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MARTIN MARIETTA

TRANFOOD
Radionuclide Transport via Terrestrial Food Chain

I. Uslu
D. E. Fields
M. G. Yalcintas

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*Turkish Atomic Energy Authority

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TRANFOOD

Radionuclide Transport via Terrestrial Foodchain*

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HIGHLIGHTS

A dynamic, time-dependent model has been developed for simulation of an acute environmental transfer of radionuclides through agricultural systems. TRANFOOD is a computer code which calculates concentration of radionuclides in surface and root-zone soil, deep soil, produce and feed, and beef and milk from a given initial surface concentration of radioactivity from fallout.

The preliminary validation of the model was carried out by comparing the results with Chernobyl Nuclear Accident data of the Federal Republic of Germany (Wi87). The measured and calculated results are in agreement, inasmuch as nearly the same amount of peak specific activities were seen, but there is a sharp reduction of measured specific activity values for both ^{137}Cs and ^{131}I after May 5, 1986. The differences in observed and simulated values for this period is likely due to some protective actions which had been taken in the Federal Republic of Germany (Go87). Cattle and other livestock had been sequestered and given stored feed to minimize uptake from contaminated forage.

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INTRODUCTION

A dynamic, time-dependent model has been developed for simulation of an acute environmental transfer of radionuclides through agricultural systems. TRANFOOD is a computer code which calculates concentration of radionuclides in surface and root-zone soil, deep soil, produce and feed, and beef and milk from a given initial surface concentration of radioactivity from fallout. Resulting cumulative dose calculations are based on ICRP 30 (ICRP79). Up-to-date age specific dose-conversion factors covering the major radionuclides released from nuclear fuel facilities are needed to allow more realistic evaluation of hazards of potential effluent releases from these facilities. So, as an option, an age-specific dose calculation procedure was also provided in TRANFOOD. Values for relative age-specific radiation dose commitment factors for radionuclides are taken from the recent studies about age dependent dose-conversion factors by Cristy et al. (Cr84,Cr86). The systems of linear first order ordinary differential equations describing the model are solved using the first order (Simple Euler) method (Ca69).

The preliminary validation of the model was carried out by comparing the results with Chernobyl Nuclear Accident data of the Federal Republic of Germany (Wi87).

THE TRANFOOD MODEL

The TRANFOOD model was based on the TERMOD (Bo71a,Bo71b) and RADFOOD (Ko86) models. It is assumed that fallout is the only source compartment and man is the only receptor compartment of interest.

There are various modifications introduced into the TRANFOOD model which are not considered in the TERMOD (Bo71a,Bo71b) and RADFOOD (Ko86) models. These are as follows:

(a) <u>Root uptake rate</u>. Since the plant growth rate is time-dependent, root uptake rate is calculated on a daily basis using the methodology given in PATHWAY (Ki83,Wh87). The same methodology is used in these calculations except that the senescence (vegetation) process is only considered in the calculation of B_{max}.

The plant growth rate is calculated during the period January 1 through July 31 as:

$$dBIO/dt = k_g f_1 f_t BIO(BIO_{max} - BIO)/(BIO_{max} - (AD)(FV)f_r)$$

During the period August 1 through December 31 as:

$$dBIO/dt = k_g f_1 f_t BIO(BIO_{max} - BIO)/(BIO_{max} - (AD)(FV)f_r)$$

where

BIO = current biomass (dry kg m^{-2})

BIO_{max} = adjusted maximum biomass (dry kg m^{-2})

BIO_{max} is calculated as:

$$BIO_{max} = k_g(BIO_{max})^2/(BIO_{max}(k_g-k_s)+k_sBIO_{min})$$

k_g = growth rate constant, typically
0.12 d^{-1} for grains,
0.12 d^{-1} for pasture, and
0.27 d^{-1} for alfalfa.

f_t, f_l = growth rate modifiers for light and temperature, respectively. The monthly estimates of f_t and f_l are derived from the figure given in PATHWAY (Wh87).

AD = grazing animal density (animals m^{-2}), typically 2.2×10^{-6} animals m^{-2} (Wh87).

FV = animals total ingestion rate, typically 16 dry kg d^{-1} (Ho76).

f_r = fraction of ingestion rate contributed by field grazing, typically 1 for cow (Wh87).

BIO_{min} = minimum winter biomass (Wh87), typically
0.015 dry kg m^{-2} for grain,
0.07 dry kg m^{-2} for pasture, and
0.08 dry kg m^{-2} for alfalfa.

