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MASTER

A SYSTEMATIC APPROACH FOR ASSESSMENT OF ALTERNATIVE NUCLEAR WASTE MANAGEMENT STRATEGIES

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ABSTRACT

A systematic approach for alternative nuclear waste management assessment is prescribed for evaluating the fate and transport of radwaste in the environment and to man. The approach consists of a system of flow dynamic and waste transport models for the physical environment, transfer models to biota, and dose models to man. Flow dynamic and waste transport models are included for computing spatial-temporal variations of the flow field and radwaste concentration in subsurface aquifers, surface water regimes, estuaries/oceans, and the atmosphere. Transfer models are linked to flow dynamic and waste transport models to study the uptake from and to the physical environment of the waste by aquatic and terrestrial biota. Dose models are used to compute both the radwaste input to man and its effects on man. With these series of computations, the radiation dose from alternative nuclear waste management strategies can be computed. Coupled with the exposure and effect analysis, the approach should facilitate the selection of the best management methodologies among many alternatives.

INTRODUCTION

One of the critical issues of nuclear power production and utilization is the safe management of potentially hazardous radioactive waste materials. Comprehensive assessments are needed to quantify effectiveness of each of the management alternatives, and thus increase public acceptance of nuclear energy. Safety assessments would inevitably include study of the transport, transformation, fate and pathway of the radwaste associated with nuclear

energy. They would also be concerned with possible exposure and the consequent adverse health, ecological and abiota effects.

Environmental release of radwastes may occur in subsurface aquifers, surface water regimes, oceans/estuaries, the atmosphere, or even directly to biota. However, following the release, there will be redistribution of the wastes into all media. The important pathways of the radionuclides from source release to man are shown in Figure 1. Accordingly, for a complete systematic approach, flow dynamic, waste transport, biological transfer, and dose models are needed to cover the entire biosphere. Flow dynamic models are required to simulate the flows of the carrier fluid. Waste transport models are necessary for predicting the concentration distribution. Biological transfer models are needed to simulate the uptake and release between the biota and physical environment. Dose models must be provided to compute radiation dose and its effect on man through external exposure and the inhalation, ingestion, immersion, submersion, and other internal exposures. The availability and minimum requirements of these models will be discussed in the next section.

Figure 1. Pathways of Radionuclides Released into the Environment to Man and the Associated Assessment Models

ASSESSMENT MODELS

For thorough assessment of alternative waste management strategies, a complete set of flow dynamic, waste transport, biological transfer, and dose models are required. Computer codes of biological transfer models (AQUAMOD and TERMOD) and dose models (AIRDOS, SWDOS, GWDOS, AQUADOS, TERDOS, and SOSDOS) have been routinely used for several years to assess the radiological impact of environmental release of radionuclides (Booth, et al., 1971, Moore, 1975, Booth and Rohwer, 1975, Halfon and Bargmann, 1975). Many of the environmental transfer coefficients and other pertinent data required for a given simulation are already available. Hence, in this paper, I will be primarily concerned with flow dynamic and waste transport models in the physical environment of subsurface aquifers, surface water regimes, estuaries/oceans, and the atmosphere.

In order to predict the concentration distribution of radwastes in the physical environment, it is envisioned that at least 36 types of models listed in Table 1 are required. These include from steady one-dimensional to transient three-dimensional models of flow dynamics and waste transport in subsurface aquifers, surface water regimes, estuaries/oceans, and the atmosphere. Most of these models are available in the literature (Owen, et al., 1979); but for a systematic approach, they must be adapted, modified, and documented in a unique format so that the flexibility and utility of combining the models can be achieved. They can then be used separately to deal with site-specific problems or combinedly to handle large scale generic study. If the combination of models is employed, iterations must be used to obtain interfacial values of the media when the feedback between media is strong. When the feedback between media is weak, the output from one media may be used as input to the subsequent media and the excessive computation of iterations may be ignored.

