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■ 論 文 ■

# Comparison of Dose Assessment Programs; DOSE, LIMCAL and PABLM

Hee-Seoung Park, Won-Jin Cho, Kyoung-Won Han and Hun-Hwee Park

*Korea Atomic Energy Research Institute,*
*Daeduk-danji, Teajeon, Korea*

## ABSTRACT

A comparison study is performed on dose assessment programs including DOSE, LIMCAL, and PABLM, DOSE is a program developed for preliminary safety assessments of the low- and intermediate- level radioactive waste disposal, and the others are existing programs applicable to similar calculations. The results show acceptable agreement within an order of magnitude(mrem/yr) except for C-14 and Pu-239. PABLM results higher dose for C-14 while lower value for Pu-239 in comparison with those from DOSE or LIMCAL. It is found that the discrepancy in C-14 is due to difference in transport model introduced and that in Pu-239 is from the different value of dose conversion factor to each program.

*Key words : Waste disposal, biosphere, dose assessment, DOSE, LIMCAL, PABLM.*

## INTRODUCTION

For preliminary safety assessment of the low- and intermediate- level radioactive waste disposal, a program named DOSE is developed to evaluate radiation dose through biosphere transport of radionuclides. DOSE adopts the models proposed in Reguratory Guide 1.109[1] by the U. S. NRC. The radiation exposure pathways considered in DOSE are potable water, aquatic foods, vegetable and crops, and animal products. In this context, this study is intended to check the reliablity of the program through a comparison with other programs being used. The selected programs for comparison are LIMCAL[2] and PABLM[3]. The computer program LIMCAL was developed by the AECL, Canada to assess the radiological effects to neighbors through food chains due to the radionuclides released into biosphere from waste repository constructed in underground host rock. The computer program PABLM was originally developed by the PNL(Pacific Northwest Laboratory), U. S. A. and intended to evaluate the internal and external radiation dose to neighbors due to the radionuclides released into surrounding environment from nuclear facilities, and later modified by the ONWI(Office of Nuclear Waste Isolation) to calculate the radiation dose from radioactive waste disposal.

The models and equations corresponding to PABLM and LIMCAL were given in Appendix.

## MATHEMATICAL MODEL

The mathematical models used in the computer program DOSE to estimate the radiation dose to man from each pathway are as follows :

1) Potable water

The annual internal dose from drinking of contaminated water is given by

$$R_{apj}=\frac{M_p\ U_{ap}}{F}\sum_i Q_i\ D_{aipj}\ \exp(-\lambda_i\ t_p) \quad (1)$$

2) Aquatic foods

The annual internal dose from consumption of aquatic foods from the contaminated river is calculated by

$$R_{apj}=\frac{M_p\ U_{ap}}{F}\sum_i Q_i\ B_{ip}\ D_{aipj}\ \exp(-\lambda_i\ t_p) \quad (2)$$

3) Vegetable and Crops

The annual internal dose from consumption of vegetable and crops irrigated by contaminated water is

$$R_{apj}=U_{ap}\sum_i C_{iv}\ D_{aipj} \quad (3)$$

where

$$C_{iv}=C_{iw}\ I\ \frac{r\text{-}[1\text{-}\exp(-\lambda_{ei}\ t_e)]}{Y_v\ \lambda_{ei}} + \frac{f_l\ B_{iv}[1\text{-}\exp(-\lambda_i\ t_b)]}{P\ \lambda_i} \times \exp(-\lambda_i\ t_h) \quad (4)$$

for all nuclides except trituim and

$$C_{iv}=C_{iw},\ \text{for trituim.} \quad (5)$$

4) Animal products

The annual internal dose from consumption of animal foods such as meat or milk from the animals that are grown by contaminated feed and forage is

