A DYNAMIC FOOD CHAIN MODEL FOR HONG KONG BASED ON RADFOOD MODEL AND BIRCHALL-JAMES ALGORITHM*

K.N.Yu (余君岳), K.P.Ng (吴国斌), T. Cheung (张 增)
and E.C.M.Young (杨健明)

(*Department of Physics and Materials Science, City Polytechnic of Hong Kong*)

ABSTRACT

In this paper a dynamic food chain model for Hong Kong which simulates the transfer of radioactive substances from a fallout deposition via the food chain into the human bodies is built. The model is based on the RADFOOD model and the Birchall-James algorithm. The radionuclides ^{131}I and ^{90}Sr representing the short-term and long-term risk situations have been studied as sample cases. Various types of crops, and the dietary pattern of the public have been considered. The resulting internal radiation doses have been calculated. The results are obtained for food consumption starting at various time after the fallout deposition and for different consumption durations.

Keywords Dynamic food chain model, Fallout deposition, ^{131}I, ^{90}Sr

1 INTRODUCTION

A dynamic food chain model which describes the transfer of radioactive substances within the food chain and ultimately into the human bodies is important for radiological protection purposes in areas affected by an accidental fallout from nuclear power plant. Such a model will involve plenty of parameters, which are always difficult to determine experimentally.

In early 1994, the nuclear power plant built at the Daya Bay near to Hong Kong went into operation and the public become more and more concerned about the effects of its possible accidental fallout. In particular, the Radiological Protection Advisory Group (RPAG) in Hong Kong suggested that a dynamic food chain model should be built for Hong Kong (RPAG 1990)[1]. However, there are not very many dynamic food chain models nor their parameters published in the literature. One rather detailed one, called the "RADFOOD" model[2] with parameters has been published.

The RADFOOD model is a compartmental model which consists of basically a series of compartments representing the various components for the food chain. The kinetics of the radionuclide transfer is described by a set of linear first order differential equations, of which each one describes the time dependence of the radioactivity concentrations of

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a given compartment. The radionuclide concentrations in each compartment and the ultimate radiation dose conveyed to the human body, which are time dependent, can be determined by solving these equations analytically[2].

In the present work, we build a dynamic food chain model for Hong Kong based on this RADFOOD model. In addition, we will further adopt a fast computer algorithm for solving first order compartmental models involving recycling[3], which is referred to as the BJ algorithm in the following discussions. The advantage of using the BJ algorithm is the large improvement in speeding up the process of finding the solutions to the differential equations, and of finding the pattern of the flow. Of course, we need to transform the differential equations set up by Koch and Tadmor[2] to equations with suitable format for the BJ algorithm, which will be shown in section II. Sample calculations for the radionuclides ^{131}I and ^{90}Sr will be presented in section III.

2 DYNAMIC FOOD CHAIN MODEL WITH BJ ALGORITHM

The compartment scheme of this model is depicted in Figs.1a, 1b and 1c. The following equations and boundary conditions are written in the suitable format for the BJ algorithm and represent the compartments with respect to time with their symbols and definitions summarized in Table 1.

Pre-harvest processes:

