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■ 論 文 ■

Radiological Dose Assessment Due to the Operation of Nuclear Facilities at KAERI Nuclear Site

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Abstract - To prevent the potential health detriment to the public from radioactive effluents, radiological dose assessments due to the operation of nuclear facilities located at Korea Atomic Energy Research Institute (KAERI) site has been performed semiannually in compliance with the Minister of Science and Technology (MOST)'s Notice in Korea. Radiological dose assessment based on the new recommendation of the International Committee on Radiation Protection (ICRP-60) has been conducted since 1998. In this manuscript, a serial activities at KAERI site to meet the regulatory standards for routine releases of radioactive effluents are introduced and discussed including technical approaches. It is clear that each nuclear facility has been operated in compliance with regulatory standards. Furthermore, it is identified that the radiation induced health effects for residents around the site are neglectable.

Key words : radiological dose assessment, radioactive effluents, regulatory standards

INTRODUCTION

The radiological dose assessment is the quantitative process of estimating the consequences to man resulting from the release of radionuclides to the biosphere. Radioactive effluents existing in air, water, or foods can be inhaled or ingested into the human body, thereby resulting in internal and external exposures.

Several nuclear facilities including HANARO research reactor of 30 MWt are in operation at KAERI (Korea Atomic Energy Research Institute) site which belongs to Yusong District, Daejeon City, Korea. This site is located at a basin of inland areas in geological characteristics, unlike the commercial nuclear power plant sites in Korea. The downtown of Daejeon City is away from 13 km in southeastern direction from the site, and the Gum River flows across the city. To prevent potential health detriment to the public from radioactive effluents, radiological dose assessment due to the operation of nuclear facilities has been performed semiannually in compliance with the Minister of Science and Technology (MOST)'s Notice[1] in Korea. Radiation protection systems based on the new recommendation of the International Committee on Radiation Protection (ICRP-60)[2] have been in force since 1998.

In this manuscript, a serial activities at KAERI site to meet the regulatory standards for routine releases of radioactive effluents are introduced and discussed including technical approaches.

MATERIAL AND METHODS

Radiological Dose Assessment from Gaseous Effluents

A straight-line Gaussian plume model is used to analyze the atmospheric dispersion of gaseous effluents released into the environment, which is well described in the U. S. Nuclear Regulatory Commission's (NRC's) Regulatory Guide 1.111[3]. Annual meteorological data is packaged in conjunction with a joint frequency distribution, which presents a three-dimensional array of probabilities of winds blowing in a given direction, within a given wind speed range, and under the influence of a given atmospheric stability. The joint frequency distribution is obtained by compiling a large number of 15 minute-averaged meteorological observations over one year. At KAERI site, the meteorological observation has been conducted at the three different heights (10m, 27m, 67m) of a tower. Pasquill's atmospheric stability classification by vertical temperature gradient is applied. Calm is categorized as wind speeds below 0.22m/sec. The NRC's computer program XOQDOQ[4] is used to predict annual dispersion and deposition factors. Options and input data to execute XOQDOQ observe strictly in compliance to the User's Guide.

Radionuclides released into the environment may cause radiation exposure to man through a variety of pathways. The major exposure pathways from gaseous effluents are 1) external exposure from radioactive plume, 2) external exposure from deposited radioactive materials, 3) internal exposure by the inhalation of radioactive plume, and 4) internal exposure by the ingestion of contaminated foods.

A computer program GASDOS[5] is used for radiological dose assessment using the output of XOQDOQ. GASDOS is a modified version of the U. S. NRC's computer code GASPAR[6] based on the U. S. NRC's Regulatory Guide 1.109. It takes into account not only Korean agricultural practice and consumption habits but also a number of site-specific data. Furthermore, internal and external dose conversion factors have been updated for the consideration of the ICRP-60 recommendation. Although dose conversion factors are categorized into six age groups in the ICRP-60, they are categorized into four age groups due to the lack of data analyzed for Korean living habits such as annual consumption rates of foods.