BIO_{max} = maximum potential biomass (Wh87), typically
0.73 dry kg m^{-2} for grain,
0.30 dry kg m^{-2} for pasture,
0.63 dry kg m^{-2} for alfalfa.

k_s = senescence (vegetation) rate constant (Wh87), typically
0.05 d^{-1} for grain,
0.05 d^{-1} for grass pasture, and
0.015 d^{-1} for alfalfa.

(b) <u>Soil ingestion by animals is considered in the radioactivity in milk and meat calculations</u>. It is given as:

radioactivity intake rate from soil = $(F_b \text{ or } F_m)(\lambda_m+\lambda_{ra})(B)FS/X_rP_s$

where

F_b = transfer coefficient from feed to meat (d kg^{-1}). Table 1 gives F_b values from U.S. Nuclear Regulatory Commission Regulatory Guide 1.109 for certain radionuclides (NRC77).

F_m = transfer coefficient from feed to milk (d L^{-1}). Table 1 gives F_m values from U.S. Nuclear Regulatory Commission Regulatory Guide 1.109 (NRC77).

FS = soil ingestion rate of livestock, 0.5 kg d^{-1} for beef cows (Wh87)

λ_m = transfer rate constant from milk compartment to the udder (d^{-1}). It is taken 2 d^{-1} (Ko86) assuming a single-compartment model for milk production.

λ_{ra} = radioactive decay rate constant (d^{-1}),

B = radioactivity concentration in soil surface layers (Bq m^{-2}),

X_r = depth of rooting zone (m), and

P_s = soil bulk density(kg/m^3), typically $X_r P_s$=240 kg m^{-2} (Ho76).

(c) Human dietary estimates are presented as 4 age groups, namely infant, child, teenager and adult. Table 2 gives recommended values by Whicker et al. (Wh87) for human dietary estimates in the PATHWAY code.

(d) Dose calculations were based on age-dependent dose-conversion factors in TRANFOOD. The radiation dose commitment factors for major radionuclides released from nuclear fuel facilities are taken from Cristy et al. (Cr84,Cr86) and considered in the calculations.

(e) Radionuclide intake rate estimates were modified for radioactive decay that occurs during the time interval between harvest and consumption of the food. Hold-up times for stored feed animals, leafy vegetables and produce were assigned by NRC Regulatory Guide 1.109 (NRC77), Terrestrial Food Chain Models section (Mi84) as 90, 14, and 14 days respectively. These values were assigned by Whicker et al. in PATHWAY (Wh87) as 1 day for all vegetables, fruits, grains, poultry and milk. Hold-up times were recommended as 3 days (commercial) for milk and 12.5 days (commercial) for beef and pork by Hoffman et al. (Ho76). These times do not include retail display time.

PARAMETERS USED IN THE MODEL

Summarized below are the major environmental and translocation factors used in the TRANFOOD model. These parameters are used in the model equations presented in the following section. Notation has been used to correspond to prior usage wherever possible. A more complete list of parameter names is provided together with parameter units in Appendix.

Table 1. F_b, F_m values (NRC77)

Nuclide	F_m	F_b
^{131}I	6.0×10^{-3}	2.9×10^{-3}
^{137}Cs	1.2×10^{-2}	4.0×10^{-3}
^{89}Sr	8.0×10^{-4}	6.0×10^{-4}
^{90}Sr	8.0×10^{-4}	6.0×10^{-4}
^{95}Zr	5.0×10^{-6}	3.4×10^{-2}
^{106}Ru	1.0×10^{-6}	4.0×10^{-1}
^{144}Ce	6.0×10^{-4}	1.2×10^{-3}

Table 2. Age-dependent human dietary estimates in the PATHWAY code (Wh87)

Age	Milk $L\ d^{-1}$	Meat $kg\ d^{-1}$	Fruit $kg\ d^{-1}$	Vegetables $kg\ d^{-1}$
Infant	0.914	0.043	0.207	0.027
Child	0.697	0.130	0.266	0.025
Teenager	0.778	0.238	0.356	0.149
Adult man	0.412	0.317	0.360	0.149
Adult woman	0.282	0.185	0.256	0.143

Table 3. λ_1, values

Radionuclide	λ_1 (d^{-1})
^{89}Sr	0.0530
^{90}Sr	0.0260
^{106}Ru	0.0796
^{131}I	0.0533
^{137}Cs	0.0770

Table 4. λ_3 values for major radionuclides (Ho76)

Nuclide	λ_3 d^{-1}
^{131}I	3.2×10^{-4}
^{137}Cs	5.8×10^{-6}
^{89}Sr	2.6×10^{-5}
^{90}Sr	2.6×10^{-5}

λ_1 = environmental weathering rate constant (the time necessary for one-half of the radioactivity to be removed by environmental processes, d^{-1}). Weathering denotes the loss of surfacial radioactivity on vegetation to the ground surface. Table 3 gives the λ_1 values for some important radionuclides (Ho76).

l_2 = rate constant for penetration into soil root zone. The rate constant for the migration into the root zone λ_2 is assumed to be independent of the specific nuclide. The typical value of λ_2 is assumed as 0.0076 d^{-1} (Ma81).

