Conf-820729--1

SIMULATION OF RADIONUCLIDE TRANSPORT IN U.S. AGRICULTURE*

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CONF-820729--1

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ABSTRACT

Because of the recent paramount concern about the impact of energy technologies on man and related health effects, there has emerged a need for models to calculate or predict the effects of radionuclides on man. This paper presents a general overview of a model implemented on digital computer that calculates the ingrowth of radionuclides into man's food chain. The FORTRAN IV computer program TERRA, Transport of Environmentally Relaxed Radionuclides in Agriculture, simulates the

* This work was sponsored by the Office of Radiation Programs, U.S. Environmental Protection Agency, Interagency Agreement No. EPA-78-D-X0394, C. B. Nelson, Project Manager.

** Assigned to Health and Safety Research Division by the Environmental Sciences Division.

*** Operated for the U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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build-up of radionuclides in soil, four plant food compartments, in meat and milk from beef and in the livestock food compartments that cause radionuclide build-up in milk and meat from beef. Any in-depth computer program that simulates environmental transport inherently requires a great amount of data about the environment. A large data set of spatially oriented parameters has naturally been developed in conjunction with TERRA. This direct-access data set is called SITE, Specific Information on the Terrestrial Environment, and contains 35 parameters for each of 3525 half-degree longitude-latitude cells which define the lower 48 states. TERRA and SITE are used together as a package for determining radionuclide concentrations in man's food anywhere within the conterminous 48 states due to atmospheric releases.

INTRODUCTION

Universal interest in quantifying the impact of radiation that man receives from his varied uses of radioactive materials and possible²⁴ resulting remedial or regulatory action has created a need to model the pathways of radiation exposure to man. This need has resulted in many computer codes that calculate dose and resulting health effects to man.(1,2,3) Day-to-day ingestion of food containing radionuclides is an important pathway for the build-up of radionuclides in man. However, prior to calculating the dose to man from radionuclides in his food, the quantity of radiation in the food must be determined. This quantity is obviously dependent upon the location where the food is grown because of the spatial variability in radiation distribution across the country. In addition, the diversity of man's food also complicates the problem. A single lumped

value for the radioactivity in man's food based on a simplified model may be inappropriate because of the different transport characteristics and physical forms of man's diet.(4,5) Therefore, we have developed a compartmental model, TERRA, to simulate transport through the diverse food chain which makes up the human diet.(6)

TERRA

The mathematical formulation in TERRA follows radionuclide transport through 19 compartments for the final calculation of radionuclide ingrowth into man's food. Figure 1 is a diagram of the compartments and transport pathways in TERRA after the initial nuclide concentration in soils has been calculated. The names and definitions of the variables in the computer program that represent the concentrations are given below. A compartment is defined as having both radionuclide input and output rates, and concentrations for the compartment are calculated over time by numerical integration. For example, this definition says that the CONLV, as defined below, is not a true compartment, but is only an output variable. CONSLV and CONILV are the true compartments. The names for true compartments are underlined:

1. CONBFC - Concentration of the nuclide in beef from cattle on grain feed.
2. CONBOC - Concentration of the nuclide in beef from other cattle, not on feed.
3. CONES - Concentration of the nuclide in surface soil (for calculating surface exposures).
4. CONEV - Total concentration of the nuclide in plants exposed to direct deposition of airborne particles.
5. CONF - Concentration of the nuclide in a forage composite weighted by relative contributions of pasture, hay, and silage.

