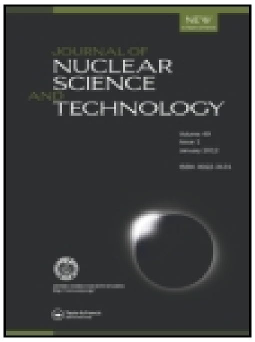

Taylor & Francis
Taylor & Francis Group

Journal of Nuclear Science and Technology

ISSN: 0022-3131 (Print) 1881-1248 (Online) Journal homepage: https://www.tandfonline.com/loi/tnst20

Development of radiation risk assessment simulator using system dynamics methodology

Kyung Min Kang & Moosung Jae

Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 5, p. 728–731 (June 2008)

Development of radiation risk assessment simulator using system dynamics methodology

. XQJ 0 LQ. 1 * DQG0 RRVXQJ -(*

Department of Nuclear Engineering Hanyang University
17 Haengdang-Dong, Sungdong-Gu, Seoul, Korea

The potential magnitudes of radionuclide releases under severe accident loadings and offsite consequences as well as the overall risk (the product of accident frequencies and consequences) are analyzed and evaluated quantitatively in this study. The system dynamics methodology has been applied to predict the time-dependent behaviors such as feedback and dependency as well as to model uncertain behavior of complex physical system. It is used to construct the transfer mechanisms of time dependent radioactivity concentration and to evaluate them. Dynamic variations of radio activities are simulated by considering several effects such as deposition, weathering, washout, re-suspension, root uptake, translocation, leaching, senescence, intake, and excretion of soil. The time-dependent radio-ecological model applicable to Korean specific environment has been developed in order to assess the radiological consequences following the short-term deposition of radio-nuclides during severe accidents nuclear power plant. An ingestion food chain model can estimate time dependent radioactivity concentrations in foodstuffs. And it is also shown that the system dynamics approach is useful for analyzing the phenomenon of the complex system as well as the behavior of structure values with respect to time. The output of this model (Bq ingested per Bq m^{-2} deposited) may be multiplied by the deposition and a dose conversion factor (Gy Bq^{-1}) to yield organ-specific doses. The model may be run deterministically to yield a single estimate or stochastic distributions by "Monte-Carlo" calculation that reflects uncertainty of parameter and model uncertainties. The results of this study may contribute to identifying the relative importance of various parameters occurred in consequence analysis, as well as to assessing risk reduction effects in accident management.

KEYWORDS: ingestion chain model, dynamic, radioecology, system dynamics

I. Introduction

The offsite consequence analysis has been performed using a tool of system dynamics. The methodology to analyze accident consequence dynamically needs to be developed. A radiation assessment framework to assess the effects on health and the environment is required to establish. The risk from a severe accident for a reference plant used to be assessed by performing level 3 probabilistic safety assessment. The potential magnitude of radionuclide releases under severe accident loadings and offsite consequences as well as the overall risk are quantitatively evaluated in this study [1-3].

II. System Dynamics

System dynamics is a method to give comprehensive analysis which verifies changes in the variables of the structure with graphical and quantitative output as a progressive and useful analysis tool. This study uses a simulation language called VENSIM (Ventana Simulation Environment) to solve homogeneous differential equations. The VENSIM is a representative computer simulation language, which easily solves variable relationships and the structural elements of a model diagram with a model equation. It provides a mutual relation software environment for development, exploration, analysis, and optimization for simulation models. Also, it is dynamic simulation language that analyzes the time interval (Δt) in the concept of time flow. It is an advantage to analyze the variable of the model with a time interval. Especially, VENSIM presents a visible output where a figure represents a graph with a value of system behavior and system status. It is useful to model comparative analysis for the complicated systems [4].

III. Modeling

The Gaussian plume model for a continuous source originates is obtained by applying Fick's law for constant diffusivity coefficient and uniform wind speed. The steady state solution of the basic transport model can be derived. The assumption of constant diffusivity is valid only for that the size of the plume is greater than the size of the dominant turbulent eddies, so that all turbulence implicit in this parameter takes part in the diffusion. The meteorological conditions are assumed to have constant values during the travel of the plume limits of short time periods and small distances. These limitations should be taken into account when applying this model. Even though these conditions are exactly met practically, the Gaussian plume model has been widely used. The mathematical description of the Gaussian model is given as follows. The basic equation for an elevated release is as follows.

