http://dx.doi.org/10.5516/NET.03.2011.063

RADIATION DOSE TO HUMAN AND NON-HUMAN BIOTA IN THE REPUBLIC OF KOREA RESULTING FROM THE FUKUSHIMA NUCLEAR ACCIDENT

DONG-KWON KEUM*, IN JUN, KWANG-MUK LIM, and YONG-HO CHOI
Korea Atomic Energy Research Institute
150 Deokjindong, Yuseonggu, Daejeon, 305-353 Republic of Korea
*Corresponding author. E-mail : dkkeum@kaeri.re.kr

Received November 21, 2011
Accepted for Publication April 23, 2012

This paper describes the radiation doses to human and non-human biota in the Republic of Korea, as a result of the Fukushima nuclear accident. By using the measured airborne activity and ground deposition, the effective and thyroid doses of five human age groups (infant, 5 years, 10 years, 15 years and adult) were estimated by the ECOSYS code, and the whole body absorbed dose rate of the eight Korean reference animals and plants (RAPs) was estimated by the K-BIOTA (the Korean computer code to assess the risk of radioactivity to wildlife). The first-year effective and thyroid human doses ranged from 5.7E-5 mSv in the infant group to 2.0E-4 mSv in the 5 years group, and from 5.0E-4 mSv in the infant group to 3.4E-3 mSv in the 5 years group, respectively. The life-time (70 years) effective and thyroid human doses ranged from 1.5E-4 mSv in the infant group to 3.0E-4 mSv in the 5 years group, and from 6.0E-4 mSv in the infant group to 3.5E-3 mSv in the 5 years group, respectively. The estimated maximum whole body absorbed dose rate to the Korean RAPs was 6.7E-7 mGy/d for a snake living in soil (terrestrial biota), and 2.0E-5 mGy/d for freshwater fish (aquatic biota), both of which were far less than the generic dose criteria to protect biota from ionizing radiation. Also, the screening level assessment for ERICA's (Environmental Risks from Ionizing Contaminants: Assessments and management) limiting organisms showed that the risk quotient (RQ) for the estimated maximum soil and water activity was significantly less than unity for both the terrestrial and freshwater organisms. Conclusively, the radiological risk of the radioactivity released into the environment by the Fukushima nuclear accident to the public and the non-human biota in the republic of Korea is considered negligible.

KEYWORDS : Fukushima Nuclear Accident, Human and Non-human Biota, Radiation Dose, ECOSYS, K-BIOTA

1. INTRODUCTION

A severe nuclear accident occurred at the Fukushima Daichi nuclear power plants (NPP) in Japan on 11 March, 2011, and a significant amount of gaseous radioactive material was released into the atmosphere and dispersed by wind. The Nuclear and Industrial Safety Agency of Japan (NISA) reported that the amount released into the environment was approximately 10% of the Chernobyl nuclear accident in 1986 [1]. About two weeks after the accident, very low activities of short- and long-lived radionuclides (^{131}I, ^{134}Cs, ^{137}Cs and ^{133}Xe) were observed in air samples collected at local monitoring sites in the Republic of Korea. Figs 1 and 2 show the monitoring sites and the airborne activity of the radionuclides that had been measured by the Korea Institute of Nuclear Safety (KINS), which is responsible for monitoring radioactivity in the Republic of Korea [2]. Airborne ^{131}I activity was first detected at a higher level than the normal on 28 March, 2011, its highest peak was observed over the region on 7 April, 2011, and it declined to the usual background level within about two months of the accident. Once the radionuclides are released to the environment, in principle, they cause risks to human health and the environment, and both humans and biota may be exposed through various pathways. The assessment of the radiation dose to human and non-human biota is essential for the evaluation of impacts to the public and the environment from the effect of ionizing radiation.

After the Fukushima accident, public attention was on the accident, focusing in particular on the monitoring results observed in specific regions of countries [3,4] or the dispersion of the contaminated cloud [5], while results from the available radiation dose assessments are very limited [6]. Recently, the United Nation's Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has launched a project with the objective to develop a scientific report on the levels and effects of radiation exposure due to the Fukushima nuclear accident. The report will address radionuclide releases, dispersion and deposition, and doses and effects for workers, the public and biota in Japan, as well as in countries outside of Japan, as a result of the Fukushima nuclear accident. The purpose of the present study is to estimate short- and long-term radiological risks to humans and biota in the Republic of Korea, which is a neighbor country of Japan, and to provide input into the world-wide efforts to study the effect of the Fukushima nuclear accident.

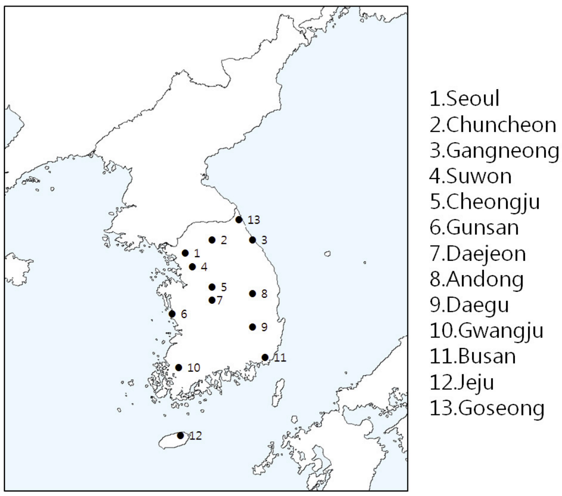

Fig. 1. Monitoring Site

2. ASSESSMENT METHOD

For the assessment of doses to humans, the ECOSYS code [7] was used; for biota dose assessment, the K-BIOTA [8,9] was used. All calculations were made based on the airborne activity and ground deposition measured in Korea. The approaches used to assess the radiation dose to human and non-human biota are described in the following.

