A STATISTICAL APPROACH TO MODELING TRANSPORT OF POLLUTANTS IN GROUNDWATER*

Benjamin Ross

Charles M. Koplik

Bard S. Crawford

The Analytic Sciences Corp.
Reading, Mass. 01867

*This work was supported by Lawrence Livermore Laboratory under Contracts 9163105 and 6064103.

ABSTRACT

The transport of pollutants in the subsurface can be affected by random geologic events. Prediction of such transport therefore requires solution of a partial differential equation whose coefficients are random processes. A method of finding the expected (mean) values of solutions of such equations is derived. This method is used to assess the impact of fault movement and formation of breccia pipes on risk from radioactive waste disposal. Preliminary results indicate that these events, considered probabilistically, do not make a large contribution to risk.

1. INTRODUCTION

The primary means by which solidified radioactive waste can escape from a repository deep underground and enter the biosphere is transport in flowing groundwater (Schneider, 1974). The prediction of radionuclide transport in groundwater is therefore essential to risk assessment of waste disposal.

Modeling of this transport in a given hydrologic setting is, in itself, not a simple problem. Moreover, the time periods during which radioactive wastes may remain dangerous are sufficiently long that the status of the repository might be altered. Such changes could be initiated as a result of the construction of the repository, by subsequent human activity, or by geologic forces. Some examples of events which could affect release of radioactivity from a repository are faulting, dissolution of soluble rock and consequent collapse of the overburden, and failure of borehole seals.

In a typical fault tree analysis (e.g., USNRC, 1975), these events would be treated as independent failure modes. Their probabilities and consequences (as well as the probabilities and consequences of common mode failures) would be evaluated independently and summed. In the cases usually treated by this technique, severe failures lead to a cessation of normal operations until corrective action has been taken. A particular airplane can only crash once and a particular reactor core can only melt once -- such, at least, is the assumption made in fault tree analysis. The same does not hold for a waste repository. In the distant future which is of concern, there is no guarantee that men will be able to detect and correct a failure. The risk analysis must therefore deal not only with the probabilities and consequences of individual failures, but also with multiple, sequential failures. In such cases, consequences will depend on the sequence and timing of events as well as the events themselves.

The radioactive decay mechanism introduces yet another element of time dependence into the problem. Because the nuclides in waste decay as time passes, the effects of a release will usually be lessened if the release occurs at a later time. Fault tree analyses of engineered systems, on the other hand, assume no explicit relationship between system age and the consequences of failures.

To address this complex situation, we have developed a model which analyzes waste repositories on two levels. A total system, composed of the repository, the waste, and the various pathways by which the waste might reach the biosphere, is described by a geologic state and a waste distribution. The geologic state is defined by the condition of the strata in which the repository is located and of the escape pathways. For a given geologic state, the permeability and porosity of different rock layers, the velocity field of ground water, etc., will be uniquely defined. The waste distribution is a description of the concentration of radioactive waste in the repository and the different pathways at any given time.

The nature of each geologic state is defined without reference to the location of waste. The movement of waste depends parametrically on the state of the geologic system. Unfortunately, the location of the waste at any time depends not only on the current geologic state, but also on what the

the geologic state was at all previous times. For example, waste will likely have moved further in a situation where an escape pathway opened just after it was emplaced and remained open t years than in a case where the same pathway has just opened t years after emplacement. In both cases the geologic state is the same -- the pathway is open.

A scenario-by-scenario study of waste transport therefore requires analysis not merely of the possible geologic states, but of the far greater number of possible histories which a repository might experience as it passes from state to state. In this paper we will present a method which makes it possible to model this situation without explicitly considering all these histories.

Mathematically, the prediction of future waste transport requires solution of a partial differential equation whose coefficients are random processes. In the next section, we will derive a method for obtaining the expectation value of the solution of such equations when the following conditions are satisfied:

- The equation is first-order in time
- It is linear
- Its coefficients can be described by a Markov chain.

We have used this method in conjunction with our waste transport model (Ross, 1978) to evaluate the risk from fault movement and formation of breccia pipes within a waste repository. Initial results indicate that neither of these events makes a significant contribution to risk (where risk is defined as the sum over all possible outcomes of the product of the damage done and the probability of that outcome) from disposal of nuclear wastes; however further studies are required to confirm this conclusion.