‡ Corresponding Author, Tel. +81-2-2290-1346,
Fax. +81-2-2293-7014, E-mail: jae@hanyang.ac.kr

$$C(x,y,z)=\frac{Q}{2\pi u_{10}\sigma_z\sigma_y}\exp\left[-0.5\left(\frac{y^2}{\sigma_y^2}+\frac{(z-h)^2}{\sigma_z^2}\right)\right] \quad (1)$$

,where C is air concentration (g s m^{-3}); Q is the release rate (g s^{-1}) or total amount released (g); u_{10} is the wind speed at 10 m above the ground (m s^{-1}); σ_z is the standard deviation of the vertical Gaussian distribution (m); σ_y is the standard deviation of the horizontal Gaussian distribution (m); x is the rectilinear co-ordinate along the wind direction (m); y is the rectilinear co-ordinate for cross-wind (m); z is the rectilinear co-ordinate above the ground (m); and h is the effective release height (m).

The origin of the co-ordinate system is considered to be at ground level beneath the discharge point. The atmospheric dispersion and its transfer mechanisms are modeled as **Fig. 1**.

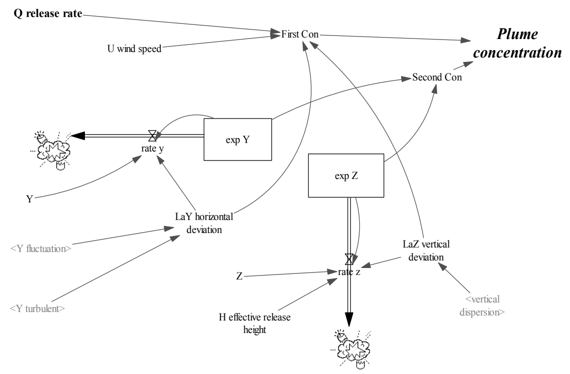

Fig. 1 Gaussian plume model using system dynamics

The transfer kinetic processes for radionuclides can be described by a set of linear first-order differential equations. Each equation corresponding to each compartment, which represents an environment element, is obtained from the change of the radioactivity concentration with respect to time based on the mass balance. The system dynamics is advantageous to model the changes over time for radionuclides process behaviors. The radionuclide concentrations in foodstuffs are then evaluated by calculating time dependent inventory. A set of differential equations are constructed for all the compartments. The coupled differential equation for each compartment is then solved numerically on daily time steps using an algorithm to yield the time-dependent inventories. And in the **Fig. 2** shows the diagram to describe the dynamic behaviors for several effects such as deposition, weathering and washout, resuspension, root uptake, translocation, leaching, senescence, intake and excretion of soil, intake and excretion of feedstuffs by animals.