6. CONGF - Concentration of the nuclide in grains used for livestock feed.
7. CONGH - Concentration of the nuclide in grains used in human food.
8. CONHF - Total concentration of the nuclide in hay feeds.
9. CONIEV - Concentration of the nuclide in the interior of exposed plants (from root uptake).
10. CONIHF - Concentration of the nuclide in the interior of hay feeds (from root uptake).
11. CONILV - Concentration of the nuclide in the interior of leafy vegetables (from root uptake).
12. CONIPG - Concentration of the nuclide in the interior of pasture grass (from root uptake).
13. CONIS - Concentration of the nuclide in the root zone of irrigated soils.
14. CONISF - Concentration of the nuclide in interior of silage feeds (from root uptake).
15. CONLV - Total concentration of the nuclide in leafy vegetables.
16. CONMLK - Concentration of the nuclide in milk from cows.
17. CONPV - Concentration of the nuclide in protected plants (plants protected from direct deposition).
18. CONS - Concentration of the nuclide in the root zone of non-irrigated soils.
19. CONSEV - Concentration of the nuclide on the surface of plants exposed to atmospheric deposition (from direct deposition).
20. CONSF - Total concentration of the nuclide in silage feeds.
21. CONSGF - Concentration of the nuclide in stored grain feeds.
22. CONSLV - Concentration of the nuclide on the surface of leafy vegetables (from direct deposition).
23. CONSPG - Concentration of the nuclide on the surface of pasture grass (from direct deposition).
24. CONSSF - Concentration of the nuclide on the surface of silage feeds (from direct deposition).
25. CONSHF - Concentration of the nuclide on the surface of hay feeds (from direct deposition).

Certain transfer rate coefficients are needed for radionuclides to go from the soil to plants or from animal feed to animal tissue or milk. These transport parameters, BV (soil to leaves and stems), BR (soil to reproductive part), FM (feed to milk), and FF (feed to beef), are element-specific and are set internally in TERRA based upon the user-defined list of radionuclides. Another important transport parameter, the fraction of falling nuclides intercepted by the plant surface, is defined in TERRA for each appropriate compartment. These are the parameters RLV, REV, RPG, RHF, and RSF in Figure 1. In addition to the input rates to the compartments as shown in Figure 1, each compartment has removal rates due to radioactive decay. Furthermore, certain plant compartments experience radionuclide removal by weathering and soil compartments experience radionuclide removal by leaching.(7) Note, these removal rates are not shown in Figure 1.

Program flow of TERRA - While coding TERRA, a central theme followed has been to make the program user-oriented and modular, two goals that complement each other. Three separate subroutines calculate the concentrations in each of the three types of compartments (soil, plant, and livestock). SITE parameters are shared by labeled COMMON. Subroutine SOILS initially calculates the concentration for the type of soil (irrigated or nonirrigated) before foodstuff concentrations are calculated. In SOILS, both radiological decay and leaching are considered as removal rates of radionuclides. Next, subroutine AGRON calculates concentrations for plant material via pathways of root uptake and direct deposition on plant surfaces, and STOCKS calculates concentrations for cattle products (milk and meat), based partly on concentrations in livestock feeds from AGRON.

construction. The user of TERRA has available to him many options for data input, control strategy, and data output. He must, however, supply certain control parameters, such as the logical unit numbers for input data, time of simulation, type of grid desired, i.e., rectangular or circular, and concentration units. He must also specify a list of nuclides with deposition rates and air concentrations by location. In addition, the user can easily override any site-specific default parameter from SITE. The computer code will automatically incorporate the decay chains into concentration calculations without user intervention. The type of grid for output depends upon the grid for deposition rates input to the code, but grid format can be one or a series of distinct points, a window of interest from a rectangular grid, or a circular grid.

SITE

SITE is a data set of site-specific agricultural, climatological, land use, and demographic parameters that fulfills the data needs of TERRA.(4) The spatial resolution of data is 0.5° longitude by 0.5° latitude, and this resolution requires 3525 data cells to represent the land area of the lower 48 states. The data in SITE is invoked by a direct-access read statement where the key that points to the appropriate data cell is defined by the longitude and latitude of a particular location under study. The expression defining the key for longitude, XLONG, and latitude, YLAT is

$$\text{KEY}=\text{IFIX}((\text{XLONG}-66.5)/.5)+116*(\text{IFIX}((\text{YLAT}-24.0)/.5)-1).$$

The range of keys for the 48 states goes from 1 to 5800, but 2275 of the cells have no data associated with them because they are located either over water or in another country.