$$R_{apj}=U_{ap}\sum_i C_{ia}\ D_{aipj} \quad (6)$$

where

$$C_{ia}=F_{ia}\ [C_{if}\ Q_f+C_{iaw}\ Q_{aw}], \quad (7)$$

for all nuclides except trituim and

$$C_{ia}=F_{ia}\ C_{iw}\ [Q_f+Q_{aw}]\quad \text{for trituim.} \quad (8)$$

## SAMPLE CALCULATION AND DISCUSSION

The radiation internal exposure pathways in the comparison are potable water, aquatic foods, vegetable and crops, and animal products. However, salt-water is not considered in aquatic foods and external exposure pathways. The radionuclides selected for comparison are H-3, C-14, Ni-59, Tc-99, I-129, Cs-135, and Pu-239, which are considered important nuclides for the safety assessment of low- and intermediate- level radioactive wastes. Since the repository site has not been determined, nominal values of release rates of the radionuclide into surface water body, mixing ratio, and ground water and surface water flow rate are assumed. The input parameters summarized in Table 1 are from Reg. Guide 1.109. Only the whole body doses for adult group are considered in this paper.

The doses from different pathways and total dose for all pathways calculated by the three computer programs are shown in Table 2 to 5 and in Figure 1. The results for the total dose agree

Table 1. The values of input parameters used in the comparsion.

| PATHWAY | PARAMETER | | DATA | |
|---|---|---|---|---|
| | $Q_i$ | Release Rate of nuclide i | $1\times10^{12}$ | 〔pci/yr〕 |
| | $M_p$ | Mixing ratio | $2.7\times10^{-6}$ | 〔dimensionless〕 |
| | F | Ground water flow rate | $1\times10^{5}$ | 〔L/yr〕 |
| | $U_{ap}$ | Food type | | 〔kg/yr〕or〔L/yr〕 |
| | | 1. Fruits and vegetables | 190 | |
| | | 2. Milk | 110) | |
| | | 3. Meat & poultry | 95 | |
| | | 4. Fish | 6.9 | |
| | | 5. Drinking water | 370 | |
| Drinking Water | $t_p$ | Environmental transit time | $1.37\times10^{-3}$ | 〔yr〕 |
| Aquatic Foods | $t_p$ | Environmental transit time | $2.74\times10^{-3}$ | 〔yr〕 |
| | r | Interception fraction | 0.25 | |
| | | (for iodine) | 0.1 | |
| Vegetable and Crops | $y_v$ | Agricultural productivity | 2.0 | 〔kg/m²) |
| | $f_i$ | Fraction of year that crops are irrigated | 0.75 | |
| | $t_e$ | Period of crop leafy vegetable, or pasture grass exposure during growing season 〔yr〕 | $1.64\times10^{-1}$ | 〔yr〕 |
| | $t_b$ | Period of long-term build up for activity in sediment or soil | 15 | 〔yr〕 |
| | p | Effective surface density of soil | 240 | 〔kg/m²) |
| | $t_h$ | Hold time | $2.74\times10^{-3}$ | 〔yr〕 |
| | I | Average irrigation rate | 100 | 〔L/m²/yr) |
| Animal Products | $Y_v$ | Agricultural productivity (Grass-cow-milk-man) | 0.7 | 〔kg/m²) |
| | $t_e$ | Same to vegetable | $8.21\times10^{-2}$ | 〔yr〕 |
| | $t_h$ | Ingestion of forage animals | 0 | 〔yr〕 |
| | | -. for stored feed | $2.46\times10^{-1}$ | |
| | $Q_f$ | Anmal's feed or forage consumption rate | | 〔kg/d〕 |
| | | -. Milk Cow | 50 | |
| | | -. Beef Cattle | 50 | |
| | $Q_{aw}$ | Animal's water consumption rate | | 〔l/d〕 |
| | | -. Milk Cow | 60 | |
| | | -. Beef Cattle | 50 | |