2.1 Human Dose Assessment

The ECOSYS code (the Microsoft Excel version) was developed based on the ECOSYS 87 model [10], which is a dynamic model for assessing the radiological consequences of a nuclear accident. The code takes into account five exposure pathways to predict the radiation dose to humans; 1) the internal exposure due to the ingestion of contaminated foodstuffs, 2) internal exposure due to the

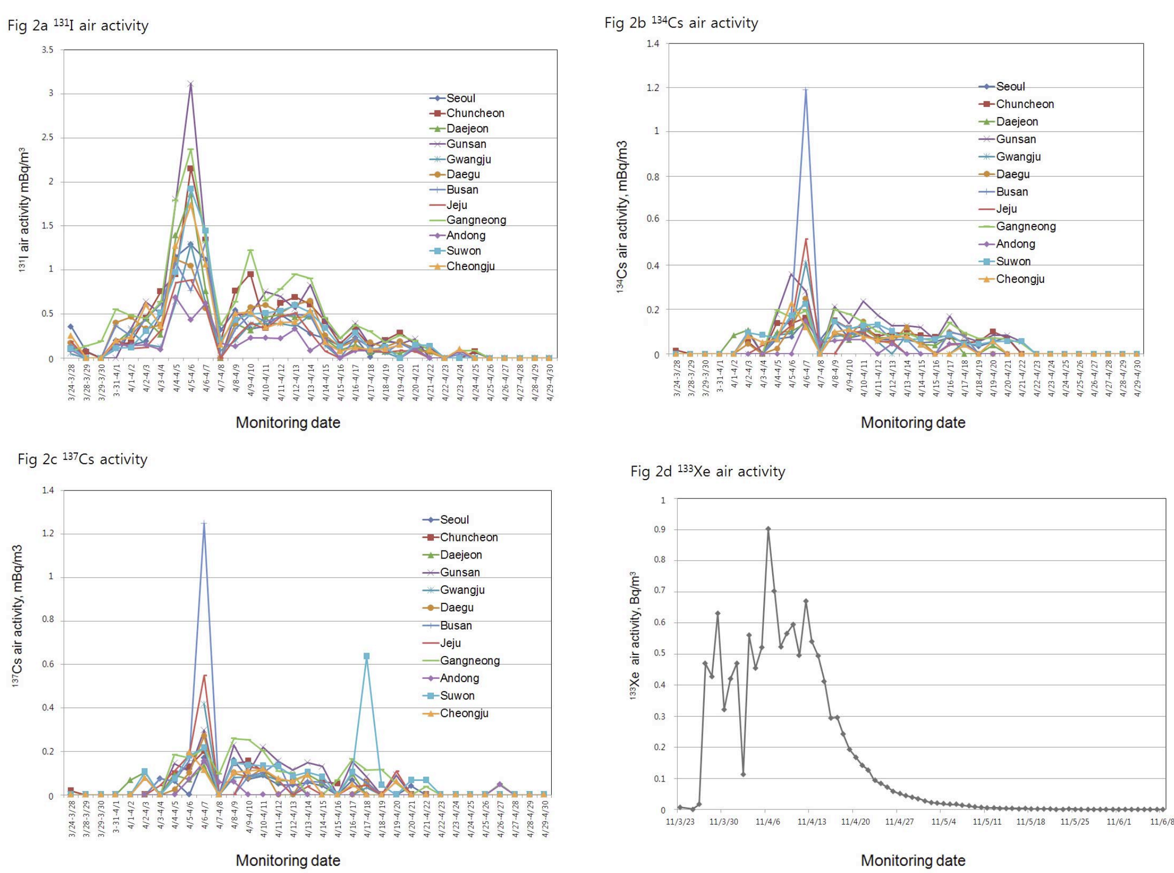

Fig. 2. Measured Time Integrated Activities in Air for (a) I-131, (b) Cs-134, (c) Cs-137, and (d) Xe-133

inhalation of airborne radionuclides, 3) external exposure from the radionuclides in the passing cloud, 4) external exposure from radionuclides deposited on the ground, and 5) external exposure due to radionuclides deposited on skin and cloths. The ingestion pathways include the processes of deposition, interception, translocation, weathering, resuspension, root-uptake, migration in soil, transfer to domestic animals, and the intake activity of animals though contaminated feedstuffs. The model can estimate in particular the contamination of foods and feeds through the uptake of radionuclides directly deposited on the foliage, and through uptake from soil. Details on the modeling of the pathways are well described elsewhere [7, 10]. In the present study, the first four pathways are considered because the contribution of the last exposure pathway to the human dose is usually very low. The considered pathways of radiation exposure to man and biota are shown in Fig 3.

Major input data for the human dose calculation are listed in Table 1. Default input parameter values in ECOSYS were generally used unless described otherwise. Time-integrated air activity of each site was calculated by integrating the area under the air monitoring peak (Fig.2), and the highest value for each radionuclide was taken as input data for the dose calculation, and is given in Table 1.

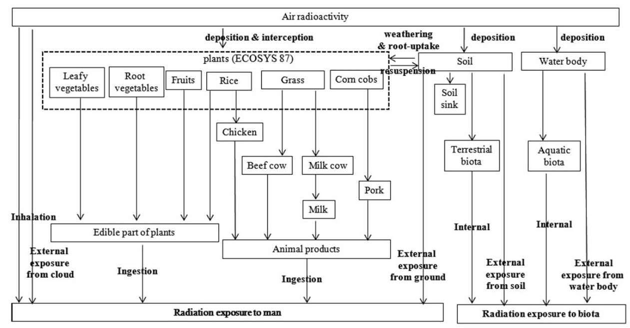

Fig. 3. Pathways of Radiation Exposure to Man and Biota used in the Present Study

Table 1. Major Input Parameters for the Human Dose Calculation

Parameter	Values	Ref.
Time-integrated air activity (mBq d/m^3) ^{131}I ^{134}Cs ^{137}Cs ^{133}Xe	 31.8 5.2 4.7 12,500	It was estimated by using air monitoring result (Fig.2)
Ground deposition	Table 2	[2]
Breathing rate (m^3/h) infant group 5 year group 10 year group 15 year group adult group	 0.18 0.42 0.6 0.9 1.2	[10]
Agricultural parameters for foodstuff Rice yield (kg-dry/m^2) begin of growth harvest date	 0.82 May 12 October 12	[12]
Other plants and animal products vegetables, fruits, milk, pork, beef, chicken	default values in ECOSYS	[7]
Feedstuffs grass, corn cobs	default values in ECOSYS	[7]
Food consumption rates	Table 3	[13]
Reduction factor of the external exposure	Table 4	[7]

After the Fukushima accident, the measured soil activities of ^{137}Cs in Korea were in the normal range (MDA ~ 16Bq/kg), indicating that there was a very little ground deposition. The net amount of ground deposition by the Fukushima accident cannot be exactly determined from the measured soil activities that are comprised of both nuclear weapon and the Fukushima accident fallout. The KINS have measured the dry and wet deposition of radionuclides by using a deposition collector at Daejeon in Korea, since 1998. Table 2 shows the dry and wet deposition that had been measured at Daejeon during March to May 2011 after the Fukushima nuclear accident [2]. The dry deposition of iodine was much lower than the wet deposition, while the amount of dry and wet deposition of cesium is very similar. The low dry deposition of iodine was likely to be ascribed by a little collection of gaseous iodine in the deposition collector, which is made of acrylic plastic. Thus the dry deposition of iodine was estimated by the following equation

Dry deposition (Bq/m^2) = [∑(Fraction of iodine form x Deposition velocity of each iodine form to soil (m/d)] x Time-integrated air activities of iodine (Bq d/m^3).