2. MATHEMATICAL DERIVATION

The derivation begins with the observation that the concentration of waste nuclides in groundwater at any point may depend on the whole history of the repository area from emplacement to the time being considered. Concentration at time t therefore depends not only on the current geologic state g(t), but on the entire evolution of the geologic system from zero to t. The history of the geologic system will be denoted by h; each value of h is an entire realization of the stochastic process whose value at time t is the random variable g(t). The expected value of the concentration of any radionuclide r at point $\underline{x}$, $C_r(\underline{x};h,t)$ will be given by integrating over all histories

$$E(C_r(\underline{x},t)) = \int C_r(\underline{x};h,t)\ p(h)\ dh \tag{1}$$

where p(h) is the probability density of history h.

We assume that waste transport is described by an equation of the form

$$\frac{\partial}{\partial t} C_r(\underline{x};h,t) = L^{(h)}\ C_r(\underline{x};h,t) \tag{2}$$

where, for any h, $L^{(h)}$ is an operator which operates on the spatial coordinates of C_r. This assumption is consistent with the usual equation for flow of dissolved material in groundwater (Scheidegger, 1964) which is:

$$\frac{\partial C_r}{\partial t} = \left[-V_{ion}\ \nabla + \alpha V_{ion}\ \nabla^2\right] C_r \tag{3}$$

where V_{ion} is the advection velocity of the ions and α is the dispersion constant. The effects of radioactive decay may be incorporated by a straightforward extension of the present proof; however, they have been omitted in order to avoid adding additional terms to the equations.

We wish to obtain an equation for waste transport which does not involve the history h, but only the current state g. In order to do so, we define a quantity ϕ_r by integrating over all histories h which reach state g at time t

$$\phi_r(\underline{x};g,t) = \int_{\Omega:\{h(t)=g\}} C_r(\underline{x};h,t)\ p(h)\ dh \qquad (4)$$

The integral is over all realizations h of the random process which take the value g at time t. In subsequent equations this integration will be understood and the Ω and brackets will be omitted. ϕ_r may be interpreted physically as the expected value of concentration of nuclide r at point $\underline{x}$ given that the system is in state g, multiplied by the probability that the system is in g. By comparing Eq. 4 and Eq. 1, it is seen that expected concentrations may be calculated from the relation

$$E(C_r(\underline{x},t)) = \sum_g \phi_r(\underline{x};g,t) \qquad (5)$$

In order for this definition to be useful, we must derive an equation for the evolution of ϕ_r which does not depend on h. We begin by taking the time derivative of Eq. 4. In order to deal with the integration over histories, we must explicitly use the definition of the derivative.

$$\frac{\partial}{\partial t} \phi_r(\underline{x};g,t)$$

$$= \lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \int_{h(t+\Delta t)=g} C_r(\underline{x};h,t+\Delta t)\ p(h)\ dh \right.$$

$$\left. - \int_{h(t)=g} C_r(\underline{x};h,t)\ p(h)\ dh \right\} \tag{6}$$

In order to separate out the time dependence of C_r, we add and subtract identical terms.

$$\frac{\partial}{\partial t} \phi_r(\underline{x};g,t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \int_{h(t+\Delta t)=g} C_r(\underline{x};h,t+\Delta t)\ p(h)\ dh \right.$$

$$- \int_{h(t+\Delta t)=g} C_r(\underline{x};h,t)\ p(h)\ dh + \int_{h(t+\Delta t)=g} C_r(\underline{x};h,t)\ p(h)\ dh$$

$$\left. - \int_{h(t)=g} C_r(\underline{x};h,t)\ p(h)\ dh \right\} \tag{7}$$

The first two terms are integrals over the same range of values of h and thus can be combined and simplified by using Eq. 2.

$$\lim_{\Delta t \to 0} \int_{h(t+\Delta t)=g} p(h)\ \frac{C_r(\underline{x};h,t+\Delta t) - C_r(\underline{x};h,t)}{\Delta t}\ dh$$

$$= \int_{h(t)=g} p(h)\ \frac{\partial}{\partial t} C_r(\underline{x};h,t)\ dh$$

$$= \int_{h(t)=g} p(h)\ L^{(h)}\ C_r(\underline{x};h,t)\ dh \tag{8}$$

In order to simplify the two remaining terms of Eq. 7, we must assume the range of possible states g is countable. Canceling terms which appear in both integrals, we then obtain