**Table 2. Calculated doses for potable water pathway(mrem/yr).**

| Nuclide | DOSE | LIMCAL | PABLM |
|---|---|---|---|
| H-3 | 0.11E-2 | 0.11E-2 | 0.67E-2 |
| C-14 | 0.58E-2 | 0.58E-2 | 0.62E-2 |
| Ni-59 | 0.17E-1 | 0.17E-1 | 0.62E-2 |
| Tc-99 | 0.90E-4 | 0.90E-4 | 0.40E-3 |
| I-129 | 0.93E-1 | 0.93E-1 | 0.53E-1 |
| Cs-135 | 0.80E-1 | 0.81E-1 | 0.49E-1 |
| Pu-239 | 0.19E+0 | 0.19E+0 | 0.17E-2 |

**Table 3. Calculated doses for aquatic pathway (mrem/yr).**

| Nuclide | DOSE | LIMCAL | PABLM |
|---|---|---|---|
| H-3 | 0.20E-4 | 0.21E-4 | 0.11E-4 |
| C-14 | 0.64E+0 | 0.65E+0 | 0.53+0 |
| Ni-59 | 0.35E-1 | 0.36E-1 | 0.58E-2 |
| Tc-99 | 0.26E-4 | 0.26E-4 | 0.16E-3 |
| I-129 | 0.27E-1 | 0.30E-1 | 0.19E-1 |
| Cs-135 | 0.32E+1 | 0.32E+1 | 0.20E+1 |
| Pu-239 | 0.65E-1 | 0.73E-1 | 0.16E-3 |

**Table 4. Calculated doses for vegetable and crops pathway(mrem/yr)**

| Nuclide | DOSE | LIMCAL | PABLM |
|---|---|---|---|
| H-3 | 0.55E-3 | 0.84E-2 | 0.48E-3 |
| C-14 | 0.78E-1 | 0.77E-1 | 0.42E+2 |
| Ni-59 | 0.62E-2 | 0.76E-3 | 0.20E-2 |
| Tc-99 | 0.84E-4 | 0.54E-4 | 0.37E-3 |
| I-129 | 0.13E+0 | 0.45E-2 | 0.43E-1 |
| Cs-135 | 0.29E-1 | 0.20E-2 | 0.35E-1 |
| Pu-239 | 0.65E-1 | 0.12E-2 | 0.15E-2 |

**Table 5. Calculated doses for animal products pathway(mrem/yr).**

| Nuclide | DOSE | LIMCAL | PABLM |
|---|---|---|---|
| H-3 | 0.68E-3 | 0.52E-2 | 0.43E-3 |
| C-14 | 0.94E-1 | 0.90E-1 | 0.61E+2 |
| Ni-59 | 0.34E-1 | 0.15E-1 | 0.25E-2 |
| Tc-99 | 0.18E-2 | 0.11E-2 | 0.31E-2 |
| I-129 | 0.88E-2 | 0.11E-2 | 0.31E-2 |
| Cs-135 | 0.51E-1 | 0.23E-1 | 0.15E-1 |
| Pu-239 | 0.13E-2 | 0.53E-3 | 0.64E-5 |