λ_3 = transfer rate constant to the soil sink (the soil loss constant due to the leaching from soil). Leaching of radionuclides from the labile soil pool (0.1-0.25 m) to the deep soil (>0.25 m) is important for the longer lived radionuclides. Values are given in Table 4 for major radionuclides (Ho76).

λ_4 = root uptake rate constant is calculated as: (Ho76,Wh87)

$$\lambda_4 = (dB/dt)B_{iv}/X_r P_s,$$

where

B_{iv} = the soil-to-plant concentration factor, the ratio of the concentration of an element in fresh vegetation to that in dry soil. Table 5 gives B_{iv} values for major radionuclides (Ng82).

X_r = depth of rooting zone (m).

P_s = soil bulk density (kg/m^3).

TF = translocation factor values, taken from Boone et al. (Bo81) and given in Table 6 for wheat. It is taken as one for alfalfa and pasture.

λ_5 = rate constant for translocation to plant edible parts calculated as:

$$\lambda_5 = TF(dBIO/dt)BIO.$$

where

TF = translocation factor,

dBIO/dt = plant growth rate,

BIO = current biomass (dry kg m^{-2}),

Table 5. The soil-to-plant concentration factor for some radionuclides (Ng82)

Element	B_{iv} values (Ng82)
Sr	1.7×10^{-2}
Zr	1.7×10^{-4}
Ru	5.0×10^{-2}
I	2.0×10^{-2}
Cs	1.0×10^{-2}
Ba	5.0×10^{-3}
Ce	2.5×10^{-3}

Table 6. Translocation factors for wheat (Bo81)

Element	TF
Sr	1.2×10^{-1}
Ru	5.0×10^{-2}
I	1.0×10^{-1}
Cs	3.5×10^{-1}
Ce	3.0×10^{-2}
Pu	1.0×10^{-2}
Am	3.0×10^{-2}
Cm	3.0×10^{-2}

Table 7. λ_b values

Radionuclide	λ_b (d^{-1})
^{89}Sr	6.25×10^{-4}
^{90}Sr	1.74×10^{-4}
^{106}Ru	9.44×10^{-2}
^{131}I	1.33×10^{-2}
^{137}Cs	1.28×10^{-2}

λ_b = excretion rate constant from meat (d^{-1}) is element dependent. It is based on metabolism in man, due to unavailability of data for grazing animals. Table 7 gives λ_b values (Bo71a,Bo71b).

λ_m = transfer rate constant from milk compartment to the udder (d^{-1}). $2d^{-1}$ was recommended in RADFOOD (Ko86).

λ_{re} = resuspension-deposition rate constant (d^{-1}). From empirical data Anspaugh (P180,An75) approximated the resuspension factor as:

$$K(t) = 10^{-4}\exp(-\lambda\ t)+10^{-9},$$
$$\lambda_{re} = K(t)V_d \quad (7),$$

where

$K(t)$ = resuspension factor (m^{-1}),

λ = an empirical factor of 0.15 $d^{-1/2}$,

V_d = deposition velocity ($m\ d^{-1}$).

MODEL EQUATIONS

The equations that describe the transfer of the radioactive fallout to man are presented below. Parameters used here are defined in the Appendix.

Radioactivity in plant leaves,

$$dA/dt = -(\lambda_1+\lambda_5+\lambda_{ra})A+\lambda_{re}S_1B/(BIO_{ex})$$

where

$A(0) = S_1F_o/BIO_{ex}$ (at time t=0, the instant when fallout initially occurred),