$$
\lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \int_{\substack{h(t+\Delta t)=g \\ \text{and } h(t)\neq g}} C_r(\underline{x};h,t)\, p(h)\, dh - \int_{\substack{h(t)=g \text{ and} \\ h(t+\Delta t)\neq g}} C_r(\underline{x};h,t)\, p(h)\, dh \right\}
$$

$$
= \lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{\substack{h(t+\Delta t)=g \\ \text{and } h(t)=g'}} C_r(\underline{x};h,t)\, p(h)\, dh - \sum_{g' \neq g} \int_{\substack{h(t)=g \text{ and} \\ h(t+\Delta t)=g'}} C_r(\underline{x};h,t)\, p(h)\, dh \right\} \qquad (9)
$$

In order to proceed further, we must examine more closely the role of h. The variable h represents the geologic history over the entire time period of concern in the analysis. We define two partial histories, e and f, as the histories from time zero through times t and t+Δt respectively. If each value of h is thought of as a sequence of states, each value of e or f will be a shorter sequence. Each sequence e or f will be included in many different h's. Different partial histories f which are identical through time t and then reach different states at time t+Δt all include the same partial history e.

Now, it is reasonable to assume causality; i.e., that the concentration of waste at a given time will depend only on the previous geologic states of the system and not on what happens at subsequent times. Since the partial history f includes a specification of the geologic state at all times prior to t, $C_r(\underline{x};h,t)$ will be the same for all histories h which include the same f. All the terms of Eq. 9 which correspond to the same f can be grouped together, and the right hand side of that equation can be written as:

$$\lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{S_{g'g}} C_r(\underline{x};f,t)\, p(f)\, df \right.$$

$$\left. - \sum_{g' \neq g} \int_{S_{gg'}} C_r(\underline{x};f,t)\, p(f)\, df \right\}$$

We have denoted the space of partial histories f which pass through state a at time t and through b at time t+Δt as S_{ab}. The membership of S_{ab} will, of course, change when the value of Δt is varied.

Each space S_{ab} may be partitioned into subspaces S^e_{ab}. Each subspace S^e_{ab} is composed of all those partial histories f which follow a particular partial history e from time zero to t, at which time they have reached state a, and then reach state b at time t+Δt, as shown schematically in Fig. 1. Since S_{ab} is equal to the union of all the S^e_{ab} corresponding to different e which reach state a at time t, we may rewrite our integrals to obtain

$$\lim_{\Delta t \to 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{e(t)=g'} de \int_{S^e_{g'g}} df\, C_r(\underline{x};f,t)\, p(f) \right.$$

$$\left. - \sum_{g' \neq g} \int_{e(t)=g} de \int_{S^e_{gg'}} df\, C_r(\underline{x};f,t)\, p(f) \right\}$$

We now invoke causality again to make concentration C_r at time t a function only of e and not of f. Since only the integral over f depends on Δt, the order of operations can be altered to obtain

$$\sum_{g'\neq g} \int_{e(t)=g'} de\, C_r(\underline{x};e,t) \lim_{\Delta t \to 0} \frac{1}{\Delta t} \int_{S^e_{g'g}} p(f)\, df$$

$$- \sum_{g'\neq g} \int_{e(t)=g} de\, C_r(\underline{x};e,t) \lim_{\Delta t \to 0} \frac{1}{\Delta t} \int_{S^e_{gg'}} p(f)\, df$$

The integral of p(f) over S^e_{ab} is simply p(e) multiplied by the conditional probability $P(b,t+\Delta t|e)$ that the system, having experienced partial history e and having reached state a at time t, will reach state b at time t+Δt. We therefore have

$$\sum_{g'\neq g} \int_{e(t)=g'} de\, C_r(\underline{x};e,t)\; p(e) \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(g,t+\Delta t|e)$$

$$- \sum_{g'\neq g} \int_{e(t)=g} de\, C_r(\underline{x};e,t)\; p(e) \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(g',t+\Delta t|e)$$

We may now define the transition rate from a to b, Γ_{ba}, by

$$\Gamma_{ba}(e) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(b,t+\Delta t)|a,t;e) \qquad (10)$$

