A SENSITIVITY ANALYSIS OF MODIFIED INPUT PARAMETERS OF GASDOS FOR A REPRESENTATIVE PERSON CONCEPT

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Recently, the ICRP has recommended the use of a 'Representative Person' as a new basic recommendation to evaluate the dose of individuals with different characteristics, habits, and lifestyles. A dose assessment method in Korea is based on the Maximum Exposed Individuals (MEI) of a critical group, which has been adopted by the U.S. NRC. The MEI concept is more conservative than a 'representative person' is. Therefore, to set the modified parameters according to the new recommendation, we performed a sensitivity analysis of a dose assessment code's input parameters as a preceding research. For the first step, we chose several qualitative parameters that occupy a relatively large part of a dose assessment. For a sensitivity analysis, we sampled the parameters with LHS, which is a Monte-Carlo method. A sensitivity analysis was performed to find how important these parameters are and to rank their importance. The sensitivity analysis of the parameters will be extended to all areas of an individual dose assessment. Then, more accurate and efficient values might be obtained for a dose assessment. The information of the dose obtained in this study might contribute to a basic tool for the optimization of radiation protection based on the new ICRP recommendation.

I. INTERODUCTION

In order to protect the population from radiation around a nuclear power plant, operators must evaluate the radiation dose of the residents. For estimating the internal dose from a nuclear power plant's gaseous effluent during normal operation, it is essential to use an appropriate evaluation model. The assessment model includes various environmental parameters. Furthermore, individuals subject to public exposure have different habits, lifestyles, and personal characteristics. Therefore, reflecting the environmental characteristics and increasing the reliability of these parameters is the key to a more accurate dose assessment. The International Commission on Radiological Protection (ICRP) recommended the concept of a 'Critical Group' to set the individual criteria, which has been useful in finding related parameters (Ref. 1). In addition, ICRP recently recommended the use of a 'representative person' in its new basic recommendation (Ref. 2). A representative person represents a highly exposed person in a population group who has reasonable, sustainable, and homogeneous habits. However, the method of dose assessment in Korea follows the more conservative concept of the 'Maximum Exposed Individuals (MEI)' of a critical group, which cannot reflect the change in the new recommendation. Moreover, the data used in a Korean environmental assessment are too old fashioned. Therefore, we need to examine the social and environmental characteristics and obtain these parameters quantitatively.

Thus, the objective of this paper is increasing the reliability of a dose assessment through analyzing these parameters. In particular, the internal dose related to food consumption mostly accounts for the radiological dose of public around an NPP. In Korea, dose related to the ingestion route accounts for more than 50% of the dose from gaseous emissions. Furthermore, dose due to the intake of marine products accounts for more than 99.5% of the dose from liquid effluent (Ref. 3). Therefore, in order to find the most effective parameter on a dose calculation, we focused on the parameters of an internal dose assessment from ingestion. We performed a sensitivity analysis of factors using a Latin Hypercube Sampling/Partial Rank Correlation Coefficient (LHS/PRCC) analysis. This is an efficient tool usually used in an uncertainty analysis to examine the parameter space of a model with a minimum number of computer simulations (Ref. 4). The goal of a sensitivity analysis is to identify the key parameters whose uncertainties contribute to an imprecise prediction and to rank them by their importance.

II. PARAMETERS FOR ESTIMATION OF INTERNAL DOSE FROM INGESTION

II.A. Model for Calculating Internal Dose from Ingestion of Radionuclides in Food

A Radiological Dose Assessment in Korea uses a calculation model according to the U.S. Nuclear Regulatory Committee guide. Shown through equation (1), The U.S. regulatory guide 1.109 presents the basic evaluation model of a dose from food ingestion. Internal dose from ingestion of contaminated food for one year represents a committed dose for life after food consumption. The radionuclides considered are Sr-90, I-131, and C-137. These important artificial radionuclides significantly affect the effluence in humans when ingested. TABLE I shows the ingestion dose factors for radionuclides.

$$R = C \times U \times D \qquad (1)$$

R: The Annual Dose of an Individual from Ingestion of Food (mrem/yr)
C: The Concentration of Radio Nuclide in Food (pCi/L or pCi/kg)
U: The Annual Intake of Food (L/yr or kg/yr)
D: The Ingestion Dose Factor (mrem/pCi-ingestion)

The pathway of internal exposure from ingestion is divided into two types: either ingestion of a contaminated crop or the ingestion of animal products that intake contaminated feed. We supposed that a typical type of the former case is grain and the latter cases are milk and meat. The evaluated age group is adults.