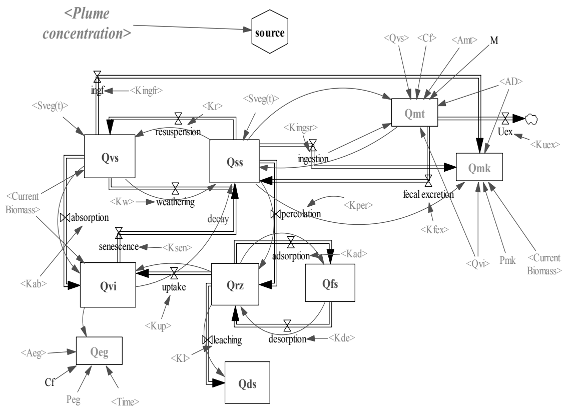

Fig. 2 Dynamic ingestion model using system dynamics

The food-chain model simultaneously simulates the flow of radionuclides through three land-management units: rangeland-grazing, human-food crops, and pasture/hay systems. Each land-management unit is represented by six state variables as shown in Fig. 3. The state variables denote the quantity of radionuclide in specific compartments. These transport process quantities, which is to be obtained from time dependent equations, include vegetation surfaces (Q_{vs}); vegetation internal tissues (Q_{vi}); soil surface, 0 - 0.1 cm (Q_{ss}); root zone, 0.1 - 25 cm (Q_{rz}); fixed soil, 0.1 - 25 cm (Q_{fs}); and deep soil, > 25 cm (Q_{ds}). In addition, land management units may have compartments with the quantities or concentrations of radioactivity in products such as fruits, vegetables(leafy, other), grains, grain plants for silage, grass and meats (beef, poultry), milk, milk products, and eggs. Other specific food sources are excluded because of either very minor effective sources to man or insufficient data [5-6].

The risk, R_i for early health effect is modeled in the accident consequence code as follows [7].

$$R_i = 1 - e^{-H_i} \quad (2)$$

,where H_i represents the cumulative hazard of early health effect. It can be modeled by a weibull function as follows.

$$H_i = \ln(2)\left(\frac{LD}{LD_{50,i}}\right)^{v_i} \quad (3)$$

for $LD > LD_{thr,I}$

where LD is the lethal dose.

$LD_{50,i}$ denotes the dose which causes 50% fatality of the exposed population due to early health effect i, v_i represents the shape parameter, and $LD_{thr,I}$ shows the dose threshold of early health. It is modeled as a function of the dose rate(DR) as follows.

$$LD_{50,i} = \frac{D_{0,i}}{DR} + D_{\infty,i} \quad (4)$$

where $D_{0,I}$ (in Gy^2/h) and $D_{\infty,I}$ approximates the $LD_{50,I}$.

The dynamic early fatality can be modeled as shown in **Fig. 3**.

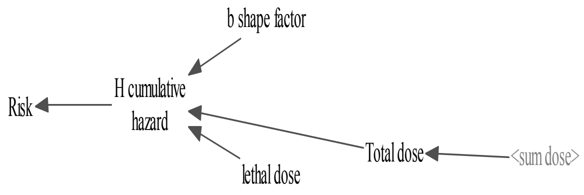

Fig. 3 Early fatality model using system dynamics

IV. Results

The food-chain model for rice after deposition in unit, Becquerel per area, has been evaluated quantitatively by system dynamics calculation algorithm. The system dynamics models the transfer of radionuclides efficiently. The values of the input parameters to the dynamic ingestion pathway model are equivalent to the values of both the site-specific environment and the agriculture data-base in the Kori area. The January data is used for the deposition times as a typical winter whether. The example radionuclides, Cs-137 is chosen in this study because it is one of significant nuclides to the ingestion doses exposed during severe accidents. The radioactivity concentration, Cs-137 deposition, might be very pronounced with deposition time. The direct deposition onto plant leaves or grains results in an important contamination due to high translocation. The time-specific and time-integrated concentrations of radionuclides for foods per unit fallout deposition are shown to vary dramatically by radionuclide as shown in **Fig. 4**. The parameter uncertainty existing in this approach may result from natural variability associated with a lack of knowledge about the actual value.

The uncertainty analysis using the Monte Carlo method has been performed in this study. The uncertainty of the median value for time-integrated concentrations of Cs-137 radionuclides has been surveyed to allow confidence intervals to be assigned as shown. The uncertainty may come from unavoidable errors in structure and various parameter uncertainties. Those are propagated through the developed model to result in **Fig. 5**.

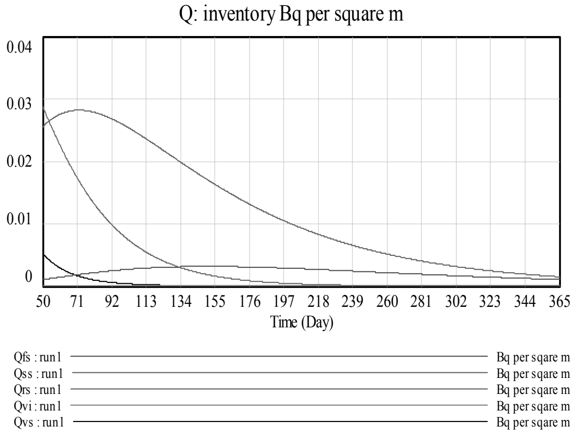

Fig. 4 Time-integrated concentrations of radionuclides in foodstuffs, inventory of compartment.