The data items in SITE are applicable not only for modeling radionuclide introduction into the food chain for man, but they are general enough for almost any type of environmental modeling. A description from the computer program of the 35 site-specific parameters in each record for every cell follows:

CELLON = LONGITUDE OF THE SOUTHEAST CORNER OF THE SITE DATA CELL,
CELLAT = LATITUDE OF THE SOUTHEAST CORNER OF THE SITE DATA CELL,
CFLAG = THE CAUTION FLAG, = 1 MEANS CELL ON ATLANTIC COAST,
 = 2 MEANS CELL ON MEXICAN BORDER,
 = 3 MEANS 1 AND 2,
 = 4 MEANS CELL HAS INTERIOR BODY OF WATER,
 = 5 MEANS 1 AND 4,
 = 6 MEANS 2 AND 4,
 = 8 MEANS CELL ON PACIFIC COAST,
 =12 MEANS 4 AND 8,
 =16 MEANS CELL ON CANADIAN BORDER,
 =20 MEANS 4 AND 16,
 =21 MEANS 1 AND 4 AND 16,
 =24 MEANS 8 AND 16,
 =32 MEANS CELL HAS DESERT OR BARREN LAND,
 =36 MEANS 4 AND 32,
ET = EVAPOTRANSPIRATION (MM/Y),
IRRI = IRRIGATION (MM/Y),
PRECIP = PRECIPITATION (MM/Y),
YEV = YIELD OF EXPOSED VEGETABLES (KG(FRESH)/M**2),
AYHF = AREAL YIELD OF HAY FEED (KG(DRY)/YR/M**2/),
YLV = YIELD OF LEAFY VEGETABLES (KG(FRESH)/M**2),
YSF = YIELD OF (CORN AND SORGHUM) SILAGE FEED (KG(DRY)/M**2),
AREAP = TOTAL AREA OF PASTURE (M**2),
NUMCC = CATTLE AND CALF INVENTORY (HEAD),
SALFC = NUMBER OF CATTLE ON FEED SOLD (HEAD/YR),
NUMMC = NUMBER OF MILK COWS (HEAD),
NUMSHP = NUMBER OF SHEEP (HEAD),
PGF = PRODUCTION OF GRAIN FOR FEED (KG),
PHF = PRODUCTION OF HAY FEED (KG),
PSF = PRODUCTION OF (CORN AND SORGHUM) SILAGE FEED (KG),

FRUFM = FRACTION OF 1980 POPULATION CLASSED AS RURAL FARM,
 FURBN = FRACTION OF 1980 POPULATION CLASSED AS URBAN,
 PLV = PRODUCTION OF LEAFY VEGETABLES (KG),
 PEV = PRODUCTION OF EXPOSED VEGETABLES (KG),
 PPV = PRODUCTION OF PROTECTED VEGETABLES (KG),
 PGH = PRODUCTION OF GRAINS FOR HUMAN CONSUMPTION (KG),
 DOMLF = DOMINANT LAND FEATURE OF THE FORM FLPPP. WHERE,
 F=1 IF THE CELL IS MORE THAN 50% FEDERAL LAND,
 I.E. LAND TYPE IS UNDETERMINED,
 F=0 LESS THAN 50 PERCENT IN FEDERAL LAND,
 L=1 MEANS TALL ROW CROPS IS DOMINANT LAND TYPE,
 L=2 MEANS SHORT ROW CROPS,
 L=3 MEANS HAY OR TALL GRASS,
 L=4 MEANS URBAN,
 L=5 MEANS SMALL LAKES,
 L=6 MEANS SHORT GRASS,
 L=7 MEANS FOREST,
 PPP = THE PERCENTAGE OF THE DOMINANT LAND TYPE,
 (MAY BE 0 IF CELL IS 100% FEDERAL),
 MMIXHT = MORNING MIXING HEIGHT (M),
 AMIXHT = AFTERNOON MIXING HEIGHT (M),
 YPV = YIELD OF PROTECTED VEGETABLES (KG(FRESH)/M**2),
 YGH = YIELD OF GRAIN FOR HUMAN FOOD (KG(FRESH)/M**2),
 YGF = YIELD OF GRAIN FOR LIVESTOCK FEED (KG(DRY)/M**2),
 FFDAYS = NUMBER OF FROST-FREE DAYS IN A YEAR.