Radiological Dose Assessment from Liquid Effluents

Liquid effluents generated from nuclear fuel fabrication facilities contain low-enriched uranium isotopes of infinitesimal quantity. Liquid effluents are released to the GUM River through the GAP Stream. Liquid effluents generated from other facilities except for nuclear fuel fabrication facilities are released to the environment as gaseous types through vaporization processes after collecting at a natural evaporation facility. The followings are considered as site-specific exposure pathways ; 1) irrigation of agricultural products, 2) consumption of drinking water excluding underground water, 3) consumption of fresh-water fish, 4) recreations on shoreline and 5) swimming in river. Radiological dose from the consumption of underground water is not considered due to the low permeability of uranium isotopes into soil. Recreations or activities on water such as occupational fishing may cause external exposure from radioactive materials on the water. It may be neglectable comparing with other exposure pathways in dose contribution because of the geological characteristics of the site.

The mathematical models of considering pathways are based on the U. S. NRC's Regulatory Guide 1.109[7] with some modification for the consideration of site-specific characteristics.

1) Irrigation of agricultural products

Vegetation

$$D_j = U\sum_i d_i \exp(-\lambda_i t_h) DF_{ij} \times \left[\frac{r f_w (1-\exp(-\lambda_{Ei} t_e))}{Y_v \lambda_{Ei}} + \frac{f_I B_{vi} [1-\exp(-\lambda_i t_b)]}{p \lambda_i} \right] \quad (1)$$

Animal Products

$$D_j = U \sum_i F_{A,i} DF_{ij} [q_F d_i \exp(-\lambda_i t_h) [\frac{r f_w [1-\exp(-\lambda_{Ei} t_e)]}{Y_v \lambda_{Ei}} + \frac{f_l B_{vi} [1-\exp(-\lambda_i t_b)]}{p \lambda_i}] + C_{w,i} q_{Aw}] \quad (2)$$

2) Drinking water

$$D_j = U \sum_i C_{w,i} DF_{ij} \exp(-\lambda_i t_h) \quad (3)$$

3) Fresh-water fish

$$D_j = U \sum_i C_{w,i} B_{fi} DF_{ij} \exp(-\lambda_i t_h) \quad (4)$$

4) Shoreline deposits

$$D_j = F_R \sum_i S_i DF_{ij} \quad (5)$$

5) Swimming

$$D_j = 1000 F_S \sum_i C_{w,i} DF_{ij} \quad (6)$$

where i : radionuclide,

j : organ

D : annual dose (Sv/yr)

U : annual food consumption rate (kg/yr or L/yr)

DF_{ij} : dose conversion factor [Sv/Bq, (Sv/yr)/(Bq/m^2) or (Sv/yr)/(Bq/m^3)]

λ_i : radioactive decay constant (1/hr)

B_{fi} : equilibrium bioaccumulation factor (L/kg)

t_b : time period exposed to the contaminated water (hr)

t_h : holdup time between gravest and consumption of the food (hr)

d_i : deposition rate (Bq/m^2 hr)

r : fraction of radionuclides retained on agricultural products

λ_{Ei} : $\lambda_i + \lambda_w$, 1/hr) effective removal rate constant (=

λ_w : removal rate constant by weathering (1/hr)

Y_v : agricultural productivity (wet-kg/m^2)

f_I : fraction of the year crops are irrigated

f_w : fraction that irrigation is done to foliar

B_{iv} : concentration factor for root uptake (pCi/wet-kg)/(pCi/kg-soil)

p : effective surface density for soil (kg-soil/m^2)

$F_{A,i}$: feed-animal products transfer factor (d/kg or d/L)

q_F : feed consumption rate of animals (wet-kg/d)

t_e : time period exposed from contamination during the growing season (hr)

$C_{w,i}$: radionuclide concentration in water (Bq/L)

q_{Aw} : water consumption rate of animals (L/d)

F_R : fraction of annual time for shoreline activity

F_S : fraction of annual time for swimming

S_i : effective surface contamination (Bq/m^2)

Neglecting radioactive decay during traveling time of radionuclide, concentration in water $C_{w,i}$ is predicted as follows :

$$C_{wj} = 3.7 \times 10^{-11} \frac{Q_i}{q_w} \quad (7)$$

where, Q_i : annual radioactivity released from facilities (Bq/yr)

q_w : flow rate of river (m^3/sec)

A number of site-specific data are taken from default values used in a computer program LIQDOS[5], which is a modified version considering Korean socio-environmental characteristics based on the U. S. NRC's computer code LIQTAP[8]. Since these are socio-environmental data for residents around coastal areas, the values of some data such as food consumption may show a large difference comparing with residents around inland areas. Nevertheless, a number of default values used in LIQDOQ are applied because of the lack of site-specific data.