Radioactivity in the soil surface layer,

$$dB/dt = -(\lambda_2+\lambda_{ra}+\lambda_{re}(S_1+S'_1))B+\lambda_1 BIO_{ex}A$$

where

$B(0) = S_2F_o$,

Radioactivity in the soil root zone,

$$dC/dt = -(\lambda_3+\lambda_4+\lambda_{ra})C+\lambda_2 B$$

where

$C(0) = 0$,

Radioactivity in deep soil,

$$dD/dt = -\lambda_{ra}D+\lambda_3 C$$

where

$$D(0) = 0,$$

Radioactivity in the edible inner parts of a plant (i=1 to 3, for grass, pasture and alfalfa respectively),

$$dE_i/dt = (-\lambda_{ra}E_i+\lambda_4 BIO_{in}C+\lambda_5 BIO_{ex}A)/BIO_{in}$$

where

$$E_i(0) = 0$$

Radioactivity in fruit parts,

$$dE'/dt = -(\lambda_1+\lambda_{ra})E'+\lambda_{re}S'_1 B/Y_{in}$$

where

$$E'(0) = S'_1 F_o/Y_{in},$$

Radioactivity in milk,

$$dF/dt = F_m(\lambda_m+\lambda_{ra})I_f(A+E_i)+F_m(\lambda_m+\lambda_{ra})(B)FS/X_r P_s-(\lambda_m+\lambda_{ra})F$$

where

$$F(0) = 0,$$

Radioactivity in meat,

$$dG/dt = Fb(\lambda_b+\lambda_{ra})I_f(A+E)+F_b(\lambda_m+\lambda_{ra})(B)FS/X_r P_s-(\lambda_b+\lambda_{ra})G$$

where

$$G(0) = 0,$$

Radioactivity ingested by man through milk consumption,

$$dI_m/t = C_m F$$

where

$$I_m(0) = 0,$$

Radioactivity ingested by man through beef consumption,

$$dI_b/dt = C_bG$$

where

$$I_b(0) = 0,$$

Radioactivity ingested by man through grain consumption,

$$dI_{v1}/dt = C_{v1}(E_1)$$

where

$$I_{v1}(0) = 0,$$

Radioactivity ingested by man through fruit consumption,

$$dI_f/dt = C_f(E')$$

where

$$I_f(0) = 0,$$

Radiation doses to man from milk,

$$RD_m = DFI_m,$$

Radiation doses to man from beef,

$$RD_b = DFI_b,$$

Radiation doses to man from grain,

$$RD_{v1} = DF_iI_{v1},$$

Radiation doses to man from fruit,

$$RD_f = DFI_{fi},$$

Total dose,

$$TD = RD_m+RD_b+RD_{v1}+RD_f.$$

RESULTS AND DISCUSSION

A sample calculation was performed using airborne radioactivity data from the Federal Republic of Germany after the Chernobyl Accident. The TRANFOOD model was used to evaluate the transfer of radionuclides through the food chain (Wi87). Simulation results, using TRANFOOD are given in Tables 8 and 9 for grain, fruit external parts, milk, meat and cumulative radiation dose for ^{131}I and ^{137}Cs. Fig. 1 shows the development of the activity in the milk of a single producer for the period from April 30 to June 2, 1986. The herd had been grazing on a pasture in Northern Munich. Calculated activity of ^{131}I and ^{137}Cs in milk is compared to the measured values in Fig. 1. The measured and calculated results are in agreement, inasmuch as nearly the same amount of peak specific activities were seen, but there was a sharp reduction of measured specific activity values for both ^{137}Cs and ^{131}I after May 5, 1986. The differences in observed and simulated values for this period is likely due to the following explanation: Some protective actions had been taken in the Federal Republic of Germany (Go87). Cattle and other livestock had been sequestered and given stored feed to minimize uptake from contaminated forage, most likely causing the sharp decrease in radioactivity shown in Fig. 1 around the fifth of May, 1986. The uptake of radionuclides into the edible part of a plant occurs via two fundamentally different processes. The first consists of direct deposition of activity from a radioactive plume onto foliage, followed by translocation to the edible part of the plant. The second process is indirect and results from the uptake of radioactivity by the plant roots from the cumulative soil deposit. Fig. 2 shows the activity of radionuclides deposited at the site of the Institute for Radiation Hygiene near Munich (Wi87). The variation of activity of radionuclides in the soil is similar to the simulation results for soil build-up from atmospheric deposition of the TRANFOOD as it is expected that vegetables will accumulate the radionuclides from the contaminated soil deposit.

RECOMMENDED MODIFICATIONS OF TRANFOOD

Some of the parameters in the model are very important and need to be examined. For example, the interception value of vegetation expressed as a fraction of the total deposition per unit surface area may be questioned. It is given as an input parameter in the model. The estimated values of this parameter can be found in Hoffman (Ho76). Secondly, the animal ingestion-to-milk transfer factor and animal ingestion-to-meat transfer factor have ranges of values that may exceed a factor of 10. The values used for these parameters in radiological assessments are usually derived from international literature. Consideration should also be given to the total dry matter intake of grazing animals.

