Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Development of radiation risk assessment simulator using system dynamics methodology

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1. Introduction

The risk from severe accidents in a reference plant is assessed using the consequence analysis being termed the level 3 PSA (Probabilistic Safety Assessment). The potential magnitude of radionuclide releases under severe accident loadings and offsite consequences as well as the overall risk (the product of accident frequencies and consequences) are calculated in this paper. System dynamics methodology useful for complex systems such as a nuclear power plant has been applied for representing the time-dependent behavior and uncertain behavior of complex physical system. System dynamic model is used to construct the transfer mechanism of time dependent radioactivity concentration. Dynamic variation of radioactivities were simulated by considering several effects such as deposition, weathering, washout, resuspension, root uptake, translocation, leaching, senescence, intake and excretion of soil by animals, intake and excretion of feedstuffs by animals.

2. Methods and Results

Time-dependent radioactivity concentrations in atmospheric dispersion and foodstuffs can be estimated by the model. And the system dynamics approach is useful for analyzing the phenomenon of the complex system as well as the behavior of structure value with respect to time. System dynamic model is used to construct the transfer mechanism of time dependent radioactivity concentration.

2.1 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 a 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 (t, t-1). 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 for comparative analysis.

2.2 Gaussian plume model structure

The mathematical description of the Gaussian model used in the present work is given as follows. The basic equation using a Gaussian plume model for an elevated release has the form.

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

where C is air concentration (g m^{-3}) or its time integral (g s m^{-3}); Q is the release rate (g s^{-1}) or total amount released (g); u10 is the wind speed at 10 m above the ground (m s^{-1}); σz is the standard deviation of the vertical Gaussian distribution (m); σy 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).

2.3 Dynamic Ingestion

The transfer kinetic of radionuclides are described by set of linear first-order differential equations. Each equation corresponding to each compartment, which represents an environment element, described the change of the radioactivity concentration with time base on the mass balance. The system dynamics method is useful for the changes over time in radionuclides behavior. The radionuclide concentrations in foodstuffs are calculated from time dependent inventory.

$$Q_h^{'} = \sum_{i=1}^{n} R_{in,i} - \sum_{j=1}^{m} R_{out,j} \qquad (2)$$

$R_{in,\,i}$= i th inflow rate to compartment h
$R_{out,,j}$= j th inflow rate to compartment h

A differential equation of this form is written for each compartment. The resulting set of coupled differential equation is then solved numerically on daily time steps using an algorithm to yield time-dependent inventories for each compartment. Each equation corresponding to each compartment, which represents an environment element, describes the change of the radioactivity concentration with time based on the mass balance. The atmospheric dispersion modeling and its transfer

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mechanisms are shown in Fig. 1 with the system dynamic modeling.

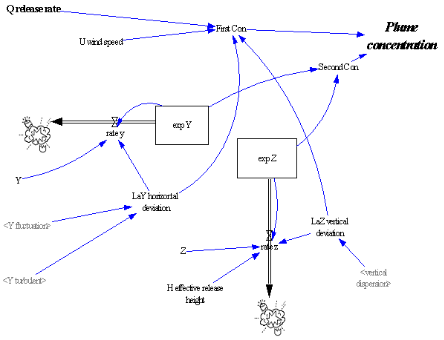

Figure 1. Gaussian plume modeling using system dynamics

And in Fig. 2., Dynamic variation of radioactivities were simulated by considering several effects such as deposition, weathering and washout, resuspension, root uptake, translocation, leaching, senescence, intake and excretion of soil by animals, intake and excretion of feedstuffs by animals.

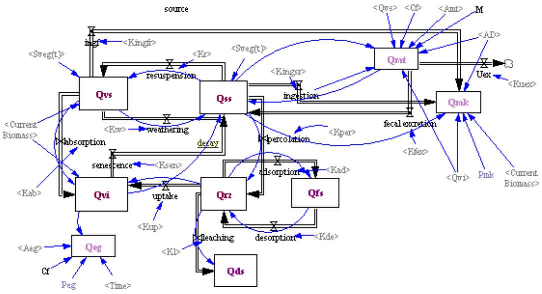

Figure 2. Dynamic ingestion modeling using system dynamics

2.4 Early Fatality

The risk of early health effect is modeled in the accident consequence codes as

$$R_i = 1 - e^{-H_i} \qquad (3)$$

In this equation H_i represents the cumulative hazard of early health effect I and it is modeled as a two-parameter weibull function

$$H_i = \ln(2)\left(\frac{LD}{LD_{50,i}}\right)^{v_i} \qquad (4) \qquad \text{for } LD > LD_{thr,I}$$

Where L_d is the lethal dose, $LD_{50,i}$ the dose which causes 50% of the exposed population to succumb due to early health effect i, vi the shape parameter and $LD_{thr,I}$ the dose threshold of early health i. is modeled as a function of the dose rate DR

$$LD_{50,i} = \frac{D_{0,i}}{DR} + D_{\infty,i} \qquad (5)$$

Where $D_{0,i}$: Gy^2/h

$D_{\infty,I}$: approximates the $LD_{50,I}$.

2.5 Results

This model was designed as a safety analysis tool that would provide greater detail on radionuclides concentration and more realistic ingestion dose impacts without requiring excessive environmental and agricultural input data that may not be available at diverse site locations.

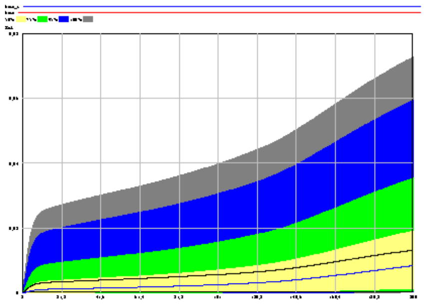

Figure 3. Uncertainty analysis for early fatality

The sample calculations were performed in order to evaluate the concentration of radionuclides and dose through the atmospheric dispersion model and the food-chain model after accident. 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 and accident management strategies.

3. Conclusion

Since the ingestion doses are very important in the consequence analysis associated with long-term exposures, it is necessary that that dynamic behaviors of radioactive nuclides released in an accident of nuclear power plant should be analyzed following accidents in the site-specific environment. In this study, a dynamic model for atmospheric dispersion model structure and ingestion pathway has been developed in order to consider several agricultural practices, and food consumption behavior, etc. It is shown that the dynamic radiological model can be used as a tool for comprehensive ingestion dose assessment during accidental release of radionuclides.

Acknowledgements

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

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