The irrigation rate of agricultural products during the growing season except for leafy vegetables and pasture is assumed to be 10.65 L/(m^2 d), which is for rice field in Korean agricultural practices[9]. For leafy vegetables and pasture, irrigation rate is assumed to be 1.065 L/(m^2 d), which is the 10% of irrigation rate for rice field, from the judgment of

Table 1. Source terms (Ci/yr) and release characteristics of for the nuclear facilities located at KAERI site.

	Year / Facility	1999	2000	2001	Release Mode
G	KAERI-1	Ar-41 266.0 H-3 7.32	Ar-41 200.1 H-3 37.47 I-131 1.32E-3	Ar-41 297.1 H-3 21.89 I-131 2.27E-3	continuous elevated release
	KAERI-2	ND	Kr-85 0.4	Kr-85 2.27E-2	intermittent elevated release
	KNFC-3	ND	ND	ND	continuous ground release
	KAERI-4	ND	ND	ND	continuous ground release
	KNFC-1	α 1.34E-5 β 9.39E-6	α 8.29E-6 β 5.68E-6	α 2.01E-5 β 1.13E-5	continuous elevated release
	KNFC-2	α 5.98E-6 β 4.23E-6	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	continuous mixed release
	KNFC-3	-	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	continuous ground release
L	KNFC-1	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	-
	KNFC-2	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	α 1.34E-5 β 9.39E-6	-

G : Gaseous effluents
L : Liquid effluents
ND : Below non-detectable limits
KAERI-1 : HANARO research reactor
KAERI-2 : Post-irradiation examination facility
KAERI-3 : Radioactive waste processing facility
KAERI-4 : Natural evaporation processing facility
KNFC-1 : PWR nuclear fuel fabrication facility
KNFC-2 : PWR and PHWR nuclear fuel fabrication facility
KNFC-3 : Heat decomposition facility

agricultural experts[10]. In Korean agricultural practices, irrigation is done onto soil surface of fields for the most part due to insufficient spring cooler systems. Therefore, in practical, agricultural contamination through foliar absorption may be neglectable, i.e., agricultural products are mainly contaminated through root uptake from soil. For the conservatism of predicted results, it is assumed that irrigation done to plant leaves for rice field and ordinary field is 10% and 30% of total irrigation amount, respectively[10]. The flow rates of river water are periodically measured at several points by a governmental agency[11]. The lowest values

Table 2. Radiation exposures from single nuclear facility during 2001. (mGy/yr or mSv/yr)

Items		RS*	KAERI-1		KNFC-1		KNFC-2		KNFC-3		KAERI-2	
			PR	%	PR	%	PR	%	PR	%	PR	%
G	Beta dose in air	0.2	1.86E-2	9.3	0	0	0	0	0	0	4.13E-5	0.02
G	Gamma dose in air	0.1	5.28E-2	52.8	0	0	0	0	0	0	3.64E-7	3.64E-4
G	Effective dose**	0.05	2.86E-2	57.2	2.07E-9	4.14E-6	1.48E-10	2.96E-7	1.19E-11	2.38E-8	4.40E-7	8.80E-4
G	Skin equivalent dose	0.15	5.87E-2	39.1	3.56E-7	2.37E-4	1.38E-8	9.20E-6	1.56E-9	1.04E-6	2.86E-5	0.02
G	Organ equivalent dose	0.15	2.40E-3	1.6	2.29E-3	1.53	1.15E-4	7.67E-2	1.21E-5	8.07E-3	0	0
L	Effective dose	0.03	-	-	7.28E-11	2.43E-7	1.14E-10	3.80E-7	-	-	-	-
L	Organ equivalent dose	0.1	-	-	2.08E-9	2.08E-6	3.17E-9	3.17E-6	-	-	-	-