The fractions of iodine form (0.23, 0.27, and 0.5 for aerosol, element, and organic bound iodine, respectively) were taken from measurement results after the Chernobyl accident [11], and the deposition velocities to soil were taken from literature [10]. The total ground deposition of iodine for the human dose assessment was assumed to the sum of the estimated dry deposition with the measured wet deposition.

The breathing rates were 0.18, 0.42, 0.6, 0.9 and 1.2 m^3/h for infant, 5 years, 10 years, 15 years, and adult age groups, respectively [10]. Eight foodstuffs of rice, leafy vegetables, root vegetables, fruits, milk, pork, beef and chicken, and three feedstuffs of rice, grass and corn cobs, were considered for the ingestion dose (Fig 3). Among those, the leafy vegetables and grass are likely to be affected by direct deposition of radionuclides on the plants, because they are considered to be harvested throughout the year. There would be no direct deposition on other plants because the accident occurred before planting, and consequently the plants would be mainly contaminated by root uptake. The ECOSYS's default agricultural parameters for the feedstuffs and foodstuffs, except rice, were applied. Rice, which is a staple crop in Korea, was assumed to be planted on May 21, and harvested with the yield of 0.82 kg-dry/m^2 on October 21 [12]. Age-dependent annual food consumption rates were taken from the off-site dose calculation manual [13] and their values are summarized in Table 3. The reduction factor of the external exposure for staying at a different location, which was taken from the ECOSYS code [7], is summarized in Table 4. The reduction factor

Table 2. Total Ground Deposition Used in the Calculation [2]

Radionuclides	Estimated dry deposition (Bq/m^2)	Measured dry deposition (Bq/m^2)	Measured wet deposition (Bq/m^2) (rainfall: 41mm)	Total ground deposition (Bq/m^2)
^{131}I	2.6	3.2E-3	2.4	5.0
^{134}Cs	-	0.7	0.7	1.4
^{137}Cs	-	0.7	0.9	1.6

Table 3. Korean Age-dependent Annual Food Consumption Rate [13]

Food	Food Consumption Rate (kg/y)			
	Infant Group	5 year group	10-15 year group	Adult group
Rice	0	125.7	196.9	188.5
Leafy vegetables	0	84.5	132.3	126.7
Root vegetables		65.3	100.2	66.3
Fruits	0	44.2	69.2	66.3
Milk	366	42.0	66.0	63.0
Beef	0	13.8	21.6	20.7
Pork	0	8.2	13.0	12.4
Chicken	0	14.6	22.9	22.0

for the exposure from cloud is very similar to the value (0.36) used for the calculation of the human dose from the Chernobyl accident [11].

2.2 Non-human Biota Dose Assessment

The assessment of exposures for biota is needed to evaluate the radiological impact to communities and populations of wildlife [14]. For planned and existing exposure situations, equilibrium models are often used to assess the radiation dose to biota [15], while for emergency exposure situations, where the activity in biota and environment varies considerably with time, dynamic models are needed. There are a number of dynamic models for the dose assessment of biota, but the kinetic transfer parameters available for the assessment are very limited. Thus, the application of a full dynamic model for biota dose assessment under accidental conditions is not practical at present. Alternatively, a semi-dynamic model can be used to consider the time variation of the environmental medium concentration. In this study, the equilibrium CR model of the K-BIOTA was simply modified to calculate the time-dependent whole body absorbed dose rate for a specific organism.

$$D_{tot}(t) = \sum_i (CR_i \times DCC_{\text{int},i} + DCC_{ext,i}) \times C_{s,i}(t) \quad \text{(terrestrial organism)} \tag{1}$$

$$D_{tot}(t) = \sum_i [CR_i \times DCC_{\text{int},i} + \{v_w + 0.5(1 + K_{d,i})v_{ws} + v_s K_{d,i}\} \times DCC_{ext,i}] \times C_{w,i}(t) \quad \text{(aquatic organism)} \tag{2}$$

where CR_i (Bq/kg per Bq/kg medium) is the equilibrium concentration ratio of radionuclide i between biota and environmental medium, $C_{s,i}$ (t) (Bq/kg soil) is the time-dependent soil activity of radionuclide *i*. $C_{w,i}$ *(t)* (Bq/l) is the time-dependent water activity of radionuclide *i*. The parameters v_w, v_{ws} *and* v_s represent the occupancy factor for an aquatic organism in water, at water-sediment interface, and in sediment, respectively. $DCC_{int,i}$ (μGy/d per Bq/kg organism) and $DCC_{ext,i}$ (μGy/d per Bq/kg for soil or μGy/d per Bq/l for water) are the internal and external dose conversion coefficients of radionuclide i for the reference organism. $K_{d,i}$ (l/kg) is the equilibrium distribution coefficient between water and sediment. Eqs (1) and (2) were made with the assumption that biota is instantaneously equilibrated with the environmental medium. Strictly speaking, the model is not a pure equilibrium model, because the medium activity concentration is dependent on time (thus, here it is called "semi-equilibrium"). The assumption of the model is generally not valid for the early phase after accident, owing to the time lag required for the bioaccumulation of radionuclides through the food chain, and may result in a pronounced overestimation of the tissue concentration of biota, and consequently, the whole body dose rate to the biota.