Because of the severe consequence that may result from unsound management practice based on poor assessment, each of the models listed in Table 1 must be capable of yielding valid results when applied to any management proposal. To achieve this goal, each model must satisfy the following minimum requirements: (i) the problem must be logically formulated and expressed in mathematical equations to include as many processes as possible, (ii) the up-to-date and efficient computational algorithm must be devised and analyzed, (iii) the model must be validated by comparing the model results with well-known analytical solution, other type of numerical simulations, laboratory experiments, and/or field measurements, and (iv) demonstrative applications must be made. The processes governing the radwaste transport within a medium may include mainly the advection of carrier fluid, hydrodynamic dispersion, radioactive decay, and the medium-dependent processes. For example, adsorption by the soil matrix will occur in the subsurface aquifer. The adsorption and desorption by sediments, which themselves are trans-

Table 1. Flow Dynamics and Waste Transport Models
Required for a Systematic Modeling Approach

	Model No.	Flow						Radionuclides						Sediments					
		S	T	1-D	2-D X-Y	2-D X-Z	3-D	S	T	1-D	2-D X-Y	2-D X-Z	3-D	S	T	1-D	2-D X-Y	2-D X-Z	3-D
Subsurface Aquifer (GWMOD)	Unsat-Sat.	1	X			X													
		2						X				X							
		3	X				X												
		4						X					X						
	Sat.	5	X		X														
		6						X			X								
		7	X	X															
		8						X	X										
Surface Water Regimes (SMOD)	Runoffs	9	X		X														
		10						X		X					X		X		
	Streams/Rivers	11	X		X														
		12		X	X														
		13						X	X						X	X			
		14	X			X													
		15	X			X												X	
		16						X			X				X				
	Surface Impoundment	17	X		X														
		18	X		X														
		19						X		X					X		X		
		20	X				X												
		21	X				X												
		22						X					X		X				X
Oceans & Estuaries (OZMOD)		24	X	X															
		25						X	X						X	X			
		26	X		X														
		27						X		X					X		X		
		28	X			X													
		29						X			X				X			X	
		30	X				X												
Atmosphere (AIRMOD)		31						X					X		X				X
		32	X		X														
		33	X		X														
		34		X			X												
		35						X					X						
		36						X					X						

S = Steady state simulation
 T = Transient state simulation
 1-D = One-dimensional
 2-D X-Y = Two-dimensional in the horizontal plane X-Y
 2-D X-Z = Two-dimensional in the vertical plane X-Z
 3-D = Three-dimensional

ported along with the radionuclide by the fluid, can occur in the surface water regimes and the estuaries/oceans. Cloud scavenging and precipitational washout may take place in the atmosphere. On the other hand, transfer of wastes across media interfaces may be induced by various kinds of processes such as deposition, resuspension, aeration, seepage, infiltration, volatilization, evaporation, and transpiration. All these processes must be included in the transformation of processes into equations. The computational algorithm may range from simple analytical and empirical methods to realistic sophisticated numerical techniques including finite difference, finite element, and Monte Carlo simulations. Analytical and empirical models are best utilized for analyzing the response of the media to the variation of model parameters. Insensitive parameters are then excluded from the sophisticated numerical based models.

EXAMPLE MODEL FOR SUBSURFACE AQUIFER

Six models (Yeh, 1979a, 1979b; Yeh and Ward, 1979a, 1979b; Yeh, 1980a, 1980b), each representing an example of model type nos. 1, 2, 3, 4, 17, and 18 in Table 1, have been completed according to the minimum requirements described above. Continuing efforts are being made to have at least one model available for each of the remaining 30 model types in the same manner. FEMWATER (Yeh and Ward, 1979a), which is an example of model type no. 1, will be used to illustrate the model buildup and documentation.