G : Gaseous effluents
L : Liquid effluents
PR : Predictive results
ND : Below non-detectable limits
KAERI-1 : HANARO research reactor
KAERI-2 : Post-irradiation examination facility
KNFC-1 : PWR nuclear fuel fabrication facility
KNFC-2 : PWR and PHWR nuclear fuel fabrication facility
KNFC-3 : Heat decomposition facility
* Regulatory standards (RS) for each nuclear facility
** Calculated only for noble gas
*** Equivalent dose for a maximum exposed organ from radioactive particulate

over 5 years from 1995 to 1999 are taken for the estimation.

RESULTS AND DISCUSSION

Annual radiation exposures due to radioactive effluents released to the environment from the nuclear facilities are calculated to demonstrate compliance with Korean regulatory standards. Maximum individual doses in each of four age groups are calculated, and compared with regulatory standards. In this manuscript, dose means effective dose based on the ICRP-60 recommendation. In the MOST's Notice, there are two different articles to protect radiation health effects to the public ; One is the regulatory standards for application to single nuclear facility, another is for single site where several nuclear facilities are in operation. Regulatory standards for collective dose have not been established in Korea yet. However, collective dose to residents within 80km radius from KAERI site has been calculated. Korean regulatory standards are applied to the most exposed individual considering extraordinary consumption habits and unusual living habits based on the U. S. NRC's Regulatory Guide 1.109.

Table 1 shows the source term and the release characteristics of radioactive effluents over 3 conservative years for each facility. For the conservatism of predictive results, it is assumed that α and β activities are emitted from U-234 and Th-234, respectively.

Table 2 shows the ratio of predictive results to regulatory standards for single nuclear facility during 2001. The predictive results are exposures at a location representing maximum individual dose of the site boundary from the operation of each facility. Therefore, a direction representing maximum individual dose may be different for each facility due to the release characteristics and the application of meteorological data measured at different heights. The predictive results of the most exposed age group are compared with regulatory standards. It is clear that each nuclear facility has been operated in compliance with regulatory standards.

Fig. 1 shows the annual individual dose due to gaseous effluents from the operation of all facilities located at KAERI site during 3 years from 1999 to 2001. The most exposed age group is child. A direction representing maximum individual dose is identical with results for HANARO which is most contributing facility in dose. External dose from plume is a dominant exposure pathway due to Ar-41 (radioactive half-life = 1.83 hr) released from HANARO. Fig. 2 shows the annual individual dose for child as a function of exposure pathways from the operation of facilities during 2001. The contribution of exposure pathways is as follows ; external exposure from the plume (~90%) > internal exposure by ingestion of contaminated foods (~7%) > internal exposure by inhalation of contaminated air (~4%) > external dose from radionuclides deposited on the ground (less than 1%).

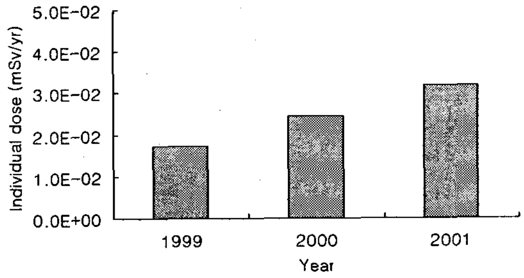

Fig. 1. Annual individual dose due to gaseous effluents from the operation of all facilities.

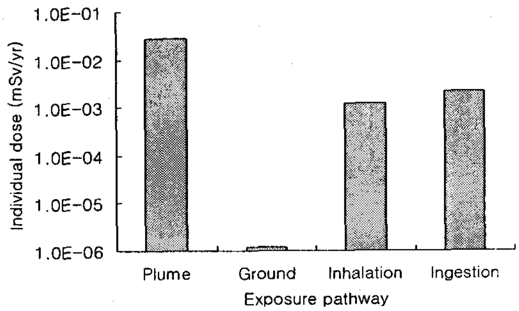

Fig. 2. Annual individual dose for child as a function of exposure pathways from the operation of facilities during 2001.