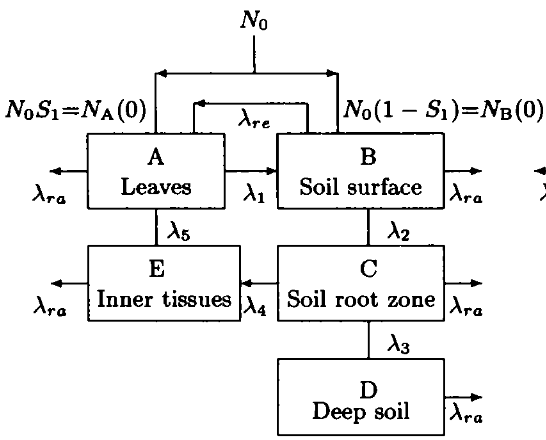


Fig.1a Compartment scheme for crops without external edible parts

Roots and tubers, leafy vegs, forage crops

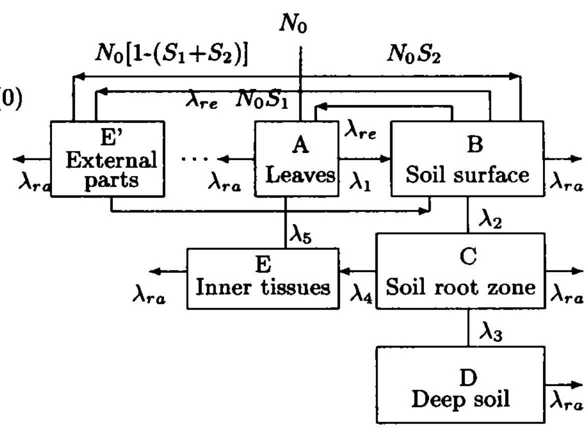


Fig.1b Compartment scheme for crops with external edible parts

Cereals, fruits

2.1 Pre-harvest time

Radioactivity concentration in plant leaves exposed to fallout:

$$\frac{\mathrm{d}N_{\mathrm{A}}}{\mathrm{d}t}=-(\lambda_1+\lambda_5+\lambda_{\mathrm{ra}})N_{\mathrm{A}}+\lambda_{\mathrm{re}}S_1N_{\mathrm{B}},\quad N_{\mathrm{A}}(0)=N_0S_1 \tag{1}$$

(at time t=0, i.e, at the start of fallout deposition time);

Table 1
List of symbols and their definitions

Symbol	Definition	Units
N_A	Radioactivity conc. on plant leaves	m^{-2}
N_B	Radioactivity conc. in soil surface layer	m^{-2}
N_C	Radioactivity conc. in soil root zone	m^{-2}
N_D	Radioactivity conc. in deep soil	m^{-2}
N_E	Radioactivity conc. in the edible inner parts of a plant	m^{-2}
$N_{E'}$	Radioactivity conc. on external parts of a plant	m^{-2}
N_F	Radioactivity conc. in milk	l^{-1}
N_G	Radioactivity conc. in beef	kg^{-1}
C_m	Daily milk consumption	l/d
C_b	Daily beef consumption	kg/d
C_{vi}	Daily consumption of each crop type by man	kg/d
DF	Weighted committed dose equivalent conversion factor	Sv/Bq
f_w	Fraction of radionuclides transferred to the organ or body of interest via ingestion of food	–
F_b	Transfer coefficient from feed to meat	d/kg
F_m	Transfer coefficient from feed to milk	d/l
$\tilde{A}_b$	Cumulated radioactivity intake through beef consumption	Bq·d
d_f	Daily feed consumption by milk cow or cattle	kg/d
$\tilde{A}_m$	Cumulated radioactivity intake through milk consumption	Bq·d
$\tilde{A}_{vi}$	Cumulated radioactivity intake through consumption of each crop type	Bq·d
i	Crop type index (I=1,2,···6)	–
$I_{m;b;vi}$	Daily intake of radioactivity via ingestion of different foodstuffs	Bq/d
N_o	Initial fallout surface radioactivity	m^{-2}
PF_i	Food preparation factor for each crop type	–
P	Radioactivity conc. in edible parts of each crop type	Bq/kg
RH_b	Individual radiation dose following meat consumption	Sv
RH_m	Individual radiation dose following milk consumption	Sv
RH_{vi}	Individual radiation dose following consumption of each crop type	Sv
S_1	Fallout interception factor of the leaves	–
S_1'	Fallout interception factor of the external parts of a plant	–
S_2	Fallout fraction depositing on the soil surface	–
TH	Total individual whole-body dose	Sv
Y_{ex}	Yield of the external parts of a plant	kg/m^2
Y_{in}	Yield of the edible inner parts of a plant	kg/m^2
λ_1	Environmental weathering rate constant	d^{-1}
λ_2	Rate constant for penetration into soil root zone	d^{-1}
λ_3	Transfer rate constant to the soil sink	d^{-1}
λ_4	Root uptake rate constant	d^{-1}
λ_5	Rate constant for translocation to edible parts of plants	d^{-1}
λ_b	Excretion rate constant from beef	d^{-1}
λ_m	Transfer rate constant from milk compartment to the udder	d^{-1}
λ_{ra}	Radioactive decay rate constant	d^{-1}
λ_{re}	Resuspension-deposition rate constant	d^{-1}
λ_E	Effective decay constant for the radionuclide in the organ or body	d^{-1}
ϵ	Effective energy deposited to the organ or body during a radionuclide transformation	MeV
m	Mass of the organ or body of interest	kg