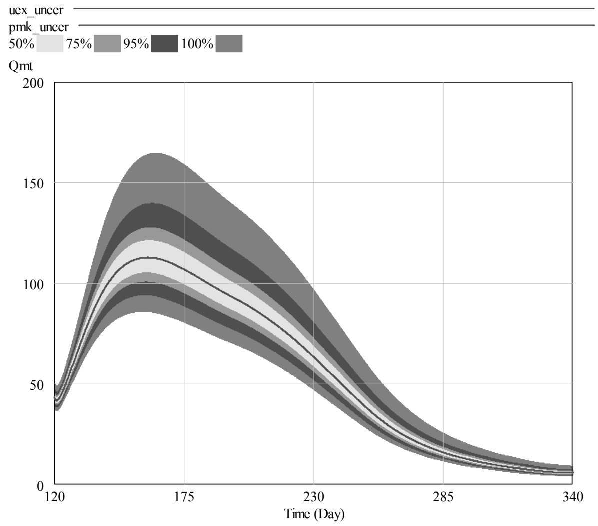

Fig. 5 Uncertainty analysis for concentrations of radionuclides in meat (Unit: 10^{-8}Bq kg^{-1})

V. Conclusions

A dynamic model for ingestion pathway has been developed and evaluated quantitatively by applying system dynamics to consequence analysis. The radioactivity concentration in foodstuffs is chosen as an example parameter for validating this dynamic approach. It is also shown that the system dynamics approach is efficient in modeling and evaluation for analyzing the phenomenon of the complex system as well as the behavior of structure values with respect to time. The major merit of this model include its ability to dynamically simulate important vegetation, soil transport processes, account for seasonal changes in these transport processes, evaluate discrete fall-out dates, and agricultural events such as tillage and harvests. It provides individual food product concentrations and contributions from specific feed sources. The uncertainty analysis using the Monte Carlo method has been performed as well. The uncertainty of the median value for time-integrated concentrations of Cs-137 radionuclides has been analyzed to allow confidence intervals. It might contribute to identifying the relative importance of various parameters occurred in consequence analysis, as well as to assessing risk reduction effects in accident management.

Acknowledgements

This work was supported by the Korean Science and Engineering Foundation (KOSEF) through the Innovative Technology Center for Radiation Safety (iTRS) and Hanyang University, Seoul, Korea.

References

1) W. T. Hwang. al., "Development of a Dynamic Ingestion Pathway Model, Applicable to Korean Environment", The Korean Association for Radiation Protection, 18(1), p. 9-24, 1993
2) Breshears, David D.; Kirchner, Thomas B.; Otis, Mark D.; Whicker, F. Ward, "Uncertainty in Predictions of Fallout Radionuclides in Foods and of Subsequent Ingestion.", Health

Physics. 57(6):943-953, December 1989.
3) Son, T. W., and Chung, H. K., “System Dynamics Approach for Analyzing Dynamic Motivation Model Using VENSIM,” Korean System Dynamics Society, pp.61-86. 1999.
4) VENSIM reference manual version 4, Ventana System, Inc; 1999.
5) Whicker, F. Ward; Kirchner, T. B, Pathway: “A Dynamic Food-chain Model to Predict Radionuclide Ingestion After Fallout Deposition,” Health Physics, 52(6), p. 717-737, 1987.
6) Abbott, Michael L.; Rood, Arthur S, Comida: “A Radionuclide Food Chain Model for Acute Fallout Deposition”, Health Physics, 66(1), p. 17-29, 1994.
7) C. H. Lee, et al., “ A development of Computer Code for Evaluating Internal Radiation Dose through Ingestion and Inhalation Pathway”, KEAR/RR-998/90, 1991.