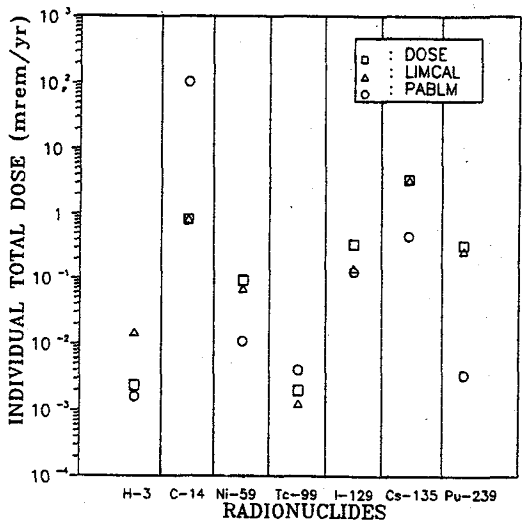


**Fig. 1. The Comparison of Total Dose Rate(mrem/yr).**

by about an order of magnitude except for C-14 and Pu-239. In PABLM, C-14 is considered as a special nuclide and it is conservatively assumed that plants receive all the carbon in the irrigation water. Such an assumption could lead to overestimate concentration of C-14 in plant and result in radiation doses considerably higher than those by other models in DOSE and LIMCAL. The results of total dose for Pu-239 is lower by about two order of magnitude than value calculated in DOSE and LIMCAL. This is due to the differences in dose conversion factors used in these three programs. Namely, the dose conversion factors in DOSE and LIMCAL are given as input data, but in PABLM, they are determined specifically as shown in appendix using the input data represented in Table 6. Here, the dose conversion factors calculated in PABLM for Pu-239 and Ni-59 are $2.121\times10^{-7}$ mrem/pci and $2.73\times10^{-7}$ mrem/pci respectively. These differ considerably from $1.191\times10^{-5}$ mrem/pci for Pu-239 and $1.63\times10^{-6}$ mrem/pci for Ni-59 used in DOSE and LIMCAL.

In the result of the nuclides which based on DOSE, C-14 show high in vegetable and crops pathway and animal products pathway in PABLM. The reason was already mentioned above. Doses from Ni-59, except for the case of vegetable and crops pathway, are relatively low due to dose conversion factor (lower about an order of magnitude) used in PABLM. The calculated doses by LIMCAL for vegetable and crops pathway are lower for I-129, Cs-135, and Pu-239 than those by DOSE. This is due to the following aspects. In DOSE and PABLM, to estimate the contribution of direct deposition to the radionuclide concentration in the edible parts of plants, the transfer of radionuclides from irrigated water to plants through water deposited on leaves is considered, while LIMCAL considers the much smaller dry deposition of resuspended radionuclides on leaves pathway. For H-3, the dose by LIMCAL in vegetable and crops pathway is higher than that by DOSE. This is due to the facts that the concentration in plants in LIMCAL is higher than those in DOSE, which is considered as a special nuclide and assumed to be equal to that in irrigated water. Pu-239 in PABLM is lower in vegetable and crops and animal products than DOSE and LIMCAL since dose conversion factor used to be low.

## CONCLUSION

For the validation of a dose assessment code, DOSE developed for preliminary safety assessment of the low- and intermediate- level radioactive waste repository, sample calculations were made and the results of calculation were compared with those by LIMCAL, and PABLM. The results show acceptable agreements by about an order of magnitude except for the discrepancies arising from difference in the dose conversion factors for some particular nuclides such as Pu-239 and in the modeling of special nuclides such as C-14. The systematic research of C-14 deposition rate in the plant and dose conversion factors are required as a future work.

## REFERENCES

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2. Reto Zach, *LIMCAL : a Comprehensive Food Chain Model for Predicting Radiation Exposure to Man in Logn-term Nuclear Waste Management,* ACEL-6827(1982).
3. B. A. Napier, W. E. Kennedy, Jr., J. K. Soldat, *PABLM - a Computer Program to Calculate Ac-*

Table 6. The input data used in dose conversion factor( $D_{iip}$ )

| | H-3 | C-14 | Ni-59 | Tc-99 | I-129 | Cs-135 | Pu-239 |
|---|---|---|---|---|---|---|---|
| $f_{wij}$ | 1.0 | 1.0 | 0.3 | 0.5 | 1.0 | 1.0 | $3\times10^{-5}$ |
| $\varepsilon^{ij}$ | $5.8\times10^{-3}$ | $5.4\times10^{-2}$ | $7.7\times10^{-3}$ | $9.5\times10^{-2}$ | $8.7\times10^{-2}$ | $6.6\times10^{-2}$ | 53 |
| TRi | 12.3 | $5.7\times10^{3}$ | $7.4\times10^{4}$ | $2.1\times10^{5}$ | $1.6\times10^{7}$ | $2.3\times10^{6}$ | $2.4\times10^{4}$ |
| TBi | $2.7\times10^{-3}$ | $2.74\times10^{-2}$ | 1.827 | $2.7\times10^{-3}$ | $2.7\times10^{-1}$ | $3.2\times10^{-1}$ | $1.8\times10^{2}$ |
| Mj | $7.0\times10^{4}$ | $7.0\times10^{4}$ | $7.0\times10^{4}$ | $7.0\times10^{4}$ | $7.0\times10^{4}$ | $7.0\times10^{4}$ | $7.0\times10^{4}$ |

