanographic or hydrodynamic information was taken into account in the OCEAN program, the model provides a good response to evaluate the radionuclide dispersion in the marine environment. The model proposed will be now applied in oceanic regions of Brazil, where the Angra Nuclear Power is located. The model can be employed because only a few parameters are required.

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The authors wish to thanks the IAEA, CNPq and CNEN for the financial support.

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