Recently, the International Commission on Radiological Protection (ICRP) presented the concept of reference animals and plants (RAPs) [16]. The ICRP reference organism approach uses a few types of organisms that are typical of the major environments, which may serve as a primary point of reference for assessing the radiation dose for non-human biota. The ICRP's approach is deemed to be the most pragmatic for the non-human biota radiation dose assessment. Based on the ICRP reference organism approach, seven animals and one plant were selected as the reference organisms in the K-BIOTA code [9]. In order to consider the ecological characteristics specific to Korea, the size of the selected organisms was taken from the "Endemic Species of Korea" [17]. The shape of all the organisms was assumed to be ellipsoid (Table 5). In the present study, the Korean reference RAPs were used as target organisms for the radiation dose to non-human biota. Given the geometry of the target organisms and radiation weighting factors (alpha=10, beta=3, and gamma=1), a uniform isotropic model was applied to calculate the internal dose conversion coefficients, and it was also used to calculate the external dose conversion coefficient for aquatic animals [18, 19]. A Monte Carlo simulation was applied to calculate external dose conversion coefficients for terrestrial organisms [20,

Table 4. Reduction Factor of the External Exposure [7]

location	Exposure from cloud (short-term)		Exposure from ground (long-term)	
	Occupancy factor	Shielding factor	Occupancy factor	Shielding factor
Outdoors, open field, suburb	0.15	1.0	0.15	1.0
Outdoors, open field, urban	0.05	0.6	0.05	0.3
Indoor, single house	0.4	0.3	0.4	0.1
Indoor, large building	0.4	0.05	0.4	0.01
Reduction factor	0.32		0.23	

Table 5. Korean Draft Reference Animals and Plant [9]

RAPs	Size(cm)			Habitats
	major axis (a)	1st minor axis (b)	2nd minor axis (c)	
Pine tree	1000	30	30	on-soil
Rat	10	3	2.5	on-soil and in-soil
Deer	105	50	50	on-soil
Frog	3.2	3	2	in water and on-soil
Snake	85	1	1	in-soil and on-soil
Pelagic fish (minnow)	8	3	1	in water
Bee	1.8	0.5	0.5	on-soil
Earthworm	9.5	0.4	0.4	in-soil

21]. The dosimetric model in the K-BIOTA was tested through an extended comparison study on the dose conversion coefficients for some selected organisms in the Biota Working Group (BWG) of the IAEA/EMRAS II project [22]. CR values were taken from the literature [23, 24]. The time-dependent soil (C_{soil}) and water activities (C_{water}) in the environmental medium of a finite volume were estimated by

$$C_{soil}(t) = \frac{A_d}{\rho_s d_s} \exp[-(\lambda_d + \lambda_{ds})t] \quad (3)$$

$$C_{water}(t) = \frac{A_t v_{d,w}}{d_w} \exp[-(\lambda_d + \lambda_t + \lambda_s)t] \quad (4)$$

where A_d (Bq/m^2) is the fallout depositions, ρ_s (kg/m^3) is the soil density, d_s (m) is the soil depth, A_t (Bq d/m^3) is the time-integrated air activity, $v_{d,w}$ (m/d) is the deposition velocity to water surface, and d_w (m) is the water body depth. The rate constants (d^{-1}), λ_d, λ_{ds}, λ_t, and λ_s represent the loss of radioactivity due to radiological decay, the loss due to migration into a deeper soil layer, the loss due to the turnover of water, and the loss due to sedimentation, respectively.

3. RESULTS AND DISCUSSION

3.1 Projected Human Dose

Effective and thyroid doses for the public in the Republic of Korea as a result of the Fukushima nuclear accident are summarized in Tables 6 and 7, respectively. It can be seen that the annual doses decrease with time continuously, after 50 years the annual dose is less than a few percent of the dose in the first year. The first-year includes doses from inhalation and from cloud-shine. From the second year, the differences of doses between age groups are very little. This is due to the fact that the long-lived radionuclides, Cs and ^{137}Cs were the main contributors to the dose, and ground exposure was the dominant pathway in the medium and long term.

The first-year effective dose ranged from 5.7E-5 mSv in the infant group to 2.0E-4 mSv in teenagers. These values are less by orders of magnitude than the annual public exposure to natural radiation (2.4mSv) [25]. It is also lower by a factor of ten than the first-year effective dose (about 7E-3 to 8E-3 mSv) of adults in the East Asia region resulting from the Chernobyl accident [11]. The first-year effective dose of the infant group was about 30 to 40% of the dose of the other age groups. This is due to the low ingestion dose for the infant group. The infant group consumed only milk, and its consumption rate was also less than the total food consumption rates of the other age groups (Table 3). Furthermore, the activity in milk decreased during processing. Other age groups consumed vegetables that were the main contributor of an ingestion dose from the end of deposition. It is interesting that the effective dose from inhalation in the 5 years group was slightly greater than that for the infant groups. This is due to the fact that the breathing rate differs more (a factor of 2.33) between both age groups than the dose conversion factor (a factor of 0.57) of ^{131}I, which was the main contributor to the inhalation dose. The first-year thyroid dose ranged from 5.0E-4 mSv in the infant group to 3.4E-3 mSv in the 5 years group. The effect of inhalation appeared to be higher in the thyroid dose than the effective dose. The inhalation dose contributed 68% (32%) and 24% (10%) to the first-year thyroid dose (effective dose) of infants and adults, respectively.

On the other hand, the annual external cloud dose ranged from 4.8E-7 mSv to 6.9E-7 mSv over all age groups, and turned out to be less than other exposure pathways. The contribution of the external ground exposure to the

Table 6. Cumulated and Annual Effective Dose

(Infant group)

Time	Cumulated total dose (mSv)	Annual dose (mSv)				
		Total	Internal ingestion	Internal inhalation	External cloud	External ground
1. year	5.7E-05	5.7E-05	2.3E-05	1.8E-05	6.9E-07	1.6E-05
2. years	7.0E-05	1.3E-05	3.0E-06	0	0	9.8E-06
5. years	8.8E-05	4.5E-06	3.0E-07	0	0	4.2E-06
10. years	1.0E-04	2.6E-06	2.2E-07	0	0	2.3E-06
50. years	1.4E-04	4.4E-07	2.6E-09	0	0	4.4E-07
70. years	1.5E-04					

(5 years group)

1. year	2.0E-04	2.0E-04	1.7E-04	2.4E-05	5.2E-07	1.3E-05
2. years	2.2E-04	1.0E-05	1.6E-06	0	0	8.9E-06
5. years	2.3E-04	4.7E-06	4.3E-07	0	0	4.2E-06
10. years	2.5E-04	2.5E-06	2.7E-07	0	0	2.2E-06
50. years	2.9E-04	4.4E-07	2.6E-09	0	0	4.4E-07
70. years	3.0E-04					

(10 years group)