Table 8. Simulation results of TRANFOOD for ^{131}I (initial fallout = 65000 Bq m^{-2})

Date	Grain (Bq/kg)	Fruit external parts (Bq/kg)	Milk (Bq/L)	Meat (Bq/kg)	Cumulative dose (msv)
		NUCLIDE ^{131}I			
04/30/86	10.80	328.17	305.48	7.01	0.043
05/01/86	48.14	1466.16	341.92	28.07	0.158
05/02/86	69.48	2118.05	367.03	42.21	0.225
05/03/86	85.52	2608.79	381.15	55.78	0.284
05/04/86	97.14	2965.34	386.52	68.38	0.337
05/05/86	105.12	3211.01	385.04	79.78	0.385
05/06/86	110.11	3365.84	378.37	89.83	0.427
05/07/86	112.69	3446.87	367.76	98.46	0.465
05/08/86	113.33	3468.58	354.30	105.66	0.498
05/09/86	112.42	3443.16	338.85	111.47	0.528
05/10/86	110.31	3380.86	322.11	115.95	0.555
05/11/86	107.28	3290.25	304.65	119.18	0.579
05/12/86	103.53	3178.44	286.90	121.29	0.601
05/13/86	99.35	3051.29	269.20	122.36	0.620
05/14/86	94.81	2913.64	251.79	122.51	0.637
05/15/86	90.06	2769.41	234.87	121.84	0.652
05/16/86	85.24	2621.79	218.57	120.48	0.666
05/17/86	80.41	2473.31	202.99	118.51	0.679
05/18/86	75.63	2325.99	188.16	116.03	0.690
05/19/86	70.96	2181.40	174.15	113.12	0.699
05/20/86	66.42	2040.74	160.95	109.87	0.708
05/21/86	62.03	1904.90	148.58	106.35	0.716
05/22/86	57.83	1774.90	137.02	102.61	0.723
05/23/86	53.83	1651.57	126.26	98.73	0.730
05/24/86	50.03	1534.94	116.27	94.74	0.736
05/25/86	46.44	1424.95	107.01	90.70	0.741
05/26/86	43.06	1321.48	98.44	86.64	0.745
05/27/86	39.88	1224.35	90.51	82.60	0.749
05/28/86	36.90	1133.36	83.19	78.59	0.753
05/29/86	34.12	1048.29	76.42	74.65	0.757
05/30/86	31.52	968.87	70.19	70.80	0.760
05/31/86	29.09	894.84	64.44	67.04	0.762
06/01/86	26.91	828.51	59.25	63.39	0.765
06/02/86	24.87	766.16	54.44	59.87	0.767
06/03/86	22.96	707.92	50.01	56.48	0.769
06/04/86	21.18	653.61	45.92	53.22	0.771
06/05/86	19.52	603.04	42.15	50.09	0.772
06/06/86	17.98	556.01	38.68	47.10	0.774
06/07/86	16.56	512.34	35.49	44.25	0.775
06/08/86	15.24	471.82	32.55	41.53	0.776
06/09/86	14.01	434.27	29.85	38.95	0.777
06/10/86	12.88	399.51	27.37	36.50	0.778
06/11/86	11.84	367.36	25.09	34.17	0.779
06/12/86	10.88	337.64	22.99	31.97	0.780
06/13/86	9.99	310.19	21.07	29.89	0.781

Table 9. Simulation Results of TRANFOOD for ^{137}Cs (initial fallout = 11000 Bq m^{-2})