TABLE I. The Ingestion Dose Factor for Radionuclides (Ref. 5)

Nuclides	Dose Coefficient (Adults)
^{137}Cs	7.14×10^{-5}
^{90}Sr	1.86×10^{-3}
^{131}I	3.41×10^{-6}

II.B. Vegetation

II.B.1. Concentration of radionuclide in vegetation

Crops can be contaminated simply through two types of pathways. The former is contamination on the surface of leafy vegetables (Ref. 5). The latter is absorbing the radioactive contaminants through the root from soil. The equation of the concentration of radionuclide in leafy vegetable contaminated by a direct deposit is shown in (2).

$$C_L = \frac{3.17\times10^{-8} C_{si} r}{Y \lambda_{ei}} (1 - e^{-\lambda_{ei} T_e}) e^{-\lambda T_h} \qquad (2)$$

C_L: the concentration of radionuclide i in leafy vegetables (pCi/kg)
r: the fraction of deposited activity retained on crops
Y: the agricultural productivity (kg-wet weight/m^2)
λ_{ei}: the effective removal rate constant for radionuclide I from crops, where λ_w is the removal rate constant for physical loss by weathering, and λ_i is the radioactive decay constant (1/day)
T_e: the period in which crops are exposed to contamination during the growing season (day)
T_h: the holdup period in which crops are exposed to contamination during the growing season (day)

TABLE II. Parameters Involved in Leafy Vegetable Ingestion

Parameter	Unit	Dist. Type	Nuclides	Minimum	Maximum
r/Y	m^2/kg	Lognormal	-	0.892	3.795
λ_{ei}	day^{-1}	Lognormal	^{137}Cs	0.030	0.071
			^{90}Sr	0.030	0.071
			^{131}I	0.123	0.195
T_e	day	Lognormal	-	120	180
T_h	day	Lognormal	-	14	166

The characteristics of the parameter distribution were obtained with reference from U.S. NRC Guide. The minimum and maximum values are 90% range values of each parameter's distribution (Ref. 6). The equation of the concentration of radionuclides in vegetable contaminated through its root is shown in (3).

$$C_R = \frac{3.17 \times 10^{-8} C_{si} B_{iv}}{P \lambda_i}(1 - e^{-\lambda_i T_b}) e^{-\lambda_i T_h} \tag{3}$$

C_R: the concentration of radionuclide i in vegetation contaminated via root absorption (pCi/kg)
P: the effective surface density for soil (kg-soil/m2)
B_{iv}: the concentration factor for uptake of radionuclide I from soil by edible parts of crops (pCi/kg-wet weight per pCi/kg-soil)
T_b: the period of time for which sediment or soil is exposed to contaminated water (day)

TABLE III. Parameters Involved in Vegetation Contaminated via Root Absorption

Parameters	Unit	Dist. Type	Nuclides	Minimum	Maximum
U_C	kg/yr	Lognormal	-	69	520
P	kg-soil/m2	Lognormal	-	65	260
B_{iv}	pCi/kg-wet per pCi/kg-soil	Lognormal	^{137}Cs	4.1×10^{-4}	1.7×10^{-1}
			^{90}Sr	1.8×10^{-3}	2.9×10^{-1}
			^{131}I	1.1×10^{-3}	1.3×10^{-2}
T_b	day	Lognormal	-	9.1×10^{2}	1.3×10^{4}

II.B.2. Intake Rate of Crops for an Individual

The distribution of individual Annual Intake of crops was obtained by assuming the annual intake value of MEI and the population as 95% and the mean values of a lognormal distribution. The food intake values of the MEI and population are from the population dose calculation guideline of Korea (Ref. 7).