1. year	1.9E-04	1.9E-04	1.6E-04	1.8E-05	5.2E-07	1.3E-05
2. years	2.0E-04	1.1E-05	2.4E-06	0	0	8.6E-06
5. years	2.2E-04	4.5E-06	5.7E-07	0	0	3.9E-06
10. years	2.4E-04	2.5E-06	2.5E-07	0	0	2.2E-06
50. years	2.8E-04	4.5E-07	2.7E-09	0	0	4.5E-07
70. years	2.8E-04					

(15 years group)

1. year	1.7E-04	1.7E-04	1.4E-04	1.8E-05	4.8E-07	1.2E-05
2. years	1.8E-04	1.1E-05	2.9E-06	0	0	8.2E-06
5. years	2.0E-04	4.5E-06	5.4E-07	0	0	3.9E-06
10. years	2.1E-04	2.5E-06	2.5E-07	0	0	2.2E-06
50. years	2.6E-04	4.5E-07	2.7E-09	0	0	4.5E-07
70. years	2.6E-04					

(adult group)

1. year	1.4E-04	1.4E-04	1.1E-04	1.5E-05	4.8E-07	1.2E-05
2. years	1.5E-04	1.1E-05	2.8E-06	0	0	8.2E-06
5. years	1.7E-04	4.5E-06	5.4E-07	0	0	3.9E-06
10. years	1.8E-04	2.5E-06	2.5E-07	0	0	2.2E-06
50. years	2.2E-04	4.5E-07	2.7E-09	0	0	4.5E-07
70. years	2.3E-04					

Table 7. Cumulated and Annual Thyroid Dose

(Infant group)

Time	Cumulated total dose (mSv)	Annual dose (mSv)				
		Total	Internal ingestion	Internal inhalation	External cloud	External ground
1. year	5.0E-04	5.0E-04	1.4E-04	3.4E-04	5.9E-07	1.6E-05
2. years	5.1E-04	1.3E-05	2.9E-06	0	0	1.0E-05
5. years	5.3E-04	5.0E-06	2.8E-07	0	0	4.7E-06
10. years	5.5E-04	2.8E-06	2.1E-07	0	0	2.6E-06
50. years	5.9E-04	4.8E-07	2.6E-09	0	0	4.8E-07
70. years	6.0E-04					

(5 years group)

1. year	3.4E-03	3.4E-03	2.9E-03	4.8E-04	5.6E-07	1.5E-05
2. years	3.4E-03	1.1E-05	1.5E-06	0	0	9.8E-06
5. years	3.4E-03	5.1E-06	4.2E-07	0	0	4.7E-06
10. years	3.4E-03	2.6E-06	2.7E-07	0	0	2.4E-06
50. years	3.4E-03	4.8E-07	2.6E-09	0	0	4.8E-07
70. years	3.5E-03					

(10 years group)

1. year	2.5E-03	2.5E-03	2.2E-03	3.4E-04	5.6E-07	1.5E-05
2. years	2.5E-03	1.2E-05	2.4E-06	0	0	9.4E-06
5. years	2.5E-03	4.8E-06	5.7E-07	0	0	4.2E-06
10. years	2.6E-03	2.6E-06	2.5E-07	0	0	2.4E-06
50. years	2.6E-03	4.8E-07	2.6E-09	0	0	4.8E-07
70. years	2.6E-03					

(15 years group)

1. year	1.8E-03	1.8E-03	1.5E-03	3.3E-04	5.5E-07	1.3E-05
2. years	1.9E-03	1.2E-05	2.9E-06	0	0	8.9E-06
5. years	1.9E-03	4.7E-06	5.2E-07	0	0	4.2E-06
10. years	1.9E-03	2.6E-06	2.5E-07	0	0	2.4E-06
50. years	1.9E-03	4.8E-07	2.6E-09	0	0	4.8E-07
70. years	1.9E-03					

(adult group)

1. year	1.2E-03	1.2E-03	9.3E-04	2.9E-04	5.5E-07	1.3E-05
2. years	1.2E-03	1.2E-05	2.7E-06	0	0	8.9E-06
5. years	1.3E-03	4.7E-06	5.2E-07	0	0	4.2E-06
10. years	1.3E-03	2.6E-06	2.5E-07	0	0	2.4E-06
50. years	1.3E-03	4.8E-07	2.6E-09	0	0	4.8E-07
70. years	1.3E-03					

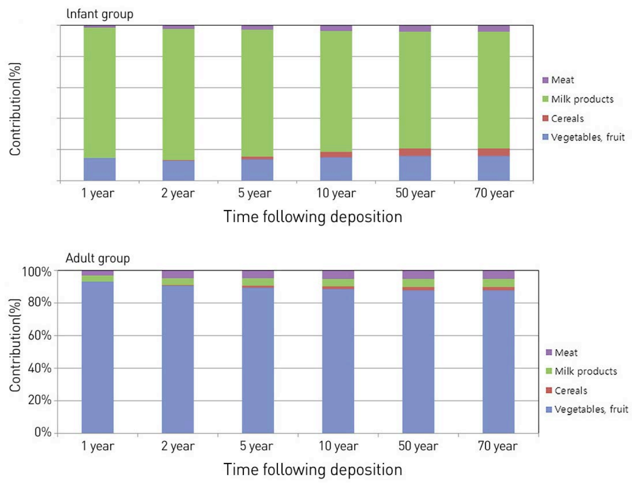

Fig. 4. Contribution of Foodstuffs on the Effective Ingestion Dose of Infant and Adult Group

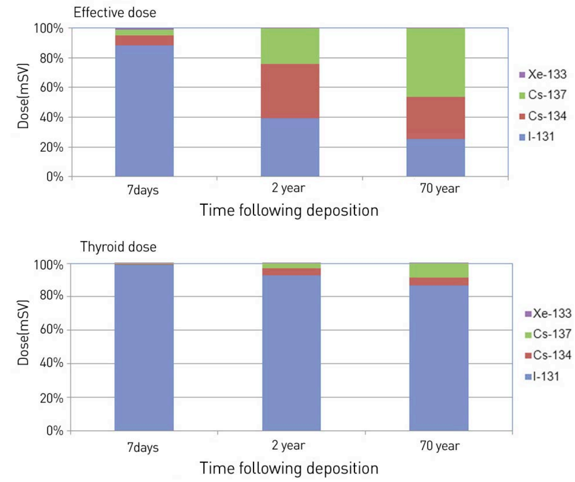

Fig. 5. Contribution of Radionuclides to Cumulated Effective and Thyroid Dose of Adult Group

total dose increased with time. For example, the external ground exposure contributed about 8.6% to the total effective dose of the adult group in the first year, while it increased to more than 99.9 % after 50 years.