In this definition the transition rate has been written so as to show that it may be a function of past history e; in what follows we will not explicitly show this dependence. In the cases we are considering, the value of e at time t is defined by the restrictions on the integrals over e, and so we can substitute the definition directly to obtain

$$\sum_{g'\neq g} \int_{e(t)=g'} C_r(\underline{x};e,t)\ p(e)\ \Gamma_{gg'}\ de$$

$$- \sum_{g'\neq g} \int_{e(t)=g} C_r(\underline{x};e,t)\ p(e)\ \Gamma_{g'g}\ de$$

In order to restore simplicity of notation, the integrals over e may be expanded back into integrals over h. Substituting into Eq. 7 the values we have obtained for its terms, a formula for the derivative of ϕ_r is obtained.

$$\frac{\partial}{\partial t}\phi_r(\underline{x};g,t) = \int_{h(t)=g} p(h)\ L^{(h)}\ C_r(\underline{x};h,t)\ dh$$

$$+ \sum_{g'\neq g} \int_{h(t)=g'} \Gamma_{gg'}\ p(h)\ C_r(\underline{x};h,t)\ dh$$

$$- \sum_{g'\neq g} \int_{h(t)=g} \Gamma_{g'g}\ p(h)\ C_r(\underline{x};h,t)\ dh \qquad (11)$$

The first term in this equation represents the flow through space of radionuclide r. The second term represents the increase in ϕ_r due to transitions into g from other states, and the third term represents transitions out of state g.

We now make two assumptions about the transport operator L; that L depends only on g and not on h, and that it operates linearly on C_r. We may then move it outside the integral so that

$$\int_{h(t)=g} p(h)\ L^{(h)}\ C_r(\underline{x};h,t)\ dh$$

$$= L^{(g)} \int_{h(t)=g} p(h)\ C_r(\underline{x};h,t)\ dh$$

$$= L^{(g)}\ \phi_r(\underline{x};g,t) \qquad (12)$$

At this point we make the assumption that the system described by the geologic states is a Markov process. Consequently the transition rates Γ are independent of the past history. They also may be moved outside the sum. Equation 11 for the evolution of ϕ_r reduces to

$$\frac{\partial}{\partial t} \phi_r(\underline{x};g,t) = L^{(g)} \phi_r(\underline{x};g,t) + \sum_{g' \neq g} \Gamma_{gg'} \phi_r(\underline{x};g',t) - \sum_{g' \neq g} \Gamma_{g'g} \phi_r(\underline{x};g,t) \qquad (13)$$

Equation 13 involves only the current state g and may be solved for the ϕ_r; Equation 5 may then be used to calculate expected values of concentration.

With this result, one need not calculate the motion of waste for each history, but may instead solve for the quantities $\phi_r(\underline{x};g,t)$, which were defined as the expected value of concentration of radionuclide r at point $\underline{x}$, given that the system is in geologic state g, multiplied by the probability of the system being in state g. These quantities represent an aggregation of the various histories which could lead to state g at time t. It is not necessary to solve an infinite number of partial differential equations corresponding to an infinity of possible histories, but only a system of as many equations as there are geologic states and radionuclides.

The principal assumptions made in the above derivation are as follows:

- The operator describing motion of waste must depend only on the current geologic state and not on past geologic states

- The operator describing waste motion in any given state must be linear in waste concentration
- The transition rates between geologic states cannot depend on the past history of the system
- The geologic system is restricted to a countable set of states.

The first two of these assumptions restrict waste transport to flows which can be described by linear instantaneous operators. These assumptions are satisfied by the most commonly used transport equation, as described above in the discussion of Eq. 3.

The other two assumptions govern the geologic states. They require that the system of geologic states form a Markov chain. (The term "Markov chain" is used here in a strict mathematical sense. It encompasses cases in which transition rates are independent of both past and present states as well as cases in which transition rates depend on the present state, but not on past states). Whether this requirement is satisfied depends on the particular set of states used in a model.

Like other macroscopic stochastic processes, future geologic events must be treated probabilistically because we lack sufficient information to make deterministic predictions. For example, if all the movements of heat in the earth, and the structural features along which that heat might rise, were known, it might well be possible to predict where and when new volcanoes will erupt. Without that information, the eruption of new volcanoes must be treated as a random process. The rates of transition between geologic states will therefore depend on how much information about underlying causative processes is included in the specification of the states. Whether these transitions form a Markov chain will depend entirely on how the states are defined. The Markov chain assumption is therefore to be treated as a condition to be satisfied when sets of states are chosen.