Date	Grain (Bq/kg)	Fruit external parts (Bq/kg)	Milk (Bq/L)	Meat (Bq/kg)	Cumulative dose (msv)
		NUCLIDE ^{137}Cs			
04/30/86	2.85	24.74	44.44	0.10	0.008
05/01/86	14.31	124.55	58.48	0.43	0.030
05/02/86	22.37	194.84	68.10	0.71	0.044
05/03/86	29.82	259.92	76.68	1.02	0.058
05/04/86	36.70	320.05	84.31	1.36	0.072
05/05/86	43.03	375.48	91.07	1.72	0.084
05/06/86	48.84	426.52	97.05	2.11	0.097
05/07/86	54.18	473.42	102.31	2.51	0.109
05/08/86	59.07	516.47	106.94	2.93	0.121
05/09/86	63.54	555.94	111.00	3.37	0.131
05/10/86	67.63	592.08	114.55	3.81	0.142
05/11/86	71.36	625.12	117.64	4.26	0.152
05/12/86	74.76	655.30	120.34	4.72	0.162
05/13/86	77.85	682.83	122.69	5.17	0.172
05/14/86	80.66	707.91	124.72	5.64	0.181
05/15/86	83.22	730.73	126.48	6.11	0.190
05/16/86	85.56	751.46	128.00	6.58	0.199
05/17/86	87.69	770.26	129.30	7.04	0.207
05/18/86	89.64	787.27	130.42	7.51	0.215
05/19/86	91.42	802.64	131.36	7.97	0.223
05/20/86	93.03	816.49	132.16	8.44	0.231
05/21/86	94.50	828.94	132.84	8.90	0.238
05/22/86	95.83	840.23	133.41	9.35	0.245
05/23/86	97.03	850.65	133.91	9.80	0.252
05/24/86	98.13	860.28	134.34	10.25	0.259
05/25/86	99.14	869.16	134.71	10.69	0.266
05/26/86	100.06	877.35	135.03	11.13	0.270
05/27/86	100.90	884.90	135.31	11.57	0.278
05/28/86	101.66	891.86	135.55	12.00	0.284
05/29/86	102.35	898.25	135.75	12.43	0.290
05/30/86	102.98	904.13	135.91	12.85	0.296
05/31/86	103.55	909.53	136.05	13.26	0.301
06/01/86	104.28	916.57	136.33	13.68	0.307
06/02/86	104.93	922.79	136.56	14.08	0.312
06/03/86	105.52	928.45	136.75	14.49	0.317
06/04/86	106.03	933.60	136.91	14.89	0.322
06/05/86	106.49	938.26	137.05	15.28	0.327
06/06/86	106.90	942.47	137.16	15.67	0.332
06/07/86	107.26	946.26	137.25	16.05	0.337
06/08/86	107.59	949.65	137.32	16.44	0.341
06/09/86	107.88	952.68	137.37	16.82	0.346
06/10/86	108.14	955.36	137.40	17.19	0.350
06/11/86	108.36	957.72	137.42	17.55	0.354
06/12/86	108.56	959.78	137.41	17.92	0.358
06/13/86	108.73	961.55	137.39	18.27	0.363

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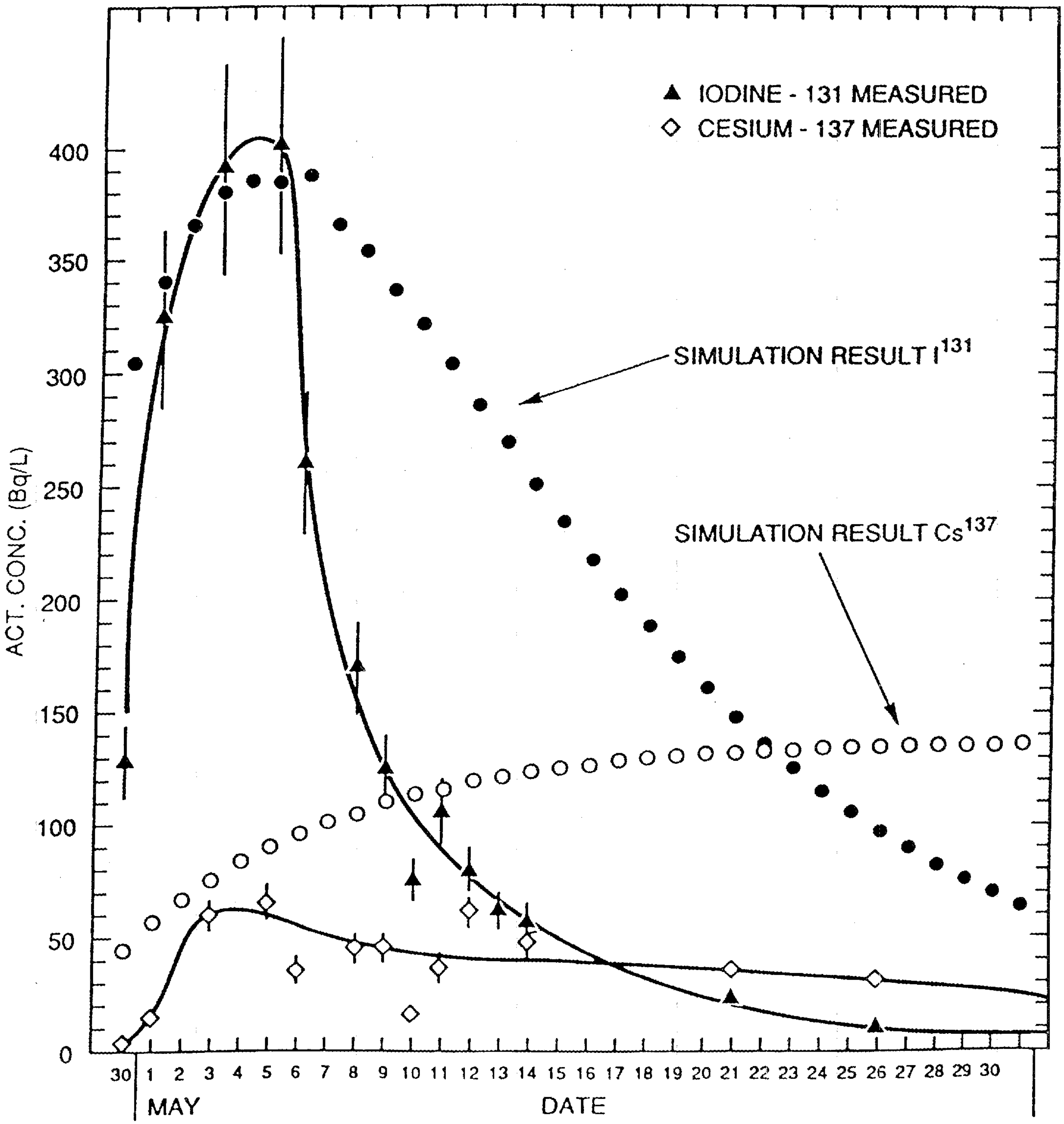