TABLE IV. The Individual Annual Intake of Crop

Parameters	Unit	Dist. Type	μ	σ	Mean	Minimum	Maximum
U_C	kg/yr	Lognormal	5.25	0.61	190	69	520

II.C. Animal Product

The animal products are categorized as milk, beef, pork, chicken, etc. It is assumed that the radionuclide concentration in animal feed is the same as the concentration in the previously calculated crop. In particular, it is supposed that cattle eat the grass in a pasture or stored feed. In this study, the animal products considered were milk and beef.

II.C.1. Concentration of radionuclides in animal products

The cattle eat the grass in a pasture or stored feed. Thus, the concentration of radionuclides in milk is presented as equation (4).

$$C = FQ[C_p f_p f_s + C_s[f_p(1-f_s) + (1-f_s)]]e^{-\lambda_i T_t} \quad (4)$$

C_M: the concentrations of radionuclide in milk (pCi/kg)
F_m: the estimation of cow milk activity from that in feed (d/L)
Q: the amount of feed consumed by an animal per day (kg/d)
f_p: the fraction of the year that animals graze on pasture
f_s: the fraction of daily feed that is pasture grass when the animal grazes on pasture
C_p: the concentration of radionuclides on pasture grass (pCi/kg)
C_s: the concentration of radionuclides in stored feeds (pCi/kg)
T_h: the average transport time of the activity from the feed into milk and to the receptor (day)

In addition, the concentration of radionuclides in beef is presented in equation (5). Most of the factors are same as the factors for a calculation of the internal dose from milk ingestion.

$$C = FQ[C_p f_p f_s + C_s[f_p(1-f_s) + (1-f_s)]]e^{-\lambda_i T_t} \quad (5)$$

C_F: the concentrations of radionuclides in meat (pCi/kg)
F_f: the estimation of meat activity from that in feed (d/kg)
T_h: the average transport time of the activity from feed into meat and to the receptor (day)

Likewise, the characteristics of the parameter distribution are obtained with reference from the U.S. NRC Guide. The minimum and maximum values are 90 % range values of each parameter's distribution (Ref. 6).

TABLE V. Parameters Involved in Animal Product Ingestion

Parameter	Unit	Dist. Type	Nuclides	Minimum	Maximum
F_m	day/L	Lognormal	^{137}Cs	6.1×10^{-4}	6.8×10^{-2}
			^{90}Sr	3.4×10^{-4}	4.3×10^{-3}
			^{131}I	4.0×10^{-4}	2.5×10^{-2}
F_f	kg/L	Lognormal	^{137}Cs	4.7×10^{-3}	9.6×10^{-2}
			^{90}Sr	2.0×10^{-4}	9.2×10^{-3}
			^{131}I	2.0×10^{-3}	3.8×10^{-2}
Q	kg/day	Normal	-	11.7	20.3
f_p	-	Normal	-	0.216	0.644
f_s	-	Normal	-	0.038	0.762
T_s	day	Normal	-	2	6
T_h	day	Normal	-	12	28

II.C.2. Intake Rate of Animal Products for an Individual

Same as in the calculation of crop intake, the distribution of individual Annual Intake of crops was obtained by assuming the annual intake value of MEI and population as 95% and mean values of a lognormal distribution.

TABLE VI. The Individual Annual Intake of Animal Products

Parameter	Unit	Dist. Type	μ	σ	Mean	Minimum	Maximum
U_M	L/yr	Lognormal	4.70	0.63	110	39	310
U_F	kg/yr	Lognormal	4.55	0.09	95	82	110

III. SENSITIVITY ANALYSIS

A sensitivity analysis is a method for quantifying uncertainty in any type of complex model. The objective of an SA is to identify critical inputs (parameters and initial conditions) of a model and quantify how input uncertainty affects the model outcomes (Ref. 7).