It is common practice to bury low level radwastes in shallow trenches above groundwater table. Under such circumstances, unsaturated groundwater flow is important in moving radionuclides to the water table and transporting them to other media through the saturated zone. Therefore, the model used to simulate the water movement must describe unsaturated as well as saturated flow. If the burial ground is located in humid climates, the model must allow for relatively large fluctuation of the water table elevation. The major input of water to the subsurface aquifer system is the infiltration by direct precipitation and indirect surrounding surface waters. The accuracy required in this simulation can only be obtained by numerical solution of the nonlinear differential equations of the modified Richards type and of Darcy's law. During the rainfall storm, the aquifer may or may not have the capacity to receive all the excess rainfall. During and after the storm, the water in the aquifer may move to the sloping air-land interface or to streams, rivers, or impoundments. These necessitate the consideration of Dirichlet, Neumann, and variable boundary conditions. Mathematical equations that govern the saturated-unsaturated flow and three types of boundary conditions are described in FEMWATER (Yeh and Ward, 1979a), which is a member of GWMOD in Table 1.

Because of its flexibility to handle complex boundaries and the ease in treating Neumann boundary conditions, the finite element method (FEM) is chosen to approximate the governing partial differ-

ential equation of continuity. To obtain a continuous flow field, FEM is also applied to the Darcy's law. After incorporating the boundary conditions, two matrix equations are obtained; one for the pressure field and the other for the velocity field. Six up-to-date alternative numerical schemes are used to solve the matrix equations for the pressure head and velocity components (Yeh and Ward, 1979a). Numerical experiments on a small laboratory-sized watershed given by Freeze (1972) show that all six schemes yield comparable results and the expected behavior of the model are obtained.

FEMWATER is validated by comparing the model simulations with Philip's exact solution (1960) for an ideal horizontal infiltration, with Freezes transient finite difference model (1972) for a hypothetical watershed, and with Hewlett and Hibbert's laboratory experiment (1963). To compare the numerical simulation with Philip's exact solution, a diffusivity function of the moisture, θ , $D(\theta) = (1/2\theta - 1/4\sqrt{\theta})$, is used. Initial and boundary conditions are specified as: $\theta(x,0) = 0.1$ and $\theta(0,t) = 0.4$, $\theta(\infty,t) = 0.1$. Figure 2 shows the comparisons of moisture content profiles as simulated by FEMWATER and Philip's exact solution. Excellent agreement is obtained, thus the reliability of the computer code is assured. Freeze (1972) employed a hypothetical watershed measured 6 X 3 -m with sloping surfaces (Figure 3) to test his finite difference model. The watershed is assumed to be filled with highly permeable sands. The bottom, right, and left sides and the right sloping segment on the surface are considered impervious. The left horizontal segment on the surface is treated as a Dirichlet boundary. The left sloping and right horizontal segments on the surface are assumed to be variable boundaries to simulate the dynamic alteration of seepage and infiltration. Comparisons of simulated results at several points by FEMWATER and Freeze's finite difference model are also shown in Figure 3. General agreement is obtained. Thus, the accuracy of the numerical algorithm can be asserted. Hewlett and Hibbert's experimental watershed is a 92 X 92 X 1400 -cm inclining concrete trough on a 40% slope. The structure was packed with a natural sandy-loam soil to a bulk density of 1.3 for the experiment. Continuous measurement of outflow was taken for 150 days after the watershed was soaked by a sprinkling system for several days. The simulated outflow hydrograph by FEMWATER is compared with the measured values in Figure 4. The agreement is considered acceptable.

CONCLUSION

A system of flow dynamic, waste transport, biological transfer, and dose models are prescribed for a systematic approach of assessing the effects of alternative nuclear waste management strategies on man. The minimum requirements for every flow dynamic and waste transport models are described. These minimum requirements are exemplified by a groundwater flow model, FEMWATER. FEMWATER is one of six models that have been completed satisfying the minimum requirements. Continuing efforts are being made to have at least one model available for each of the 36 model types prescribed in Table 1.

Figure 2 (Left)
Comparisons of
Philip's analytical
solution and the
FEMWATER simulation.

Figure 3 (Right)
Comparison of Freeze's
Finite-difference and FEMWATER
simulation.

Figure 4 (Left)
Comparison of
FEMWATER and Hewlett
and Hibbert's measured
hydrographs.

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