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An Improved Dose Assessment Model for Carbon-14 Released from PWR Stations

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1. Introduction

Carbon-14 is a long-lived(T_H = 5730 yr), low-energy pure beta(E_{AVG} = 50 keV) emitter.

Carbon-14 makes up about 70 % of annual effective doses for a PWR offsite individual since it is atmospherically released in a large amount with its long half-life and high environmental mobility. Recently, annual individual doses to the general public from PWR normal operation are approaching the design objective values and carbon-14 is the main contributor.

So far, the calculations of individual doses to the general public from carbon-14 have been based on the guidelines in references [1] and [2]. However, the recent studies and measurement data indicate that the calculation model needs to be revised. In this paper, the improved dose assessment model for carbon-14 incorporating the recent development is presented.

2. Methods and Results

In this section, the updated input data and assumptions are described first, and the revised calculation methods incorporating the updates are presented and finally, the sample calculation results are described in comparison with the existing calculation results.

2.1 Data and Assumptions

According to the recent measurement data presented in references [3] and [4], the annual release amount of carbon-14 is somewhat smaller than that in reference [2] and the chemical forms of carbon-14 released are predominantly hydrocarbons(primarily methane, $^{14}CH_4$) as opposed to the assumption of 100 % carbon dioxides($^{14}CO_2$) in reference [2].

According to the recent studies in references [5] through [7], the ingestion doses from carbon-14 are best assessed using models that employ a specific activity approach for animals as well as plants rather than the transfer factor approach for animals in reference [2].

Based on the descriptions above, the major updates are as follows.

(a) The power-normalized annual gaseous release amount of carbon-14 from a PWR is 5.95 Ci/GW(e)-yr.

(b) The chemical composition of carbon-14 released from PWRs is,
- inorganic(carbon dioxide) : 50 %
- organic(hydrocarbon) : 50 %

(c) The concentration of natural carbon in the atmosphere is 0.18 g/m^3.

(d) The specific activity model is applied to the calculation of carbon-14 concentrations in livestock as well as agricultural produce.

2.2 Calculation Methods

Since the organic forms of carbon-14 can not participate in the ingestion pathway which is the dominant exposure pathway, the concentration of carbon-14 in agricultural produce is calculated using the specific activity model as follows.

$$C_{C14}^{agri} = 0.5 \times Q_{C14}^{gas} \times [\chi / Q] \times F_{carbon}^{agri} / \chi_{carbon} \quad (1)$$

where
C_{C14}^{agri} : concentration of carbon-14 in agricultural produce
0.5 : fraction of inorganic carbon-14
Q_{C14}^{gas} : annual gaseous release rate of carbon-14
$[\chi / Q]$: annual average atmospheric dispersion factor
F_{carbon}^{agri} : fraction of plant mass that is natural carbon
χ_{carbon} : concentration of natural carbon in the atmosphere

The agricultural produce is divided into leafy vegetable, gimchi, grain and fruit, the F_{carbon}^{agri} values for which are 0.028, 0.050, 0.40 and 0.052, respectively.

In the same way as for agricultural produce, the concentration of carbon-14 in livestock is calculated using the specific activity model as follows.

$$C_{C14}^{lvst} = 0.5 \times Q_{C14}^{gas} \times [\chi / Q] \times F_{carbon}^{lvst} / \chi_{carbon} \quad (2)$$

where
C_{C14}^{lvst} : concentration of carbon-14 in livestock
F_{carbon}^{lvst} : fraction of animal mass that is natural carbon

The livestock is divided into milk and meat, the F_{carbon}^{lvst} values for which are 0.061 and 0.15, respectively.

The ingestion dose from carbon-14 for each organ of each age group is calculated by the following equation.

$$D_{C14}^{ing} = DCF_{C14}^{ing} \times [\Sigma(C_{C14}^{agri} \cdot U^{agri} \cdot f) + \Sigma(C_{C14}^{lvst} \cdot U^{lvst})] \quad (3)$$

where

D_{C14}^{ing} : annual ingestion dose from carbon-14

DCF_{C14}^{ing} : ingestion dose conversion factor for carbon-14

U^{agri} : annual ingestion rates of agricultural produce

U^{lvst} : annual ingestion rates of livestock

The annual average atmospheric concentrations of inorganic and organic carbon-14 are as follows.

$$\chi_{C14-CD} = \chi_{C14-HC} = 0.5 \times Q_{C14}^{gas} \times [\chi / Q]^{D} \quad (4)$$

where

χ_{C14-CD} : atmospheric concentration of inorganic carbon-14

χ_{C14-HC} : atmospheric concentration of organic carbon-14

$[\chi / Q]^{D}$: annual average atmospheric dispersion factor considering decay and depletion

The inhalation dose from inorganic and organic carbon-14 is calculated by the following equation.

$$D_{C14}^{inh} = DCF_{C14-CD}^{inh} \times \chi_{C14-CD} \times R + DCF_{C14-HC}^{inh} \times \chi_{C14-HC} \times R \quad (5)$$

where

D_{C14}^{inh} : annual inhalation dose from carbon-14

DCF_{C14-CD}^{inh} : inhalation dose conversion factor for inorganic carbon-14

DCF_{C14-HC}^{inh} : inhalation dose conversion factor for organic carbon-14

R : annual inhalation rate

The total internal doses from carbon-14 are the sum of ingestion and inhalation doses. That is,

$$D_{C14} = D_{C14}^{ing} + D_{C14}^{inh} \quad (6)$$

where

D_{C14} : annual internal dose from carbon-14

2.3 Calculation Results

In this study, the updated data and assumptions and revised calculation methods were applied to a SWN unit with other operational and site specific environmental data being the same as those in the existing calculations.

The comparison of results with those of existing calculations illustrates the following.

(a) The ingestion doses are reduced to 48 % of the previously evaluated doses due mainly to the updated assumption of chemical forms. In this study, inorganic carbon-14($^{14}CO_2$)which can contribute to ingestion pathway is assumed to be only 50 % of total carbon-14 released.

(b) The inhalation doses are increased to 3854 % of the previously evaluated doses due also to the changed assumption of chemical forms. In this study, organic carbon-14($^{14}CH_4$) which has the inhalation dose conversion factors about 100 times larger than those for inorganic carbon-14($^{14}CO_2$)is considered additionally.

(c) The total doses are still 48 % of the previously calculated doses because the inhalation doses are much less than the ingestion doses for carbon-14.

3. Conclusion

The updates of input data and assumptions and changes in the calculation methods for the annual doses from carbon-14 released from normal operation of a PWR were presented. And the sample calculation applying the improved calculation model to a SWN unit was performed and the calculation results were compared with those of existing calculations. From the comparison, it was shown that the total doses from carbon-14 were reduced to about 50 % of the previously evaluated doses.

Therefore, the evaluated annual individual doses to the general public from PWR normal operation using the improved calculation model can be significantly reduced since doses from carbon-14, which are the main contributor to internal doses are decreased to about half the previously evaluated doses.

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