3. APPLICATION OF THE METHOD

This probabilistic method has been used in conjunction with our "stream tube" hydrology model (Ross, 1978) in order to assess the impact of possible geologic events on risk from nuclear waste repositories. In the stream tube approach, the flow field of groundwater is approximated by a network of path segments. A one-dimensional equation describes flow within each path segment. The output of one segment is the input to the next.

The probabilistic element is introduced into this scheme by dividing the output of each path segment among the various states in proportion to the probability that the system has entered each state while the waste was passing through the segment. Eq. 13 is thereby approximated by transferring waste among the different $\phi_r(g)$ not at the time the geologic state transition occurs, but at the next subsequent time the waste passes from one path segment into another.

A quantity $F_{r\ell mg}$ may be defined, analogously to $\phi_r(g)$, as the amount of nuclide r passing point m during time interval ℓ given that the system is in geologic state g, multiplied by the probability of the system being in state g. The output in state g of a path leading from m' to m, $F_{r\ell mg}$, may then be calculated (assuming pathways do not branch at m') by summing over different states which the system could have been in when the waste entered the path segment:

$$F_{r\ell mg} = \sum_{\ell'} \sum_{g'} F_{r\ell' m' g'} \, G_{r\ell' \ell g'} \, \Psi_{\ell' \ell g' g}$$

$G_{r\ell\ell'g}$ is the proportion of an impulse of nuclide r which entered the path segment during interval ℓ' which would reach m during interval ℓ. $\Psi_{\ell'\ell g'g}$ is the conditional probability that the system is in state g during interval ℓ if it was in state g' during interval ℓ'.

This method has been used to study the effects of two types of geologic events: formation of breccia pipes and movement of faults. The states that were defined for these two cases are shown in Fig. 2.

Breccia pipes are formed by the collapse of overburden into a cavity formed by the dissolution of salt. Eventually a column of breccia extends upward, often reaching the surface. Although breccia pipes in evaporite basins have been observed to reseal, we have assumed conservatively that they remain open.

The primary effect of movement along a preexisting fault has been assumed to be an increase in permeability immediately before and after an earthquake due to stress in the fault. After the earthquake the fault reseals; however some residual permeability remains. The mean time to resealing has been assumed to be 70 years. Fault movement has been studied for a shale repository, since in a salt repository the plasticity of salt would presumably result in a much smaller permeability increase.

Both the shale and the salt repositories were assumed to have aquifers both above and below the mined cavity, with the lower aquifer under pressure. Flow proceeds from the repository to the upper aquifer through undisturbed rock, through a fracture zone resulting from construction of shafts and tunnels, and through the fault or breccia pipe.

The network of flow paths for State 1, in which fault movement or breccia pipe formation has not yet occurred, is shown in Fig. 3. The flow path network after either event is shown in Fig. 4. Values assumed for geologic parameters are listed in Tables 1 through 5. These values are believed to be typical of those likely to be found in repository sites (Holdsworth, 1977), but they do not represent any particular site.

The calculation of rates of occurrence for such unlikely events as fault movement in aseismic areas and breccia pipe formation is difficult given the current state of geologic knowledge. There is even an argument that such rates have no real meaning (de Marsily, 1977). However, assessments of the significance of these events are still possible by postulating different rates of occurrence. On the basis of order-of-magnitude arguments (Holdsworth, 1977), we first assumed both events occurred at a rate of 5×10^{-7} events/yr. In order to test the sensitivity of our results to this assumption, calculations were also made for a rate of 5×10^{-5} events/yr.

Rates of radionuclide release were converted into doses to humans by use of a model of environmental transport and human uptake (Koplik, 1978). Because the dose to any individual was very small compared to natural background radiation, the more appropriate measure of consequences for human health is the "population dose", which is the sum of the doses received by every individual in the population (Crump, 1976). In order to combine all effects, doses incurred from the present to three million years in the future were summed into a single total.

4. RESULTS

Doses to humans were calculated with the assumptions described above. The results are to be treated as illustrative calculations for the purpose of comparing different scenarios; they do not by themselves constitute an estimate of the risk actually to be expected from disposal of nuclear waste, and therefore units are omitted.

Results are presented in Table 6 for two deterministic cases in which breccia pipes were assumed to form after 100 and 10,000 years respectively, as well as probabilistic cases. These results indicate that if breccia pipes form rapidly (100 yr) there will be a noticeable increase in dose. Indeed, the dose would be much higher in this case were it not for the long time interval required for the waste to pass through the overlying aquifer to its discharge into surface waters (Ross, 1978).