III.A. LHS Sampling

The first step of a sensitivity analysis of the model input parameters is a sampling of those parameters considering their characteristics such as distribution, range of value, and correlation. For sampling, we used Latin Hypercube Sampling (LHS) based on a Monte-Carlo method. LHS allows an un-biased estimate of the average model output, with the advantage that it requires fewer samples than simple random sampling to achieve the same accuracy (Ref. 8). The LHS method assumes that the sampling is performed independently for each parameter. In this study, we sampled each parameter 500 times with LHS sampling.

III.B. Partial Rank Correlation Coefficient (PRCC) Analysis

III.B.1. Partial Rank Correlation Coefficient (PRCC)

For linear trends, the linear relationship measures that work well are the Pearson's correlation coefficient (CC), partial correlation coefficients (PCCs), and standardized regression coefficients (SRC). For nonlinear but monotonic relationships between outputs and inputs, measures that work well are based on rank transforms such as Spearman's rank correlation coefficient (RCC or Spearman's rho), partial rank correlation coefficient (PRCC), and standardized rank regression coefficients (SRRC) (Ref. 7). A correlation provides a measure of the strength of a linear association between an input and an output. A Spearman's rho (ρ) represent the simple correlation between X_1 and X_2, and is calculated as equation (6) (Ref. 9).

$$\rho_{12} = \frac{\sum\left(r_{x_{1i}} - \frac{n+1}{2}\right)\left(r_{x_{2i}} - \frac{n+1}{2}\right)}{\sqrt{\sum\left(r_{x_{1i}} - \frac{n+1}{2}\right)^2 \sum\left(r_{x_{2i}} - \frac{n+1}{2}\right)^2}} \qquad (6)$$

Here, n is the sampled number of input parameters. To measure the amount of non-linear relationship between two variables after adjusting or controlling for the effect of some sets of variables, PRCC can be obtained with the correlation matrix (R) and the inverse correlation matrix (R^{-1}), as shown in equation (7) (Ref. 9).

$$\begin{matrix} & X_1 & X_2 & & Y \end{matrix}$$
$$R = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1k} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2k} \\ \vdots & & & \\ \rho_{k1} & \rho_{k2} & \cdots & \rho_{kk} \end{bmatrix} \qquad (7)$$

$$R^{-1} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1k} \\ b_{21} & b_{22} & \cdots & b_{2k} \\ \vdots & & & \\ b_{k1} & b_{k2} & \cdots & b_{kk} \end{bmatrix} \quad (8)$$

$$PRCC_{ij \cdot (all\ others)} = -\frac{b_{ij}}{\sqrt{b_{ii}\ b_{jj}}} \quad (9)$$

The PRCC result has a value between -1and 1. If a parameter's PRCC has a higher absolute value, it means that the parameter has more influence on the result. In particular, the Partial Rank Correlation analysis equips us with a PRCC and corresponding p-values with which to assess the level of uncertainty that an LHS parameter contributes to the model. Each value sampled from the distribution of the parameters makes up a parameter set. The parameter data obtain the dose results after being put into the model.

III.B.2 PRCC Results

A sensitivity analysis of parameters related to an internal dose assessment using the PRCC method has been conducted. The considered radionuclides are Sr-90, I-131, and C-137. The considered ingestion pathways of internal exposure were from intakes of grain, milk, and meat. The evaluated age group is adults. Tables VII through IX and figures 1 through 9 show the results of the sensitivity analysis with PRCC. In a PRCC analysis in general, the parameters with large PRCC values (> 0.5 or <-0.5) and corresponding small p-values (< 0.05) are deemed the most influential in the model. As a result, the relatively more important parameters of an entire radionuclide for the ingestion of crops are the agricultural productivity of the deposited crop and the annual intake of crops. In the case of milk and meat, the amount of feed consumption of cows and the transfer rate of radionuclides from feed to milk or meat were the most important. The annual intakes of milk or meat were also important. In particular, it was interesting that the PRCC of the transport time of milk and meat for I-131 was higher than that of the other parameters. This is because I-131 has a very short half -life. This means that the type of radionuclides has a significant role in the dose assessment.