The cumulated life-time (70 years) effective and thyroid doses ranged from 1.5E-4 to 3.0E-4 mSv, and from 6.0E-4 to 3.5E-4 mSv, respectively. It means that in the first year after the deposition, the public received 38 to 67% of the life-time effective dose, and 83 to 97% of the life-time thyroid dose, according to age group.

Fig 4 shows the contribution of foodstuffs to the effective ingestion dose of the infant and adult groups. Vegetables were the most predominant contributor to the ingestion dose for the adult group. For the scenario considered, the contribution of vegetables to first-year ingestion dose was 93%, and its contribution to the life-time ingestion dose was 87%. The same trend was observed for all groups above 5 years. All age groups above 5 years were assumed to consume vegetables daily from the end of deposition, since there were no actions to restrict the consumption of domestic vegetables in the Republic of Korea after the Fukushima accident, due to the very low activities in leafy vegetables. Generally, the interception by plant leaves is initially the main contamination pathway of vegetables, and thus the consumption of contaminated vegetables, if relevant, may cause an increase of the ingestion dose. In western countries, where milk products are among the major food stuffs, the grass-cow-milk pathways can also be important pathways with particular importance for the early phase after an accident, since radioiodine ingested by milk cows is rapidly absorbed in the animals, and transferred to milk. In Korea, the consumption of vegetables is much larger than milk, and therefore, vegetables are the highest contributor to the ingestion dose. Other foodstuffs, such as meat and cereal, take time for storage and processing until eaten, and thus their activity decreases much by the time of consumption. Therefore, the contribution of those foodstuffs to the ingestion dose was not greater than that of vegetables. On the contrary, the ingestion dose for the infant group was greatly attributed to the consumption of milk. The contribution of milk to the first-year ingestion dose for the infant group was estimated at about 83%, and its contribution to life-time ingestion dose was estimated at 75%.

The contributions of radionuclides to the cumulated dose are shown in Fig 5. For the effective dose, ^{131}I was the highest contributor (about 87%) in the first week after the end of deposition, while ^{134}Cs and ^{137}Cs were major contributors in the medium and long term. This is due to the activity of ^{131}I and its short half-life. The dose factor of ^{131}I for thyroid is larger by a factor of hundreds than that of ^{134}Cs and ^{137}Cs. Thus, ^{131}I is the main contributor to the life-time thyroid dose. The radiological impact due to ^{133}Xe was very low, although the airborne activity of the radionuclide was higher by three to four orders of magnitude than those of other radionuclides, and it played the role of dominant contributor to the external cloud dose. This result was consistent with the very low contribution of the external cloud exposure to the total dose.

3.2 Non-human Biota Dose

Soil and water activities were calculated from eqs (3) and (4) by using the time-integrated air activity and fallout deposition. In the calculation, the same time-integrated air activities and soil deposition as those used for the human dose assessment were used for consistency (Table1 and 2). The model parameter values used were a soil density of 1500 kg/m^3, soil depth of 10cm, and water body depth of 5m. The deposition velocity to water surface ($v_{d,w}$ = 1000 m/d) was taken from the IAEA/SRS 19 [26].

Reduction in radioactivity due to transport to the deeper soil layer, the turnover of water, and the sedimentation was neglected. This resulted in an overestimated soil and water activity to some extent.

Fig 6 shows the calculated time-dependent soil and water activities (left: water activity, right: soil activity). The estimated maximum soil activities were 3.3E-2 Bq/kg for ^{131}I, 9.3E-3 Bq/kg for ^{134}Cs, and 1.1E-2 Bq/kg for ^{137}Cs. The estimated maximum water activities were 6.4E-3 Bq/l for ^{131}I, 1.1E-3 Bq/l for ^{134}Cs, and 9.3E-4 Bq/l for ^{137}Cs. For all radionuclides considered, the maximum values were obtained at the end of deposition, due to the least reduction in the radioactivity by radiological decay. It is a natural result that because of the short half-life (8 days) of ^{131}I, the activity decreased to a negligible level a few months after the deposition, while the activity of the long-lived Cs-isotopes (^{134}Cs=2.06 years, ^{137}Cs=30years) decreased slowly.

Fig 7 shows the time-dependent whole body absorbed dose rates of the Korean reference animals and plants. For all organisms considered, the maximum dose rate was obtained at the end of deposition because the soil and water activities were at the maximum at the time. If the trophic chain between biota is considered, the delayed maximum dose rates may be obtained for a predatory organism, owing to the time required for the transport of radionuclide through the food web [27]. The dose rates to the terrestrial organisms increased in the order of snake (in-soil) > deer > snake (on-soil) > mouse (in-soil) > frog > mouse (on-soil) > earthworm > bee > pine tree. The different whole body absorbed dose rates between organisms were caused by the difference in size, habitat, and CR value of the organisms. The value of the highest dose rate for terrestrial organisms was 6.7E-7 mGy/d for the snake (in-soil), and the value of the lowest dose rate for terrestrial organisms was 1.5E-7 mGy/d for the pine tree. The maximum whole body dose rate to aquatic frogs and fish (Chinese minnow) was about 2.0E-5 mGy/d. For the aquatic animals considered, the occupancy factors were assumed to be $\nu_w = 1$, ν_{ws} and $\nu_s = 0$ since frogs and fish generally live in a water body. The results for the terrestrial and aquatic organisms clearly show that even the maximum dose rate are several orders of magnitude below the generic criteria to protect the environment from ionizing radiation; 1 mGy/d for terrestrial animals, and 10 mGy/d for terrestrial plants and aquatic biota [28], indicating the very low probability of a harmful effect on the ecosystem in the Republic of Korea as a result of the Fukushima nuclear accident. In fact, this result was expected because the activities deposited on the ground were very low.