Note: The above table is similar to Table 1 given by Koch and Tadmor[2]

Radioactivity concentration in the soil surface layer:

$$\begin{aligned} \frac{\mathrm{d}N_{\mathrm{B}}}{\mathrm{d}t} &= -[\lambda_2 + \lambda_{\mathrm{ra}} + \lambda_{\mathrm{re}}(S_1 + S_1')]N_{\mathrm{B}} + \lambda_1 N_{\mathrm{A}} && \text{(5 compartments)} \\ &= -[\lambda_2 + \lambda_{\mathrm{ra}} + \lambda_{\mathrm{re}}(S_1 + S_1')]N_{\mathrm{B}} + \lambda_1 N_{\mathrm{A}} + \lambda_1 N_{\mathrm{E'}} && \text{(6 compartments)} \\ N_{\mathrm{B}}(0) &= [1 - (S_1 + S_1')]N_0 = S_2 N_0; \end{aligned} \tag{2}$$

Radioactivity concentration in the soil root zone:

$$\begin{aligned} \mathrm{d}N_{\mathrm{C}}/\mathrm{d}t &= -(\lambda_3 + \lambda_4 + \lambda_{\mathrm{ra}})N_{\mathrm{C}} + \lambda_2 N_{\mathrm{B}} \\ N_{\mathrm{C}}(0) &= 0 \end{aligned} \tag{3}$$

Radioactivity concentration in the deep soil:

$$\mathrm{d}N_{\mathrm{D}}/\mathrm{d}t = -\lambda_{\mathrm{ra}} N_{\mathrm{D}} + \lambda_3 N_{\mathrm{C}}, \quad N_{\mathrm{D}}(0) = 0 \tag{4}$$

Radioactivity concentration in the edible inner parts of a plant:

$$\mathrm{d}N_{\mathrm{E}}/\mathrm{d}t = -\lambda_{\mathrm{ra}} N_{\mathrm{E}} + \lambda_5 N_{\mathrm{A}} + \lambda_4 N_{\mathrm{C}}, \quad N_{\mathrm{E}}(0) = 0 \tag{5}$$

Radioactivity concentration in external parts exposed to fallout:

$$\mathrm{d}N_{\mathrm{E'}}/\mathrm{d}t = -(\lambda_1 + \lambda_{\mathrm{ra}})N_{\mathrm{E'}} + \lambda_{\mathrm{re}} S_1' N_{\mathrm{B}}, \quad N_{\mathrm{E'}}(0) = S_1' N_0 \tag{6}$$

2.2 Post-harvest time

Radioactivity in milk:

$$\frac{\mathrm{d}N_{\mathrm{F}}}{\mathrm{d}t} = F_{\mathrm{m}}(\lambda_{\mathrm{m}}) \cdot I_f[\frac{N_{\mathrm{A}}}{Y_{\mathrm{ex}}} + \frac{N_{\mathrm{E}}}{Y_{\mathrm{in}}}] - (\lambda_{\mathrm{m}} + \lambda_{\mathrm{ra}})N_{\mathrm{F}}, \quad N_{\mathrm{F}}(0) = 0 \tag{7}$$

Radioactivity in beef:

$$\frac{\mathrm{d}N_{\mathrm{G}}}{\mathrm{d}t} = F_{\mathrm{b}}(\lambda_{\mathrm{b}}) \cdot I_{\mathrm{f}}[\frac{N_{\mathrm{A}}}{Y_{\mathrm{ex}}} + \frac{N_{\mathrm{E}}}{Y_{\mathrm{in}}}] - (\lambda_{\mathrm{b}} + \lambda_{\mathrm{ra}})N_{\mathrm{G}}, \quad N_{\mathrm{G}}(0) = 0 \tag{8}$$