TABLE VII. Sensitivity Analysis Results (Crop)

	Cs-137		Sr-90		I-131	
	PRCC	p-value	PRCC	p-value	PRCC	p-value
r/Y	0.917	0.000	0.907	0.000	0.741	0.000
λ_{ie}	-0.809	0.000	-0.789	0.000	-0.287	0.000
T_e	-0.082	0.069	-0.051	0.261	-0.068	0.132
T_h	-0.011	0.805	-0.009	0.838	-0.996	0.000
P	-0.011	0.814	-0.061	0.178	0.055	0.219
B_{iv}	0.129	0.004	0.232	0.000	-0.038	0.400
T_b	-0.063	0.162	-0.024	0.599	-0.072	0.108
U	0.954	0.000	0.951	0.000	0.84	0.000

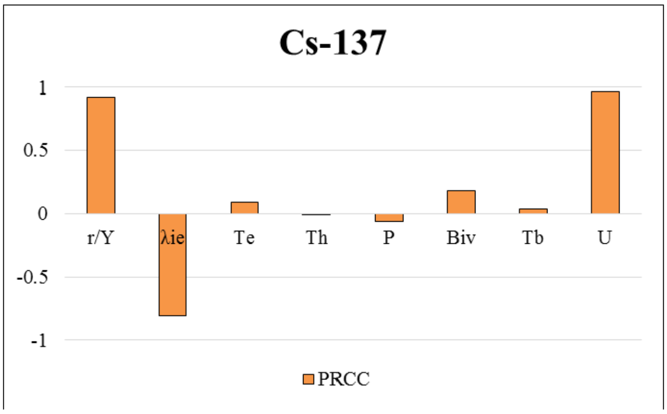

Fig. 1. PRCC Sensitivity Analysis Results (Crop, Cs-137)

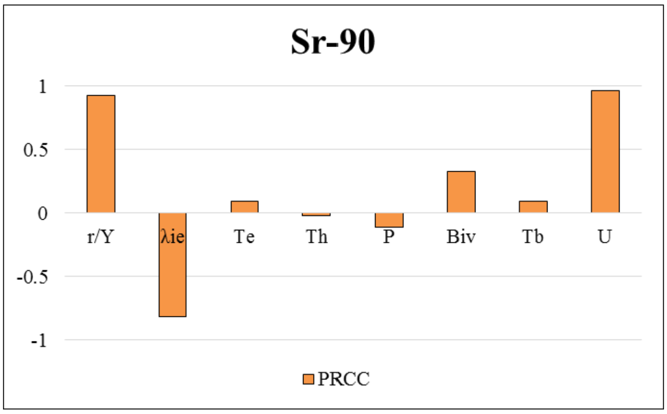

Fig. 2. PRCC Sensitivity Analysis Results (Crop, Sr-90)

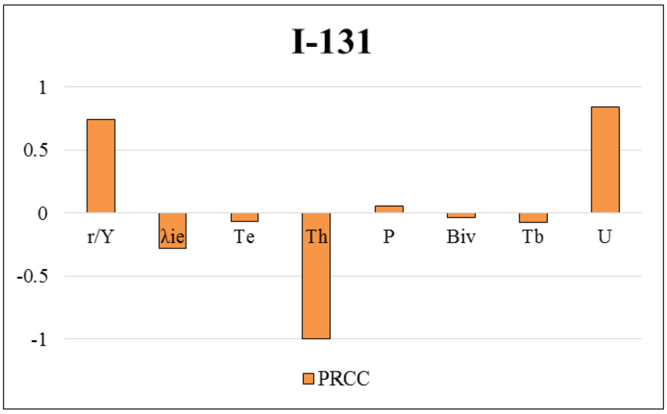

Fig. 3. PRCC Sensitivity Analysis Results (Crop, I-131)

TABLE VIII. Sensitivity Analysis Results (Milk)