Fig. 1. Activity of I-131 and Cs-137 in milk after Chernobyl accident as a function of time

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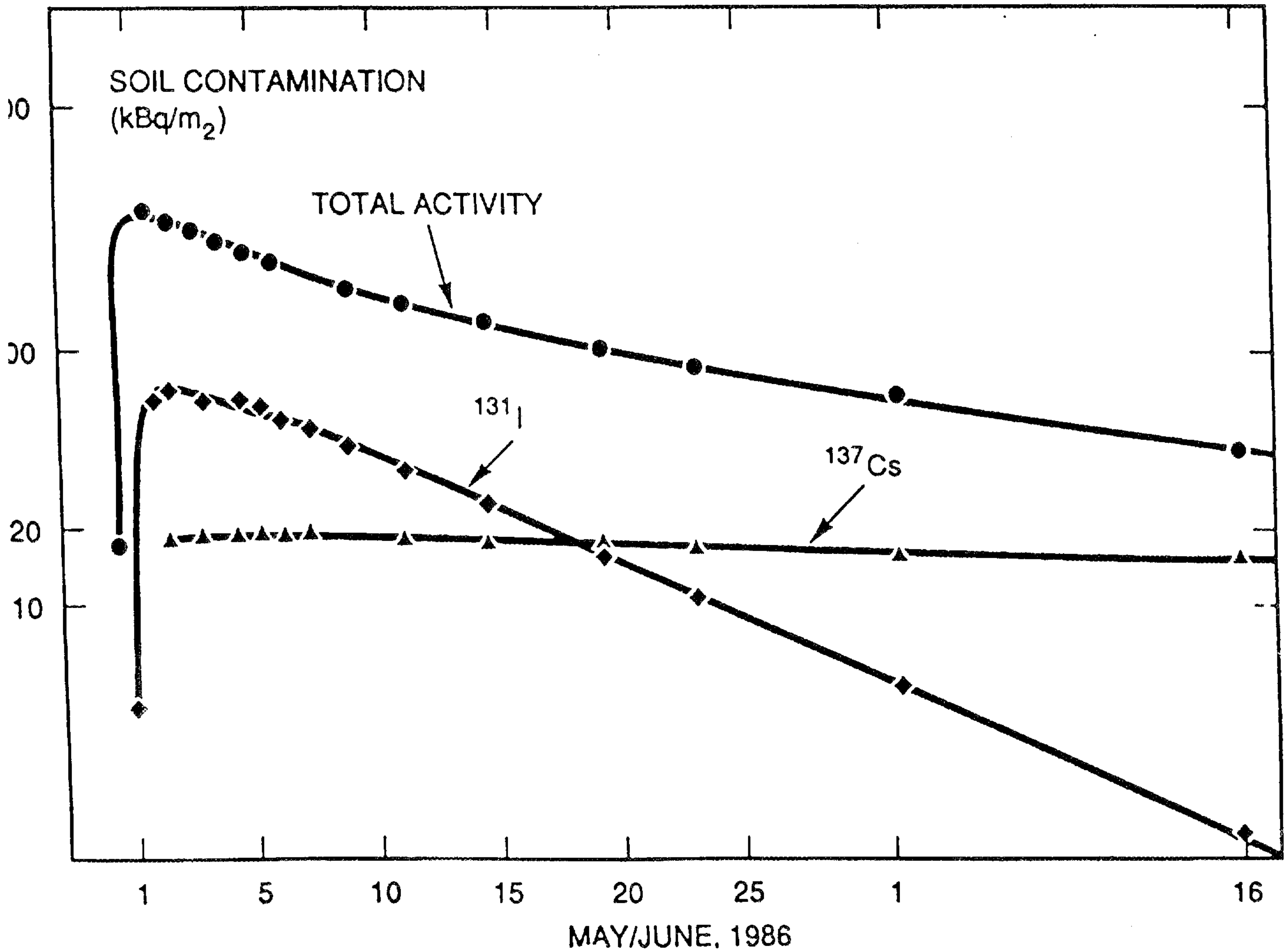