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## Appendix : Mathematical Models of LIMCAL and PABLM

### LIMCAL

1) Potable water

The annual internal dose from ingestion of contaminated water is

$$R_{apj}=\frac{M_p\ U_{ap}}{F}\sum_i \exp(-\lambda_i\ t_p)Q_i\ D_{aipj} \quad (9)$$

2) Aquatic foods

The annual internal dose from consumption of aquatic foods from the contaminated fresh water is

$$R_{apj}=\frac{M_p\ U_{ap}}{F}\sum_i B_{ip}\ \exp(-\lambda_i\ t_p)Q_i\ D_{aipj} \quad (10)$$

3) Vegetable and Crops

The annual internal dose from consumption of Vegetable and crops irrigated by contaminated water is

$$R_{apj}=[U_{ap}\sum_i (C_{ir}+C_{il})\ D_{aipj}] \quad (11)$$

Here, the radionuclide concentrations in edible portion of Vegetable and crops from root uptakes radionuclides, Cir, and from air deposition of radionuclides on leaf, Cil are given as follows

- Root pathway

$$C_{ir}=[SD_i\ B_{iv}\ \exp(-\lambda_i\ t_h)] \quad (12)$$

- Leaf pathway

$$C_{il}=[d_{ia}\ \{r_j\ (1-\exp(-\lambda_{ei}\ t_{ej})\}/(y_j\ \lambda_{ei})\ \exp(-\lambda_i\ th)] \quad (13)$$

Using the resuspension factor, the annual average concentration of a radionuclide at a reference height of 1 to 1.5m ACi(pCi/m$^3$) is given by :

$$AC_i=SD_i\ SSD\ SBD\ K \quad (14)$$

The dry deposition rate of a radionuclide from air, $d_{ia}$ is given by

$$d_{ia}=AC_i\ V_{di} \quad (15)$$

4) Animal products

The annual internal dose from consumption of animal foods that are grown by contaminated feed and forage is

$$R_{apj}=U_{ap}\sum_{i} C_{ia}\ D_{aipj} \quad (16)$$

The radionuclide concentration in animal foods is given by :

$$C_{ia}=F_{ia}\ [(C_{ir}+C_{il})\ Q_{f}+C_{iaw}\ Q_{aw}] \quad [17]$$

## PABLM

Accumulated radiation dose $AR_{aijp}$ to man from radionucides in the environment is

$$AR_{aijp}=\sum_{i=1}^{no.of\ yrs} C_{ip}(t)\ U_{ap}\ D_{ijp}(t) \quad (18)$$

The equation for committed radiation dose equivalent per picocurie per year ingested, $D_{ijp}$ for organ j, for an arbitrary period following ingestion for a period Ti is :

$$D_{ijp}=0.0187\frac{F_{wij}\varepsilon_{ij}}{M_j(\lambda_e)^2}T_1\ \lambda_e+e^{-\lambda T2}-e^{-\lambda e(T2-T1)} \quad (19)$$

radionuclide concentration in the medium of each pathway is given as follow :