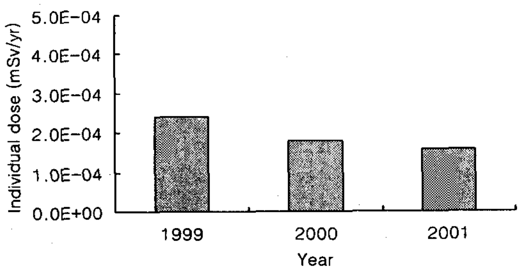

Fig. 3. Annual individual dose due to liquid effluents from operation of all facilities.

Fig. 3 shows the annual individual dose due to liquid effluents from operation of all facilities located at KAERI site during 3 years from

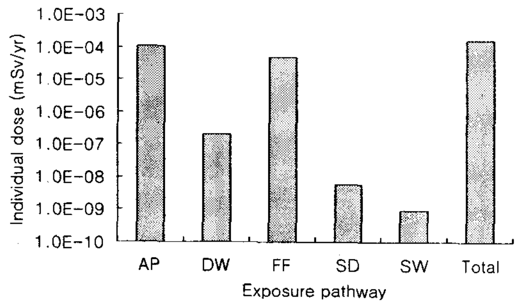

Fig. 4. Annual individual dose for teen as a function of exposure pathways from the operation of facilities during 2001 (AP : irrigated agricultural products, DW : drinking water, FF : fresh-water fish, SD : shoreline deposits, SW : swimming).

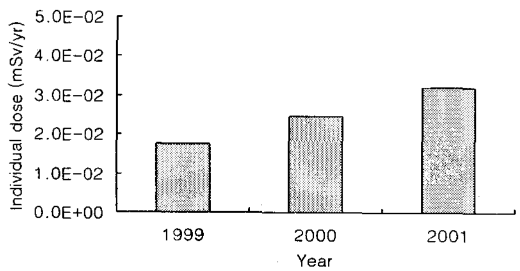

Fig. 5. Annual individual dose due to gaseous and liquid effluents from the operation of all facilities.

1999 to 2001. Unlike gaseous effluents, the most exposed age group is teen. Fig. 4 shows the annual individual dose for teen as a function of exposure pathways from the operation of facilities during 2001. The major exposure pathways are irrigation of agricultural products (~68%) and fresh-water fish (~31%), others are minor (less than 1%). Owing to the geological characteristics of the site, it may be unreasonable results that the ingestion of fresh-water fish represents relatively high contribution in dose. Therefore, for more realistic estimation, the analysis of site-specific data such as consumption habits should be conducted in detail.

Fig. 5 shows the annual individual dose due to gaseous and liquid effluents from the operation of all facilities located at KAERI site during 3 years from 1999 to 2001. Dose contribution due to gaseous effluents is much higher than that due to liquid effluents. In the MOST's Notice, regulatory standard for a site is 25 mSv/yr in effective dose. Thus, it is identified that the radiation induced health effects for residents around the site are neglectable.

Korean regulatory standards are more rigorous than regulatory standards in most Member States of European Community. The former is applied to the most exposed individual, the latter is applied to a typical or average member of the critical group open to a number of pathways for maximum exposure and having what might be termed realistic (rather than extraordinary) living habits. Radiological doses based on the most exposed individual may higher by at least a factor of ten than those based on average member of the critical group[12].

CONCLUSIONS

To prevent potential health detriment to the residents from radioactive effluents, radiological dose assessment due to the operation of nuclear facilities located at KAERI site has been performed semiannually in compliance with the MOST's Notice in Korea. In this manuscript, a serial activities at KAERI site to meet the regulatory standards for routine releases of radioactive effluents were introduced and discussed including technical approaches. It is clear that each nuclear facility has been operated in compliance with regulatory standards. Furthermore, it is identified that the radiation induced health effects for residents around the site are neglectable.

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