In addition to the Korean reference animals and plants, the default reference organisms of the ERICA (Environmental Risks from Ionizing Contaminants: Assessments and management) assessment tool [29] were also studied. Of the default ERICA reference organisms, the organisms that receive the highest dose from a specific radionuclide in an ecosystem were selected for the target biota. The ERICA limiting terrestrial organism is reported to be bird egg for ^{131}I, and mammal (deer) for ^{134}Cs and ^{137}Cs; the limiting freshwater organism is phytoplankton for ^{131}I, and insect larvae for ^{134}Cs and ^{137}Cs. For the screening level assessment, the *RQ* (Risk Quotients) for the limiting organisms were calculated.

$$RQ = \sum_i \frac{C_{m,i}}{EMCL_i} \quad (5)$$

where $C_{m,i}$ (Bq/kg or Bq/l) is the activity for radionuclide *i* in a medium, and $EMCL_i$ (Bq/kg or Bq/l) is the environmental media concentration limit for radionuclide *i*, which has been derived based on the screening dose rate of 10μGy/h for a generic terrestrial and freshwater ecosystem. When the RQ is less than unity, it is generally assured that the dose rate to any organism does not exceed the screening dose rate. In the ERICA manual, the EMCL for the terrestrial limiting organisms are 1.8 E2 Bq/kg for ^{131}I (bird egg), 1.7E3 Bq/kg for ^{134}Cs (deer), and 3.1E3 Bq/kg for ^{137}Cs (deer). The EMCL for the freshwater

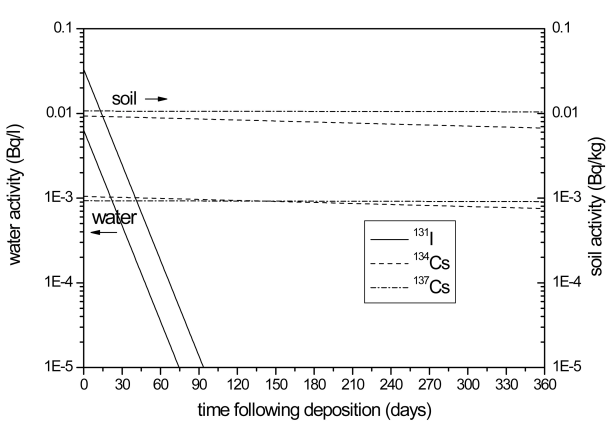

Fig. 6. Time-dependent Activity in Soil and Water

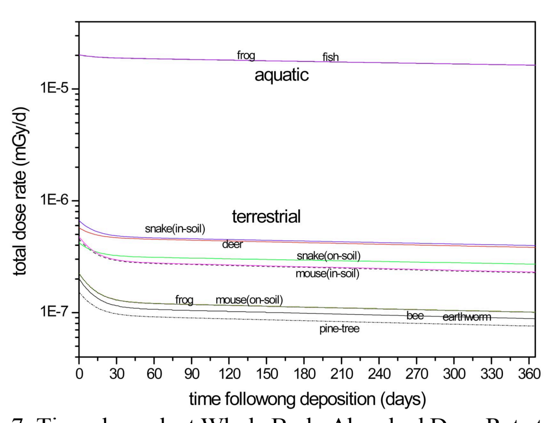

Fig. 7. Time-dependent Whole Body Absorbed Dose Rate to the Korean Reference Animals and Plants

limiting organism are 2.1E1 Bq/l for ^{131}I (phytoplankton), and 2.1E-2 Bq/l for ^{134}Cs (insect larvae), and 5.1E-2 Bq/l for ^{137}Cs (insect larvae). For the estimated maximum soil and water activities (Fig 6), the calculated RQ value by Eq(5) was 1.9E-4 for the terrestrial ecosystem and 9E-2 for the freshwater ecosystem. Both values are well under the unity, and this result supported that the radiological risks to non-human biota as a result of the Fukushima nuclear accident is considered negligible. The DMCL for the screening level assessment was derived with the assumption of the constant medium activity concentration, based on the equilibrium model, and thus the approach may be invalid when there is pronounced time-dependence of exposure in the early phase after an accident. However, the equilibrium model is a basically conservative approach since the biota activity for the initial phase must be less than its activity at equilibrium. Therefore, if the RQ value based on the equilibrium model is less than unity, even for the maximum environment activity concentration that are observed at the initial period after an accident, it can be assured that the radiological risks to non-human biota can be negligible over all periods.

4. CONCLUSION

The radiation doses to human and non-human biota in the Republic of Korea as a result of the Fukushima nuclear accident were estimated. The first-year effective and thyroid human doses ranged from 5.7E-5 mSv in the infant group to 2.0E-4 mSv in the 5 years group, and from 5.0E-4 mSv in the infant group to 3.4E-3 mSv in the 5 years group, respectively. The life-time effective and thyroid human doses ranged from 1.5E-4 mSv in the infant group to 3.0E-4 mSv in the 5 years group, and from 6.0E-4 mSv in the infant group to 3.5E-3 mSv in the 5 years group, respectively. Among the terrestrial organisms considered, a snake living in soil received the maximum whole body absorbed dose of 5.7E-7 mGy/d, and the freshwater fish of aquatic organisms received the maximum whole body absorbed dose rate of 2.0E-5 mGy/d. Both values for the maximum whole body absorbed dose rates are several orders of magnitude lower than the generic dose criteria to protect biota from ionizing radiation. Furthermore, the screening level assessment for ERICA's limiting organisms showed that the risk quotient (RQ) for the maximum soil and water activities was significantly less than unity for both the terrestrial and freshwater organisms. Thus, it can be concluded that the risk to the public and biota in the republic of Korea, from the radioactivity released due to the Fukushima nuclear accident is considered negligible. In fact, this is a natural result, considering that the activities deposited on the ground are very low compared to weapons fallout.

In the present study, a simple semi-equilibrium model, as an alternative to the full dynamic radioecological model, was applied to assess the dose rate to non-human biota. It should be noted that the model can lead to an excessively overestimated result, and may be not valid for the early phase after an accident where there is strong time- variation of radioactivity in environmental components. To analyze the accident situations more realistically, future studies are needed to address the development of the full dynamic radioecological model, in which the radionuclide transfer between the constituent components are linked each other, along with a measurement of the related kinetic parameters, particularly for terrestrial organisms.

ACKNOWLEDGEMENT

This study was financially supported by the nuclear research program of the Ministry of Education, Science and Technology (MEST), the Republic of Korea.

REFERENCES

[1] International Atomic Energy Agency (IAEA), *Briefing on Fukushima nuclear accident,* available from www.iaea.org /newcenter/news/tsunamiupdate01.html/,12 April, (2011).

[2] Kim, C.K., Byun, J.I., Chae, J.S., Coi, H.Y., Choi, S.W., Kim, D.J., Kim, Y.J.,, Lee, D.M., Park, W.J., Yim, S.A., Yun, J.Y., Radiological impact in Korea following the Fukushima nuclear accident, *Journal of Environmental Radioac-tivity,* 111, 70-82, (2012).