1) Potable water

$$C_{iw}=\frac{M_p\ Q_i}{F} \quad (20)$$

2) Aquatic foods

$$C_{ik}=C_{iw}\ B_{ip} \quad (21)$$

3) Vegetable and Crops

- For all radionuclides except trituim and C-14

$$C_{iv}=[C_{id}+C_{ir}]\exp(-\lambda_i\ t_h) \quad (22)$$

i) concentration of radionuclides from direct deposition, $C_{id}$

$$C_{id}=d_{i.r.}T_v(1-\exp(-\lambda_i\ t_e))/\lambda_{ei.}Y_v$$
$$d_i=C_{iw}\ I \quad (23)$$

ii) concentration of radionuclides from root uptake, $C_{ir}$

$$C_{ir}=C_{is}.\ B_{iv}/P$$

where

$$C_{is}=d_i(1-\exp(-\lambda_i\ 1)/\lambda_i \quad (24)$$

- Concentration of tritium in vegetation, $C_{hv}$

$$C_{hv}=9\ C_{hw.}\ F_{hv} \quad (25)$$

- Concentration of $^{14}C$ in vegetation, $C_{14\ cv}$

$$C_{14cv}=C_{14cw}\ \ F_{cv} \quad (26)$$

where,

$$C_{14\ cv}=\frac{\text{C-14 concentration in irrigated water(pci/l)}}{\text{carbon concentration in irrigated water (kg/l)}}$$

4) Animal Products

- For all nuclides except trituim and C- 14

$$C_{ia}=F_{ia}[C_{if}\ Q_f+C_{iaw}\ Q_{aw}] \quad (27)$$

- Concentration of tritium in the animal products, $C_{ha}$

$$C_{ha}=\left[\frac{C_{hf}\ Q_f+C_{haw}\ Q_{aw}}{F_{hf}\ Q_f+Q_{aw}/9}\right]F_{ha} \quad (28)$$

・ Concentration of $^{14}C$ in the animal products, $C_{14\,ca}$

$$C_{14ca}=\left[\frac{C_{14cf}\ Q_f+C_{14caw}\ Q_{aw}}{F_{cf}\ Q_f+F_{cw}\ Q_{aw}}\right]F_{ca} \qquad (29)$$

Total annual dose to man is calculated by the summation of the internal doses from all pathways mentioned above.

$$R_{aj}=\sum_p \sum_i R_{aijp} \qquad (30)$$

## Nomenclature

$B_{ip}$ : equilibrium Bioaccumulation factor for nuclide i in pathway p(L/Kg)

$B_{iv}$ : concentration factor for uptake of nuclide i from soil by edible parts of crop(veg/soil)

$C_{hf}$ : concentration of tritium in feed or forage (pCi/kg)

$C_{hw}$ : concentration of tritium in the environmental water(pCi/L)

$C_{haw}$ : concentration of tritium in animal drinking water(pCi/L)

$C_{ia}$ : concentration of nuclide i in animal product(pCi/kg)

$C_{iaw}$ : concentration of nuclide i in water consumed by animals(pCi/L)

$C_{if}$ : concentration of nuclide i in feed and forage(pCi/kg)

$C_{ik}$ : concentration of nuclide i in aquatic food (pCi/kg)

$C_{ip}$ : concentration of nuclide i in the medium of pathway p at time t(pCi/kg, pCi/L, pCi/m$^2$)

$C_{is}$ : concentration of nuclide i in soil(pCi/kg)

$C_{iv}$ : concentration of nuclide i in vegetable and crops(pCi/kg)

$C_{iw}$ : concentration of nuclide i in water(pCi/l)

$D_{aipj}$ : dose factor, specific to a given age group a, nuclide i, pathway p, and organ j(mrem/pCi)

$D_{ijp}$ : dose commitment factor for organ j from nuclide i through pathway p(rem/pCi)

$d_i$ : deposition rate of nuclide i(pCi/m$^2$ per hr)

$d_{ia}$ : dry deposition rate of nuclide i from air (pCi/m$^2$ per day)

F : surface water flow rate(l/yr)

$F_{ca}$ : fraction of carbon in animal product

$F_{ha}$ : fraction of hydrogen in animal product

$F_{cf}$ : fraction of carbon in feed or forage

$F_{hf}$ : fraction of hvdrogen in animal feed

$f_i$ : fraction of year that crops are irrigated(dimensionless)