Fig. 2. Activity of I-131 and Cs-137, deposited at the site of the Institute for Radiation Hygiene near Munich (in situ gamma ray spectrometry)

Many radionuclides are products from a decay series, either as long-lived parent or as shorter-lived daughters. Almost all daughters within series have unique chemical characteristics that govern the leaching phenomena from soil compartment and these processes are described by model plant root uptake parameters. The model should be modified to consider the decay products associated with each respective parent.

All models are an abstraction of reality, therefore, their predictions are always subject to uncertainties. The model will be validated using radioactivity measurements taken in Turkey and in Greece after the Chernobyl Accident (Fi87,GAEC86).

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APPENDIX

List of symbols used in TRANFOOD

Symbol	Definition	Units
A	radioactivity concentration on plant leaves	Bq kg^{-1}
B	radioactivity concentration in soil surface layers	Bq m^{-2}
BIO_{ex}	yield of external parts of plant	dry kg m^{-2}
BIO_{in}	yield of internal parts of plant	dry kg m^{-2}
BIO_{max}	maximum potential biomass	dry kg m^{-2}
BIO_{max}	adjusted maximum biomass	dry kg m^{-2}
BIO_{min}	minimum winter biomass	dry kg m^{-2}
C	radioactivity concentration in the soil root zone	Bq m^{-2}
D	radioactivity concentration in deep soil	Bq m^{-2}
E	radioactivity concentration in the edible inner parts of a plant	Bq kg^{-1}
E′	radioactivity concentration in fruit external part	Bq kg^{-1}
F	radioactivity concentration in milk	Bq L^{-1}
G	radioactivity concentration in beef	Bq kg^{-1}
C_m	daily milk consumption	L d^{-1}
C_b	daily beef consumption	kg d^{-1}
C_{v1}	daily consumption of grain	kg d^{-1}
C_f	daily consumption of fruit	kg d^{-1}
DF	weighted committed dose equivalent conversion factor	Sv Bq^{-1}
F_o	initial fallout surface radioactivity	Bq m^{-2}
F_b	transfer coefficient from feed to meat	d kg^{-1}
F_m	transfer coefficient from feed to milk	d L^{-1}
FS	soil ingestion rate	kg d^{-1}

Symbol	Definition	Units
i	crop type index (i=1 to 3, for grain, pasture, alfalfa)	
I_m	human radioactivity intake through milk consumption	Bq
I_b	human radioactivity intake through meat consumption	Bq
I_{v1}	human radioactivity intake through grain consumption	Bq
I_f	human radioactivity intake through fruit consumption	Bq
$K(t)$	resuspension factor	m^{-1}
P_s	soil bulk density	$kg\ m^{-3}$
RD_b	individual retention dose following meat consumption	Sv
RD_m	individual radiation dose following milk consumption	Sv
RD_{v1}	individual radiation dose following grain consumption	Sv
RD_f	individual radiation dose following fruit consumption	Sv
S_1	fallout interception factor of the leaves	
S'_1	fallout interception factor of the fruits	
S_2	fallout fraction depositing on the soil surface	
V_d	deposition velocity	$m\ d^{-1}$
X_r	depth of rooting zone	m
t	time elapsed since fallout deposition	d^{-1}
TD	total individual whole body dose	Sv
TF	translocation factor values	--
Y_{in}	productivity of fruits	$kg\ m^{-2}$
L_1	environmental weathering rate constant	d^{-1}
L_2	rate constant for penetration into soil root zone	d^{-1}
L_3	transfer rate constant to the soil sink	d^{-1}
L_4	root uptake rate constant	d^{-1}
L_5	rate constant for translocation to plant edible parts	d^{-1}

Symbol	Definition	Units
L_b	excretion rate constant from meat	d^{-1}
L_m	transfer rate constant from milk compartment to the udder	d^{-1}
L_{ra}	radioactive decay rate constant	d^{-1}
L_{re}	resuspension-deposition rate constant	d^{-1}

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