	Cs-137		Sr-90		I-131	
	PRCC	p-value	PRCC	p-value	PRCC	p-value
F_m	0.982	0.000	0.959	0.000	0.981	0.000
Q	0.532	0.000	0.577	0.000	0.457	0.000
f_p	0.043	0.336	-0.022	0.633	-0.039	0.389
f_s	0.015	0.738	0.115	0.010	-0.046	0.303
T_s	0.019	0.675	-0.063	0.165	-0.319	0.000
T_h	-0.039	0.385	-0.046	0.311	-0.778	0.000
U_m	0.915	0.000	0.941	0.000	0.878	0.000

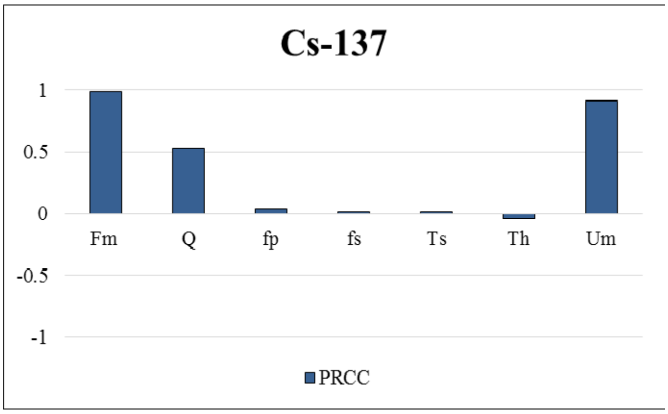

Fig. 4. PRCC Sensitivity Analysis Results (Milk, Cs-137)

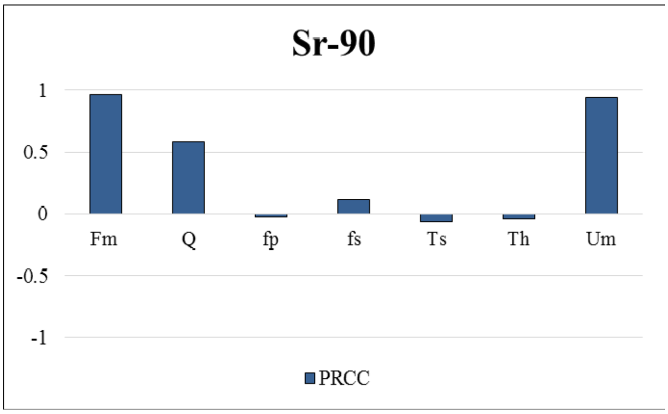

Fig. 5. PRCC Sensitivity Analysis Results (Milk, Sr-90)

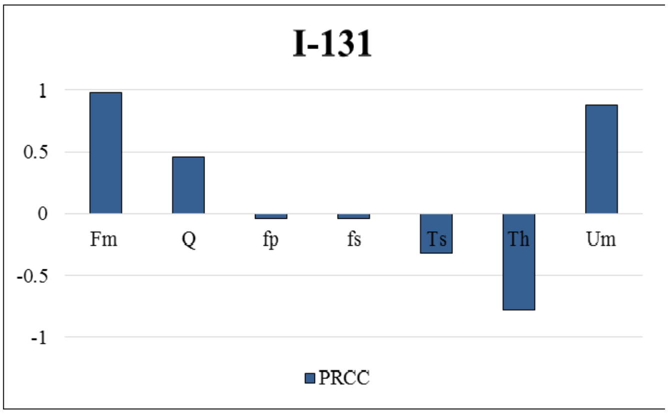

Fig. 6. PRCC Sensitivity Analysis Results (Milk, I-131)

TABLE IX. Sensitivity Analysis Results (Meat)

	Cs-137		Sr-90		I-131	
	PRCC	p-value	PRCC	p-value	PRCC	p-value
F_f	0.996	0.000	0.997	0.000	0.977	0.000
Q	0.873	0.000	0.871	0.000	0.619	0.000
f_p	-0.025	0.572	-0.001	0.991	-0.033	0.467
f_s	-0.071	0.116	0.071	0.116	0.012	0.787
T_s	0.065	0.150	-0.045	0.315	-0.378	0.000
T_h	0.04	0.380	0.016	0.731	-0.901	0.000
U_f	0.709	0.000	0.7	0.000	0.401	0.000

