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Scenario and Parametric Sensitivity and Uncertainty Analyses in Nuclear Waste Disposal Risk Assessment: The Case of GESAMAC

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13.1 INTRODUCTION: THE GESAMAC PROJECT

Nuclear fission, as an energy source, has been employed in the United States and Europe for more than 40 years (Balogh, 1991), and yet the problem of safe disposal of radioactive waste arising as a by-product of power generation is still under study. Deep geological disposal—in which radioactive materials (e.g., spent fuel rods) are encapsulated and placed in a facility far below ground—is still the most actively investigated option, although in the 1970s disposal of nuclear waste in deep sea sediments was considered (Bishop and Hollister, 1974) and some objections to underground storage persist today (Keeney and von Winterfeldt, 1994; Schrader-Frechette, 1994). It is fair to say that even after decades of research, the physico-chemical behavior of deep geological disposal systems over

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geological time scales (hundreds or thousands of years) is far from known with certainty (Pereira, 1989; Draper *et al.*, 1999).

From 1996 to 1999, with partners at the Physics Department at Stockholm University, we were involved in a project for the European Commission, GESAMAC (GEosphere modeling, geosphere Sensitivity Analysis, Model uncertainty in geosphere modeling, Advanced Computing in stochastic geosphere simulation: see http://www.ciemat.es/sweb/gesamac/), whose principal aim was to make progress in capturing all relevant sources of uncertainty when predicting what would happen if deep geosphere disposal barriers were compromised in the future by processes such as *geological faulting, human intrusion*, and/or *climatic change*. We used sensitivity analysis (SA) and uncertainty analysis (UA) in predicting the radiological dose for humans on the Earth's surface as a function of time, how far the disposal facility is underground, and other factors likely to be strongly related to dose. Complex computer simulation modelling features prominently in our work.

13.1.1 The System Model

The system model on which our predictions are based consists of a hypothetical underground radioactive waste disposal system represented by three coupled submodels: the *near field* (the radiological source term), a *far field* (the geosphere), and the *biosphere* (the region on, above, or near the Earth's surface in which people live and work). The first submodel—the near field (the underground repository itself)—does not include any consideration of spatial structure or chemical complexities. This submodel assumes an initial containment time for the waste materials (only radioactive decay is considered), followed by a constant leaching rate of the radioactive inventory present at the time containment fails. The third GESAMAC submodel—the biosphere—is very simple and assumes that the radionuclides leaving the geosphere enter a stream of water from which a human population obtains drinking water, so that the dose received depends on the ratio of the drinking water consumption to the stream flow rate. This is clearly not a real, site-specific safety study, but a simplified framework in order to illustrate SA and UA methodology.

The main focus of our computer simulations deals with the second submodel, the geosphere. GESAMAC has released for public use a program called GTMCHEM, which uses Monte Carlo methods to simulate the transport of radionuclides by groundwater through geologic formations, represented by a one-dimensional column of porous material (consisting of one or more layers) whose properties can change along the pathway and in which different chemical reactions (homogeneous or heterogeneous) can take place. An earlier version of the code, GTM-1 (Prado, 1992; Saltelli *et al.*, 1989; Prado *et al.*, 1991), was extensively tested through its inclusion in several versions of the LISA code and in the international PSACOIN benchmark exercises (NEA PSAG User's Group, 1989, 1990). The only chemical process considered in GTM-1 was adsorption by linear isotherm.

GTMCHEM expands on this by incorporating a number of other chemical phenomena (Eguilior and Prado, 1998), including equilibrium complexation in solution, homogeneous first-order chemical kinetics in solution, slow reversible adsorption, and a sink associated with filtration or biodegradation. The program works by solving the equation

$$\frac{\partial C_i}{\partial t} = -V\frac{\partial C_i}{\partial X} + D\frac{\partial^2 C_i}{\partial X^2} + \text{SoSi}, \qquad (13.1)$$

where C represents concentration (mols/m^3), t is time (yr), X is the space coordinate (m), V is the groundwater velocity (m/yr), D is the hydrodynamic dispersion (m^2/yr), and SoSi is the