Cumulated radioactivity ingested by man through the food chain:

$$\tilde{A}_{\mathrm{m}}(t) = \frac{I_{\mathrm{m}}}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}} t} - 1)] = \frac{C_{\mathrm{m}} \cdot F \cdot f_{\mathrm{w}}}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}} t} - 1)]$$

$$\tilde{A}_m(0) = 0 \tag{9}$$

$$\tilde{A}_{\mathrm{b}}(t) = \frac{b}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}} t} - 1)]$$

$$\tilde{A}_{\mathrm{b}}(t) = \frac{C_{\mathrm{b}} \cdot G \cdot f_{\mathrm{w}}}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}} t} - 1)] \tag{10}$$

$$\tilde{A}_{\mathrm{b}}(0) = 0$$

$$\tilde{A}_{\mathrm{vi}}(t) = \frac{I_{\mathrm{vi}}}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}}t} - 1)] = \frac{C_{\mathrm{vi}} \cdot P \cdot f_{\mathrm{w}} \cdot PF_{\mathrm{i}}}{\lambda_{\mathrm{E}}}[t + \frac{1}{\lambda_{\mathrm{E}}}(e^{-\lambda_{\mathrm{E}}t} - 1)] \quad (11)$$

$$\tilde{A}_{\mathrm{vi}}(0) = 0$$

Cumulated radiation doses to man and health effects:

$$RH_{\mathrm{m}} = \left[1.3824 \times 10^{-8}/m\right] \cdot \epsilon \cdot \tilde{A}_{\mathrm{m}}(t) \quad (12)$$

$$RH_{\mathrm{b}} = \left[1.3824 \times 10^{-8}/m\right] \cdot \epsilon \cdot \tilde{A}_{\mathrm{b}}(t) \quad (13)$$

$$RH_{\mathrm{vi}} = \left[1.3824 \times 10^{-8}/m\right] \cdot \epsilon \cdot \tilde{A}_{\mathrm{vi}}(t) \quad (14)$$

$$TH = RH_{\mathrm{m}} + RH_{\mathrm{b}} + \sum_{i=1}^{6} RH_{\mathrm{vi}} \quad (15)$$

These equations are solved separately for different radionuclides which contribute significantly to the radiation dose. The present study divides the crops into 5 groups,

Table 2
The compartments relevant to different foodstuffs

Foodstuff	Compartment
Cereals	E'
Roots and Tubers	E
Leafy vegetables	A+E
Fruits	E'
Forage crops	A+E
Milk	F
Beef	G

Table 3
The annual food consumption rates for the public in Hong Kong

kg/a

Foodstuff	Adult	Child (10 a old)	Infant (1 a old)
Cereal	141	105	56
Roots and tubers	13	10	4
Leafy vegetables	93	70	21
Fruit	66	50	31
Meat	74	56	12
Beef(1)	25	19	4
Milk(2)	35	26	260

(1) The amount of beef consumed is calculated as 1/3 of the amount of meat consumed by the public

(2) IAEA infant critical group assumption rate used

i.e., cereals, roots and tubers, leafy vegetables, fruits and forage crops, and the radioactivity concentration for a particular crop at a certain time can be obtained by summing up the amount evaluated in the corresponding compartments. The relation between the crop type and their corresponding compartments is shown in Table 2. The BJ algorithm yields the radioactivity concentration, which should be converted back to activities by the following expressions:

Post-harvest processes

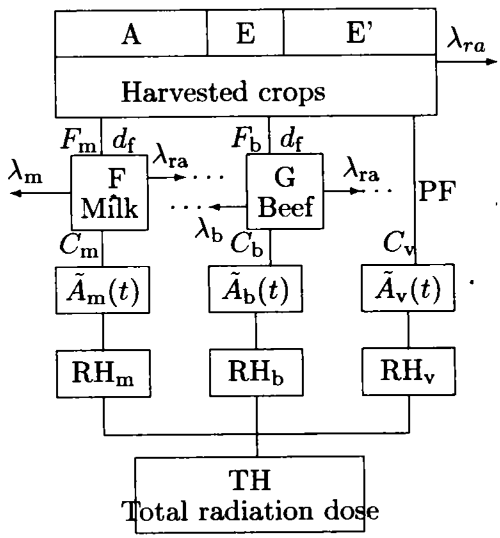


Fig.1c Compartment scheme for foodstuffs in the post-harvest processes

$$A = \frac{\lambda_{ra} N_A}{Y_{ex}} \quad (Bq/kg) \tag{16}$$

$$B = \lambda_{ra} N_B \quad (Bq/m^2) \tag{17}$$

$$C = \lambda_{ra} N_C \quad (Bq/m^2) \tag{18}$$

$$D = \lambda_{ra} N_D \quad (Bq/m^2) \tag{19}$$

$$E = \frac{\lambda_{ra} N_E}{Y_{in}} \quad (Bq/kg) \tag{20}$$

$$E' = \frac{\lambda_{ra} N_{E'}}{Y_{in}} \quad (Bq/kg) \tag{21}$$

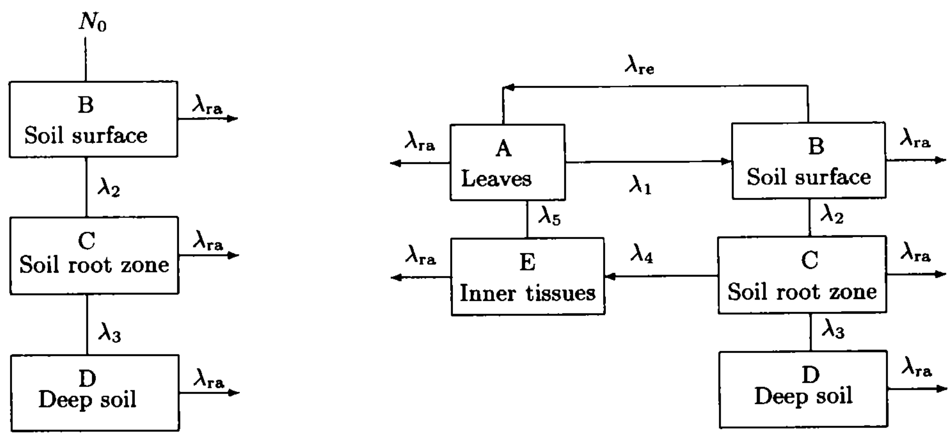
$$F = \lambda_{ra} N_F \quad (Bq/L) \tag{22}$$

$$G = \lambda_{ra} N_G \quad (Bq/kg) \tag{23}$$

3 SAMPLE CALCULATIONS FOR ^{131}I AND ^{90}Sr

Two radionuclides ^{131}I and ^{90}Sr have been chosen for demonstrating the dynamic

^{90}Sr:



Figs.2a,2b Compartment scheme for the transfer processes before growing periods of the crops (a) and for the growing of crops (Roots and tubers, leafy vegs, forage crops) one year after fallout deposition (b)

food chain model. The individual whole body dose will be calculated after consumption of the contaminated food. These two radionuclides allow us to study the short term (days to weeks) and long term (months to years) risks to the public after the fallout deposition respectively. Because of the rather long half-life of ^{90}Sr, the compartment scheme for it is modified as shown in Figs.2a, 2b and 2c. The data for the 2 radionuclides have been given by Koch and Tadmor[2].

In order to evaluate the radiation dose to the public in Hong Kong, the annual consumption rates of different food-stuffs suggested by World Health Organization[4] and other sources are used (see Table 3). As the population of Hong Kong is highly homogeneous, the whole of the Hong Kong population can be taken as the critical group, i.e., the calculation of the radiation dose is based on an "average" person in Hong Kong, and the average consumption rate by an adult is used. On the other hand, the intake of contaminated milk by infants is calculated separately as the dietary pattern of an infant is completely different from an adult. Since the intake of food for children is proportionately smaller and there is already a large degree of conservatism built in the consumption pathway, the children will not be catered for their intake of radioactivity. Moreover, the calculation of the radiation dose has presumed that all food in a particular category (say vegetables) comes from the contaminated area. The above assumptions have been explained in more details by RPAG[1].

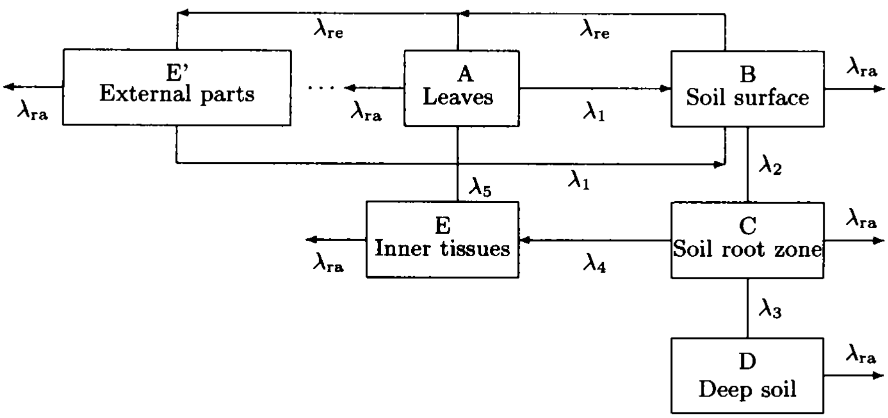


Fig.2c Compartment scheme for the growing of crops (Cereals and fruits) one year after fallout deposition