[3] Tagami, K., Uchida, S., Uchihori, Y., Ishii, N., Kitamaru, H., Shirakawa, Y., "Specific activity and activity ratios of radionuclides in soil collected about 20km from the Fukushima Daiichi Nuclear Power plant: radionuclide release to south and southwest," *Science of the Total Environment,* 409, 4885-4888, (2011).

[4] Pittauerova, D., Hettwig, B., Fischer, H.W., "Fukushima fallout in northwest German environmental media," *Journal of Environmental Radioactivity*, 102, 877-880, (2011).

[5] Lozano, R.L., Hernandez-Ceballos, M.A., Adame, J.A., Casa-Ruiz, M., Sorribas, M., San Miguel, E.G., Bolivar, J.P., "Radioactive impact of Fukushima accident on the Iberian Peninsula: Evolution and plume previous pathway," *Environment International,* 37, 1259-1264, (2011).

[6] Institut de Radioprotection et De Sŭreté Nucléaire (IRSN), *Assessment on the 66th day of projected external doses for populations living in the north-west fallout zone of the Fukushima nuclear accident-outcome of populations evacuation measures,* Report DRPH/2011-10, IRSN, France, (2011).

[7] Müller, H., Pröhl, G., *ECOSYS for Excel (version 1.3HK),* ConRad-Consulting in Radioecology, Germany, (1999).

[8] Keum, D.K., Jun, I., Lim, K.M., Choi, Y.H , *K-BIOTA V1.0 user's manual,* Korea Atomic Energy Research Institute, KAERI/TR-4230/2010, December (Korean), (2010).

[9] Keum, D.K., Jun, I., Lim, K.M., Choi, Y.H., "Approach to non-human species radiation dose assessment in the republic of Korea," *Radiation Protection Dosimetry,* 146, 299-302, (2011).

[10] Müller, H., Pröhl, G., "EOCSYS87: A dynamic model for assessing radiological consequences of nuclear accidents," *Health Phys,.* 64, 232-252, (1993).

[11] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources and effects of ionizing*

radiation, UNSCEAR 1988 report to the General Assembly with Scientific Annexes, Annexes D. Exposure from the Chernobyl, United Nations, New York, (1988).

[12] Keum, D.K., H.S. Lee, H.J. Choi, H.S. Kang, K.M. Lim, Y.H. Choi, C.W. Lee, A dynamic compartment model for assessing the transfer of radionuclide deposited onto flooded rice field, *Journal of Environmental Radioactivity,* 76, 349-367, (2004).

[13] Korea Atomic Energy Research Institute (KAERI), *Radiological dose assessment from the operation of the Gori Nuclear Power Plant*, KAERI/NSC-39/89, KAERI, Korea (Korean), (1989).

[14] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources and effects of ionizing radiation*, UNSCEAR 2008 report to the General Assembly with Scientific Annexes, Volume II Scientific Annexes E. Effects of ionizing radiation on non-human biota, United Nations, New York, (2011).

[15] International Atomic Energy Agency (IAEA), *Handbook of parameter values for the prediction of radionuclide transfer to wildlife (draft report)*, IAEA, Vienna, (2011).

[16] International Commission on Radiological Protection (ICRP), *Environmental protection: the concept and use of the reference animals and plants*, ICRP Publication 108, Pergamon Oxford, (2008)

[17] Ministry of Environment (ME), *Endemic species of Korea*, Ministry of Environment, Korea (Korean), (2005).

[18] Ulanovsky, A., Pröhl, G., "A practical method for assessment of dose conversion coefficients for aquatic biota," *Radiat. Environ. Biophys*., 45, 203-214, (2006).

[19] Keum, D.K., Jun, I., Lim, K.M., Choi, Y.H., "Absorbed internal dose conversion coefficients for domestic reference animals and plant," *Nuclear Engineering and Technology*, 42, 89-96, (2010).

[20] Taranenko, V., Pröhl, G., Comez-Ros, J.M. " Absorbed dose rate conversion coefficients for reference terrestrial biota for external and internal exposures," *Journal of Radiological Protection*, 24, A35-A62, (2004).

[21] Keum, D.K., Jun, I., Lim, K.M., Choi, Y.H., "External dose conversion coefficients to assess the radiological impact of an environmental radiation on aquatic and terrestrial animals," *Progress in Nuclear Science and Technology*, 1, 368-371, (2011).

[22] Vives i Batlle J, Beaugelin-Seiller K, Beresford NA, Copplestone D, Horyna J, Hosseini A, Johansen M, Kamboj S, Keum D-K, Kurosawa N, Newsome L, Olyslaegers G, Vandenhove H, Ryufuku S, Vives-Lynch S, Wood MD, Yu C, "The estimation of absorbed dose rates for non-human biota: an extended inter-comparison," *Radiat. Environ Biophys*, 50, 231-251, (2011).

[23] International Commission on Radiological Protection (ICRP), *Annals of the ICRP, Environmental Protection: Transfer parameters for reference animals and plants (draft for consultation)*, ICRP ref 4817-0644-3078, 2010.

[24] Beresford, B.A., Barnett, C.L., Howard, B.J., Scott, W.A., Brown, J.E., Copplestone, D.," Derivation of transfer parameters for use within the ERICA tool and default concentration ratios for terrestrial biota," *Journal of Environmental Radioactivity*, 99, 1393-1407, (2008).

[25] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources and effects of ionizing radiation*, UNSCEAR 2008 report to the General Assembly with Scientific Annexes, Volume 1, Annexes B. Exposure of the Public and Workers from Various Sources of Radiation, United Nations, New York, (2010).

[26] International Atomic Energy Agency (IAEA), *Generic models for use in assessing the impact of discharges of radioactive substances to the environment*, Safety Reports Series No.19, IAEA, Vienna, (2001).

[27] Kryshev, I.R., Alexakhin, K., Makhonko, *Radioecological consequences of the Chernobyl accident*, Nuclear Society, Moscow, (1992).

[28] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources and effects of ionizing radiation*, UNSCEAR 1996 report to the General Assembly with Scientific Annexes, United Nations sales publications E.96IX.3, New York, (1996).

[29] Larsson, C., "An overview of the ERICA integrated approach to the assessment and management of environmental risks from ionizing contaminants," *Journal of Environmental Radioactivity*, 99, 1364-1970, (2008).