An example of the spatial resolution of the SITE data base for protected produce is given in Figure 2.

Program OUTPUT

Output from TERRA consists of a list of program control parameters, user-input radionuclide information, SITE parameters for each location of interest, and the calculated nuclide-specific concentrations in soil, leafy vegetables, exposed produce, protected produce, grains for human consumption, and beef and milk. In addition, the user can select an option to write out all intermediate parameters and calculated results. See Table 1 for a listing of selected portions of the output from TERRA for a hypothetical site.

SUMMARY

Because of the complex nature of modeling the food chain for human food, TERRA was programmed to be modular and user-oriented. Many diverse processes for the introduction of radionuclides into food are already included in TERRA, but there may be other important pathways now omitted. Additional processes can be included into TERRA with minimal effort. In addition, to minimize user effort, a list of default parameters is built into TERRA or included in the data base SITE. If the user can find better data for the program, he can easily enter his own estimates. In conclusion, TERRA, used with SITE, is a multi-faceted tool for estimating radionuclide build-up in food for humans.

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ACKNOWLEDGMENTS

The authors are indebted to A. L. Sjoreen for her diligent effort in creating the SITE data base along with the accompanying maps, and to Paul Johnson for data necessary for the creation of SITE.

Figure 1. Conceptual Model of TERRA Showing Compartments and Radionuclide Transport Pathways.

TABLE 1. SAMPLE OUTPUT FROM TERRA

THE NUMBER OF EXPOSURE RADIONUCLIDES= 8

IN	NUCLIDE	DEPOS. RATE (CI/M**2*SEC)	AIR CONC. (CI/M**3)
1	RN-222	0.0	0.1836514E-11
2	PO-218	0.1837531E-13	0.1837531E-11
3	PB-214	0.1846149E-13	0.1846149E-11
4	BI-214	0.1852847E-13	0.1852847E-11
5	PO-214	0.0	0.0
6	PB-210	0.9884639E-17	0.9884639E-15
7	BI-210	0.0	0.0
8	PO-210	0.0	0.0

THE FOLLOWING ELEMENT OR NUCLIDE-SPECIFIC PARAMETERS WERE USED IN ALL CALCULATIONS:

IN	NUCLIDE	KD DISTRIBUTION COEFFICIENT (ML/G)	BV SOIL-TO-PLANT CONCENTRATION FACTOR	BR FEED-TO-MILK TRANSFER PARAMETER (DAY/KG)	FM FEED-TO-BEEF TRANSFER PARAMETER (DAY/KG)	FF FEED-TO-BEEF TRANSFER PARAMETER (DAY/KG)	LAMI RAD. DECAY CONST. (1/SEC)
1	RN-222	.0	.0	.0	.0	.0	2.10E-06
2	PO-218	500.	2.50E-02	4.00E-03	3.50E-04	3.00E-04	3.79E-03
3	PB-214	900.	4.50E-02	9.00E-03	2.50E-04	3.00E-04	4.31E-04
4	BI-214	200.	3.50E-02	5.00E-03	5.00E-04	4.00E-04	5.81E-04
5	PO-214	500.	2.50E-02	4.00E-03	3.50E-04	3.00E-04	9.87E-10
6	PB-210	900.	4.50E-02	9.00E-03	2.50E-04	3.00E-04	1.60E-06
7	BI-210	200.	3.50E-02	5.00E-03	5.00E-04	4.00E-04	5.80E-08
8	PO-210	500.	2.50E-02	4.00E-03	3.50E-04	3.00E-04	.0

THE FOLLOWING TIME CONSTANTS OR DEFAULT PARAMETERS WERE USED IN ALL CALCULATIONS:

SOIL PARAMETERS:

DE = DEPTH OF SOIL CORRESPONDING TO SURFACE EXP. (CM) = 1.00
 DR = DEPTH OF ROOT ZONE (CM) = 15.0
 RO = BULK DENSITY OF THE SOIL (G/CM**3) = 1.35
 THETA = VOLUMETRIC WATER CONTENT OF THE SOIL = .489

TIME CONSTANTS:

THLV = TIME (DAYS) BETWEEN GERM. AND HARV. OF LEAFY VEG. = 100.0
 THEV = GERM. AND HARV. OF EXPOSED VEG. = 100.0
 THPV = GERM. AND HARV. OF PROTECTED VEG. = 100.0
 THG = GERM. AND HARV. OF GRAINS = 150.0
 THSF = GERM. AND HARV. OF SILAGE FEEDS = 150.0
 THHF = GERM. AND HARV. OF HAY FEEDS = 60.0
 FGRZ = SUCCESSIVE GRAZINGS OF PASTURE GRASS BY CATTLE = 30.0
 TMLK = FEEDING AND MILKING COWS = 1.0
 TSFC = GRAIN-FEEDING AND SLAUGHTER OF GRAIN-FED CATTLE = 365.0
 TSOC = GRAIN FEEDING AND SLAUGHTER OF OTHER CATTLE = 365.0
 TSGF = TIME THAT GRAIN IS STORED BEFORE FEEDING TO CATTLE = 90.0

FOR LOCATION # 1 THE FOLLOWING SITE-SPECIFIC PARAMETERS HAVE BEEN CALCULATED:

RLV = INTERCEPTION FRACTION FOR LEAFY VEG. = 5.46E-02
 REV = INTERCEPTION FRACTION FOR EXPOSED VEG. = 1.05E-02
 RHF = INTERCEPTION FRACTION FOR HAY FEEDS = .658
 RSF = INTERCEPTION FRACTION FOR SILAGE FEEDS = .206
 YPG = EST. YIELD OF PAST. GRASS(DRY(KG/M**2)) = 2.95E-02
 RPG = INTERCEPTION FRACTION FOR PASTURE GRASS = 8.14E-02
 NUMOC = NUMBER OF OTHER CATTLE IN THE SITE CELL = 2.87E+05

FOR LOCATION # 1 THE FOLLOWING ENVIRONMENTAL CONCENTRATIONS WERE CALCULATED:

IN	NUCLIDE	AIR CONC.	DEPOSITION RATE	SURFACE SOIL EXP. CONC.	LEAFY VEGETABLES	EXPOSED VEGETABLES	PROTECTED VEGETABLES	GRAINS	BEEF	MILK
		(CI/M**3)	(CI/M**2SEC)	(CI/M**2)	(CI/KG)	(CI/KG)	(CI/KG)	(CI/KG)	(CI/KG)	(CI/KG)
1	RN-210	.0	1.84E-12	.0	.0	.0	.0	.0	.0	.0
2	PO-210	1.84E-14	1.84E-12	4.85E-12	3.18E-13	1.25E-13	1.49E-21	1.76E-21	6.44E-17	1.05E-16
3	PB-210	1.85E-14	1.85E-12	4.77E-11	3.13E-12	1.23E-12	2.92E-19	3.43E-19	5.62E-15	6.59E-15
4	BI-210	1.85E-14	1.85E-12	7.96E-11	5.22E-12	2.05E-12	4.91E-19	5.78E-19	1.48E-14	2.27E-14
5	PO-210	.0	.0	7.96E-11	5.22E-12	2.05E-12	4.91E-19	5.78E-19	1.48E-14	2.27E-14
6	PB-210	9.88E-18	9.88E-16	9.65E-09	1.14E-12	5.00E-13	2.08E-13	3.66E-13	2.45E-11	7.97E-14
7	BI-210	.0	.0	9.65E-09	8.36E-13	3.79E-13	2.01E-13	3.59E-13	2.45E-11	1.11E-13
8	PO-210	.0	.0	9.64E-09	7.79E-14	5.89E-14	1.15E-13	2.20E-13	1.42E-11	9.30E-15