However, for cases in which breccia pipes take longer to form (e.g., 10^4 yr), doses calculated are lower than for the case in which there is no breccia pipe. This is due to depressurization of the depository cavity by the breccia pipe. The program assumes that waste which has begun to flow through flow paths other than the rock which will collapse to form the breccia pipe continues in the same direction after the breccia has formed, but with a reduced velocity due to the changed hydraulic gradients.

When breccia pipe formation is treated probabilistically with formation rate of 5×10^{-7} per year, the expected population dose is almost identical to the case of no breccia pipe. When the rate of formation is increased, the effect is a reduction of dose due to the depressurization effect. We thus conclude that even for a very high rate of breccia pipe formation, there is not enough chance of occurrence in the early, dangerous period to cause a significant added risk from this event.

For fault movement, the results are similar, as shown in Table 7. Even if the rate of movement is as high as $5x10^{-5}$ per year, and faults remain in State 2 without resealing, there is no significant addition to expected population dose.

5. CONCLUSIONS

Prediction of radionuclide migration from waste repositories requires solution of a partial differential equation whose coefficients are random processes. We have developed a method of finding expectation values of the solutions of such equations, and used it to assess the contribution of breccia pipe formation and fault movement to the risk from waste disposal. The preliminary results, assuming no water wells are constructed in the repository areas, indicate these events add little to the overall risk.

The authors would like to thank John Huebel of Lawrence Livermore Laboratory, whose suggestions greatly increased the clarity and rigor of the proof. They would also like to express their appreciation to David Pentz and Robert Plum of Golder Associates, Inc., Bart Paulding and Peter Davies of Geotechnical Engineers, Inc., and Dana Isherwood and Donald F. Towse of Lawrence Livermore Laboratory, whose work in developing repository descriptions made possible the analysis reported in this paper.

REFERENCES

Crump, K.S., Hoel, D.G., Langley, C.H., and Peto, R., 1976, Fundamental Carcinogenic Processes and Their Implications for Low Dose Risk Assessment: Cancer Research, v. 36 p. 2973-2979.

de Marsily, G., Ledoux, E., Barbreau, A., and Margot, J., 1977, Nuclear Waste Disposal: Can the Geologist Guarantee Isolation: Science, v. 197, p. 519-527.

Holdsworth, T., Towse, D.F., Isherwood, D., Harvey, T., and Heckman, R.A., 1977, Site Suitability Criteria for Solidified High Level Waste Repositories, (Draft), Lawrence Livermore Laboratory.

Koplik, C.M., 1978, The Long-Term Potential Hazard of High Level Radioactive Waste, to be published.

Ross, B., and Koplik, C.M., 1978, A New Numerical Method for Solving the Solute Transport Equation, to be published.

Scheidegger, A.E., 1964, Statistical Hydrodynamics in Porous Media: Adv. Hydrosciences, v. 1, p. 161-181.

Schneider, K.J., and Platt, A.M. (ed.), 1974, High Level Radioactive Waste Management Alternatives; Battelle Pacific Northwest Laboratories, BNWL-1900.

U.S. Nuclear Regulatory Commission (USNRC), 1975, Reactor Safety Study, An Assessment of Accident Risks in the U.S. Commercial Nuclear Power Plants, WASH-1400.

Figure Table

TABLE 1

PARAMETERS DESCRIBING ALL CASES

PARAMETER	VALUE
Dissolution Rate of the Waste (yr^{-1})	10^{-4}
Time for Resaturation of Depository (yr)	100
Excess Hydraulic Head of Lower Aquifer (m)	60
Horizontal Hydraulic Gradient of Upper Aquifer	0.005

TABLE 2

PARAMETERS DESCRIBING SALT REPOSITORY BEFORE BRECCIA PIPE FORMATION

T-1551

PATHWAY	LENGTH (m)	CROSS SECTION (m^2)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
1st Segment of Tunnel Fracture Zone	1200	3300	10^{-3}	10^{-6}	1	50
2nd Segment of Tunnel Fracture Zone	440	198	10^{-3}	10^{-6}	1	50
Fracture Zone Around Shaft in Depository Layer	100	60	10^{-3}	10^{-6}	1	50
Fracture Zone Around Shaft in Shale Barrier Layer	200	5	10^{-3}	10^{-6}	1	50
Depository Layer	100	5×10^6	10^{-2}	10^{-9}	1	50
Barrier Layer	200	5×10^6	0.05	10^{-7}	1	50
Aquifer	1.6×10^4	4×10^5	0.1	10^{-4}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50