4 RESULTS

4.1 Short-term risk

The radionuclide ^{131}I has a short radiological half-life of 8 d so it disintegrates rapidly after the fallout deposition. Its health hazards to the public is predominantly short-term. We make the assumptions that the foodstuffs are contaminated during the summer (close to the harvest) and the harvested crops are consumed during a 3 month period starting 1 day or 1 week from the fallout deposition. Besides the intake of contaminated crops by human, both milk cows and cattle are assumed to feed on contaminated forage crops and the contaminated milk and beef are then consumed by human. We first calculate the time dependent concentration of the radionuclide ^{131}I in the food chain components and then evaluate the radioactivity intaked by man and the corresponding radiation dose.

For simplicity, we have only presented the plot of the cumulated radiation dose from ^{131}I as a function of time after the fallout deposition for various food categories, which is shown in Fig.3.

Table 4
Individual whole body doses for ^{131}I for different harvest time (HT) and consumption durations (CD)

$HT^{(1)}$/d	CD /d	Dose/mSv
1	1	1.28
1	7	52.76
1	14	175.71
1	30	570.61
7	1	0.60
7	7	24.39
7	14	81.54
7	30	250.70

(1) Starting after fallout deposition to harvest

Table 5
Individual whole body doses for ^{90}Sr for different harvest time and consumption durations (CD)

$CD^{(1)}$/months	Dose/10^{-5}Sv
1	0.19
3	1.82
6	7.31
12	29.43
15	45.94
18	66.06
21	89.70
24	116.87

(1) Starting from the day of harvest

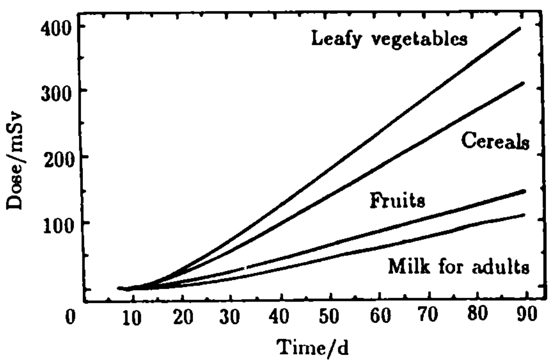


Fig.3 Cumulated radiation doses from ^{131}I as a function of time after fallout deposition

The 7-th day is the harvest day

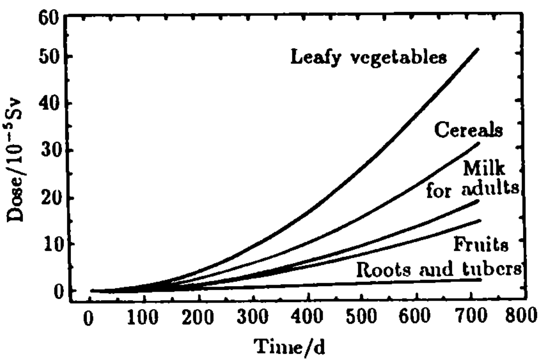


Fig.4 Cumulated radiation doses from ^{90}Sr as a function of time after the harvest day

In the calculations, we should note that when the forage crops are harvested and ingested by the milk cows and cattle, the intake of milk and beef occur several days later, so the accumulation of the radionuclides in the human body start several days after the harvest time. Furthermore, we assume that the radioactivity concentration of ^{131}I in milk and beef approach their peak values just before intake by the public, which occur on about the 6th day after the harvest time.

The individual whole body dose for ^{131}I is presented in table 4 for different harvest time and for various food consumption durations. We can see that the radiation dose received by an individual that has consumed food for a month when the food is harvested a day after fallout deposition amounts to 570mSv. This radiation dose decreases significantly when the crops are harvested 7 days after the fallout deposition for the same consumption duration. The radiation dose now reduces to 250 mSv. This is expected since the radiological half-life of ^{131}I is 8 d which indicates that a certain amount of radionuclides should have disintegrated before the crops are harvested on the 7th day. The crop that contribute most to the radiation dose is leafy vegetables, followed by cereals and fruits, while the contribution of roots and tubers and beef are very small.