$F_{ia}$ : transfer coefficient of stable element(d/l or d/kg)

$F_{cv}$ : fraction of carbon in total vegetable

$F_{hv}$ : fraction of hydrogen in total vegetable

$F_{cw}$ : fraction of carbon in water

$F_{wij}$ : the fraction of radionuclide i ingested reaching the organ j

I : the average irrigation rate, during the growing season(L/m$^2$/mon)

K : resuspension factor(pCi/m$^3$ per pCi/m$^3$)

$M_j$ :the effective mass of organ j, grams. organ masses used in PABLM are those taken from ICRP-23

$M_p$ : mixing ratio(dimensionless)

P : effective surface density for soil(kg/m$^2$)

$Q_{aw}$ : animal water consumption rate(L/day)

$Q_f$ : animal feed and forage consumption rate (kg/day)

$Q_i$ : release rate of nuclide i into surface water body(pCi/yr)

r : fraction of deposited activity retained on crops(dimensionless)

$r_j$ : interception fraction of vegetation for nuclide deposited in air(dimensionless)

$R_{apj}$ : annual dose to organ j of an individual of age group a via pathway p(mrem/yr)

SBD : soil bulk density($kg/m^3$)

$SD_i$ : averge annual soil concentration of nuclide i(pCi/kg)

$t_b$ : period of time for while soil is exposed to the contaminated water(yr)

$TB_i$ : biological half-time(yr)

$t_e$ : time period that crops are exposed to contaminated during the growing season(yr)

$t_{ej}$ : time of above-ground exposure of vegetation during the growing season(yr)

$t_h$ : holdup time(yr)

$t_p$ : averge transit time(yr)

$TR_i$ : radiological half-time(yr)

$T_v$ : factor for translocation of externally deposited radionuclides to edible parts of plants (dimensionless)

$T_1$ : the intake time, taken to be 1 year in PABLM

$T_2$ : time over which dose is accumulated(yrs), assumed to be 1 year

$U_{ap}$ : usage factor for an individual of age group associated with pathway p(L/yr or kg/yr)

$V_{di}$ : dry deposition velocity of nuclide i from air(m/yr)

$Y_v$ : agricultural productivity($kg/m^2$)

$\varepsilon_{ij}$ : the effective decay energy of radionuclide i in organ j, MeV per disintegration.

$\lambda_e$ : the effective removal half-time, related to the biological half-time, $TB_i$, and the radiological half-time, $TR_i$, as

$$\lambda_e = \frac{0.693(TR_i + TB_i)}{TR_i \times TB_i} \text{ Years}^{-1}$$

$\lambda_{ei}$ : effective removal rate constant for nuclide i from crops($yr^{-1}$) $= \lambda_i + \lambda_w$

$\lambda_i$ : decay constant of nuclide i($yr^{-1}$)

$\lambda_w$ : the removal rate constant for physical loss by weathering($yr^{-1}$)

# 방사선 피폭선량프로그램 DOSE, LIMCAL 및 PABLM의 비교

박희성, 조원진, 한경원, 박헌휘

한국원자력연구소

## 요 약

DOSE, LIMCAL 그리고 PABLM을 포함한 방사선피폭선량프로그램에 대하여 비교 연구가 행하여졌다. DOSE 프로그램은 국내 중. 저준위 방사선폐기물 처분 예비안전성평가를 위해 확립되었으며, 나머지 두 프로그램은 안전성 평가에 적용한 바 있는 프로그램들이다. 연구 결과는 C-14과 Pu-239를 제외하고 1승(mrem/yr)범위에서 잘 일치하고 있다. PA-BLM은 DOSE와 LIMCAL과 비교할때 Pu-239의 경우에서 작게 나타나고 있는 반면에 C-14의 경우에는 크게 나타나고 있다. C-14의 편차는 소개된 이동모델에서의 차이 때문이며 Pu-239의 차이는 두 프로그램과 다른 선량전환인자 값을 적용함으로써 발생한 것임을 알 수 있다.