TABLE 3

PARAMETERS DESCRIBING SALT REPOSITORY WITH BRECCIA PIPE

T-1556

PATHWAY	LENGTH (m)	CROSS SECTION (m^2)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Change from Table 2:						
Depository Layer	100	4.9×10^6	10^{-2}	10^{-9}	1	50
Barrier Layer	200	4.9×10^6	0.05	10^{-7}	1	50
Add:						
Breccia Pipe	300	10^5	0.3	10^{-2}	1	50

*The probability of a breccia pipe formation is 5×10^{-7} per year.

TABLE 4

PARAMETERS DESCRIBING SHALE REPOSITORY BEFORE FAULT MOVEMENT

T-1550

PATHWAY	LENGTH (m)	CROSS SECTION (m^2)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
1st Segment of Tunnel Fracture Zone	1200	316	0.1	0.1	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
2nd Segment of Tunnel Fracture Zone	440	18.96	0.1	0.1	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Fracture Zone Around Shaft in Depository Layer	100	10	10^{-3}	10^{-4}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Fracture Zone Around Shaft in Shale Barrier Layer	200	5	10^{-3}	10^{-4}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Depository Layer	100	5×10^6	0.05	10^{-9}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Barrier Layer	200	5×10^6	0.05	10^{-7}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Aquifer	1.6×10^4	4×10^5	0.1	10^{-4}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50

TABLE 5

PARAMETERS DESCRIBING SHALE REPOSITORY AFTER FAULT MOVEMENT

T-1555

PATHWAY	LENGTH (m)	CROSS SECTION (m^2)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Change from Table 4:						
Depository Layer	100	4.9×10^6	0.05	10^{-8}	SAME	50
Barrier Layer	200	4.9×10^6	0.05	10^{-7}	SAME	50
Add:						
Fault Open in Barrier Layer	200	1×10^5	10^{-3}	10^{-4}	^{129}I, ^{99}Tc: 1 Other Fission Products: 10^2 Actinides: 10^4	50
Fault Resealed in Barrier Layer	200	1×10^5	10^{-3}	10^{-6}	SAME	50
Fault Open in Depository Layer	100	1×10^5	10^{-3}	10^{-5}	SAME	50
Fault Resealed in Depository Layer	100	1×10^5	10^{-3}	10^{-7}	SAME	50

TABLE 6

PREDICTED EXPECTATION VALUES OF POPULATION DOSE FOR BRECCIA PIPE CASES

TYPE OF ANALYSIS	ASSUMPTION	Dose*
Deterministic	Formation at t=100 yr	2.7×10^{-3}
Deterministic	Formation at t=10,000 yr	1.2×10^{-3}
Probabilistic	$\Gamma = 5\times10^{-7}$ per yr	1.6×10^{-3}
Probabilistic	$\Gamma = 5\times10^{-5}$ per yr	1.2×10^{-3}
Deterministic	No breccia pipe	1.6×10^{-3}

*Population dose integrated over a three million year repository lifetime.

TABLE 7

PREDICTED EXPECTATION VALUES OF POPULATION DOSE FOR FAULT MOVEMENT CASES

RATE OF OCCURRENCE (yr^{-1})	RESEALING	Dose*
5×10^{-7}	Yes	1.3×10^{-3}
5×10^{-5}	No	1.3×10^{-3}
Never	-	$1.3\ 10^{-3}$

*Population dose integrated over a three million year repository lifetime.