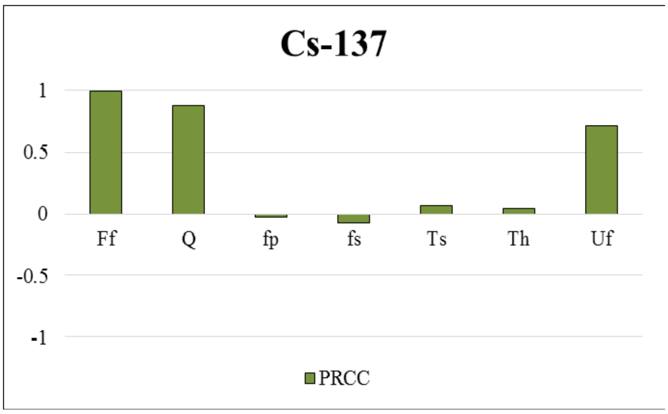

Fig. 7. PRCC Sensitivity Analysis Results (Meat, Cs-137)

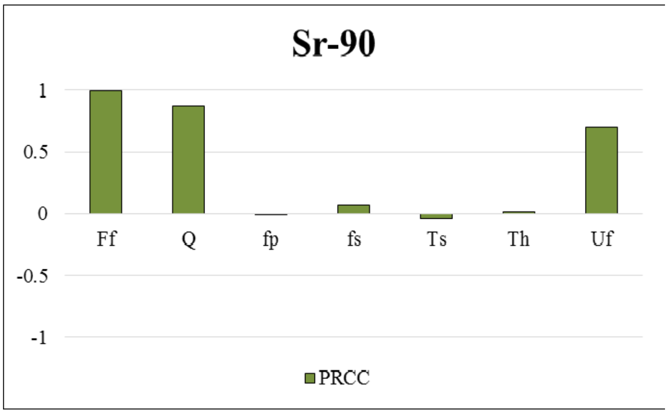

Fig. 8. PRCC Sensitivity Analysis Results (Meat, Sr-90)

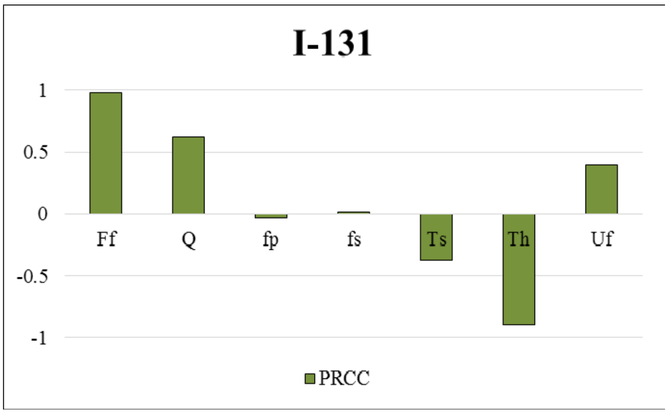

Fig. 9. PRCC Sensitivity Analysis Results (Meat, I-131)

IV. CONCLUSION

To find the important parameters and rank their importance, a sensitivity analysis was performed using the PRCC method. In particular, it was interesting that the PRCC of the transport time of milk and meat for I-131 was higher than the other parameters. This is because I-131 has a very short half-life. This means that the type of radionuclides has a significant role in the dose assessment. Therefore, a sensitivity analysis of the parameters will not only be performed for an internal dose assessment, but also be extended in terms of its range to all areas of an individual dose assessment. More accurate and efficient values can then be obtained for a dose assessment. Information on the dose obtained in this study might contribute to a basic tool for the optimization of radiation protection based on the new ICRP recommendation.

ACKNOWLEDGMENTS

This work was support by Nuclear R&D Programs of Ministry of Science, ICT and Future Planning of Korea (Grant No. 2012M2A8A4025914) and partly supported by the Nuclear Safety Research Program of the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resources from the Korean Government's Nuclear Safety and Security Commission (NSSC) (No. 1305008).

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