A point to note is that the thyroid gland is sensitive to the absorption of ^{131}I and hence the cumulated radiation dose to the thyroid should not be neglected. Nevertheless, the calculations are straightforward by using the initial intake and the retention factor of iodine in the thyroid.

4.2 Long-term risk

The radionuclide ^{90}Sr has a long half life of 29 a so it possesses a long term risk to the public. We assume that when the radionuclides are deposited on the ground, they penetrate through the soil surface and transferred to the soil root zone and to the deep soil eventually. This process lasts for 360 d and then crops begin to grow on the soil surface for 60 d (2 months) before the harvest time. Therefore, the consumption of contaminated food begins 14 months after the fallout deposition and then lasts for up to a year. The dietary pattern is the same as that for ^{131}I. Again, for simplicity, we have only presented the plot of the cumulated radiation dose from ^{90}Sr as a function of time after the fallout deposition for various food categories, which is shown in Fig.4. The individual whole body dose is presented in Table 5. We have found that the individual radiation dose for a consumption period of 12 months is about 0.3 mSv, which is much smaller than that due to ^{131}I.

5 DISCUSSIONS

The present study has evaluated the time dependence of the two radionuclides, ^{131}I and ^{90}Sr, in the human food chain through a dynamic model after fallout deposition. We can obtain the amount of radioactivity in the contaminated food as a function of time from it consequently.

Let us recall the expression of the Derived Intervention Levels (DILs) for different foodstuffs proposed in International Atomic Energy Agency Safety Series 81, which is

$$\mathrm{DIL} = \frac{\mathrm{IL} \cdot f}{m_{\mathrm{g}} \cdot D \cdot G_{\mathrm{g}}} \tag{24}$$

where IL is intervention level of dose on food restriction (Sv), m_{g} annual intake of foodstuff g (kg/a), D dose conversion factor (Sv/Bq), f food preparation factor, G_{g} ratio of the integral over one year of the nuclide concentration in foodstuff g to the concentration in that foodstuff at a specific time (Bq/kg·a per Bq/kg) and can be written as:

$$G_{\mathrm{g}} = \left[\int_0^{\mathrm{1a}} C_{\mathrm{g}}(t)\right] \mathrm{d}t / C_{\mathrm{g}}(t_{\mathrm{p}}) \tag{25}$$

where $C_g(t)$ is the concentration of the nuclide in the foodstuff g at time t (Bq/kg), t_p is the time at which the DIL is applicable and is the time at which the concentration should be measured for direct comparison with the DIL.

The DIL can also be written as:

$$\mathrm{DIL} = [IL/m_g \cdot D] \times k \tag{26}$$

where $k \equiv f/G_g$ with $k \geq 1$.

The term $(k\text{-}1)$ is named as "contamination factor" by the Nuclear Energy Agency[5]. The values of $C_g(t)$ and eventually $G_g(t)$ can be evaluated by putting appropriate values in the dynamic model. This allows us to determine the values of k, which paves the way for calculating the DILs for different foodstuffs.

It should be noted that this dynamic model does have uncertainties, which mainly consists of the uncertainties in the setting up of the model itself and the uncertainties in the values of the selected parameters. In particular, the parameters for the model, which are borrowed from the RADFOOD model, are typical to the soil and crops in Israel, but may not be representative of those in the local environment of Daya Bay. Experimental determination of these parameters are being carried out, and a more accurate dynamic food chain model can be established afterwards.

In general, the distribution of radioactivity concentration for the crops depends on several factors, including the distance from the site of the nuclear accident, the time elapsed since the radioactive fallout, the time and seasoning of the nuclear accident and the impact situation of the accident. Because of the complicated mechanisms of the transfer of radionuclides in the environment, it is hard to estimate the effects of variations in time and area for the above factors. The present study has assumed that the radioactive fallout occur in summer just before harvest for ^{131}I and after harvest time for ^{90}Sr, and that the contaminated foodstuffs are imported to Hong Kong for local consumption. It is therefore inevitable that some safety factors have been introduced into the model. Modifications to these assumptions may give more realistic results rather than the worst-case results, which may be beneficial to the economics. This will be studied in future investigations.

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