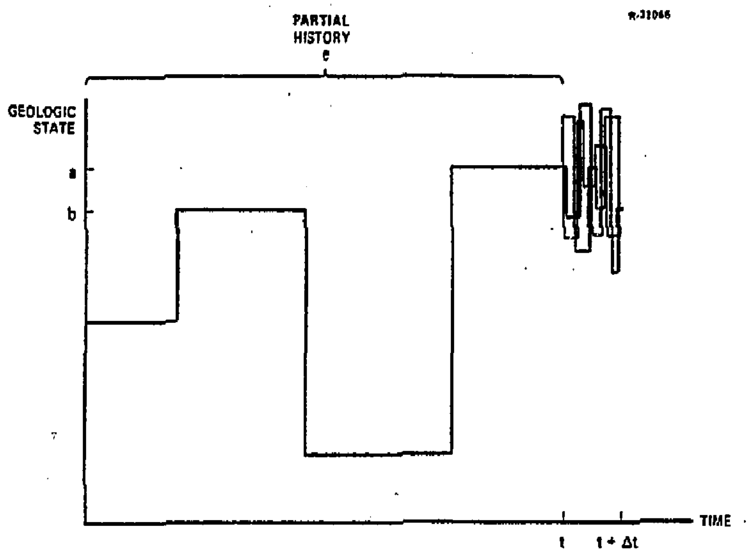

Figure 1 Schematic Representation of Some Partial Histories Belonging to the Subspace S^e_{ab}

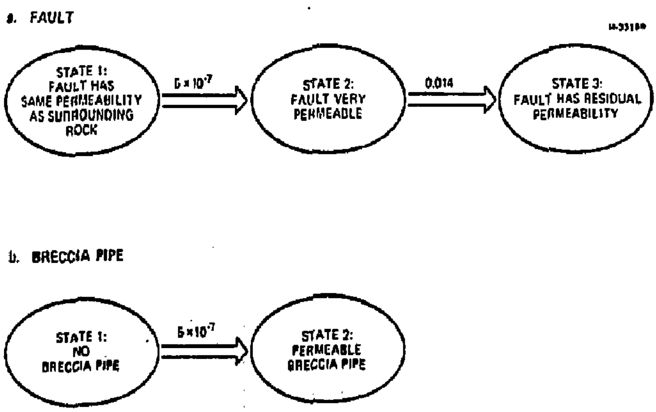

Figure 2 Assumed States and Baseline Transition Rates

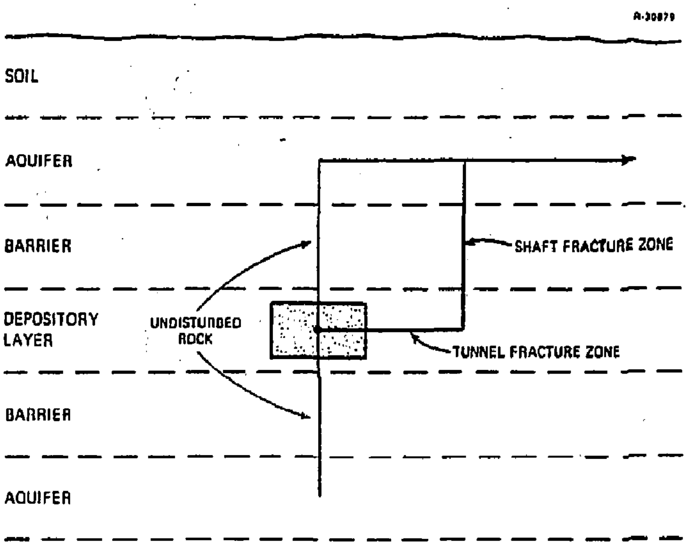

Figure 3 Flow Paths for Unflawed Repository

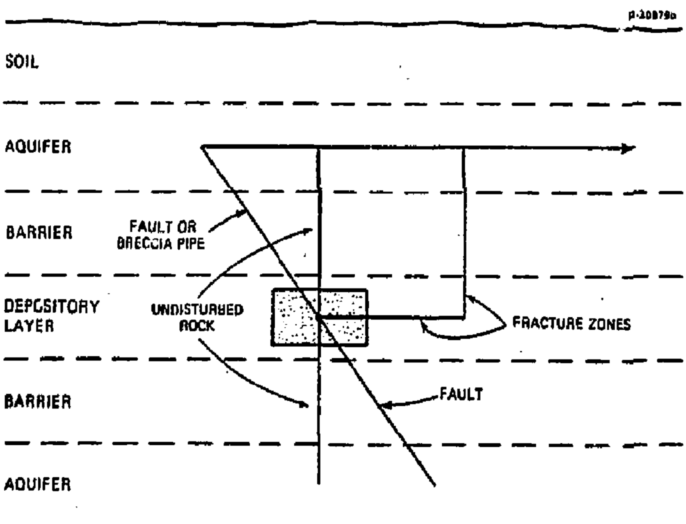

Figure 4 Flow Paths After Breccia Pipe
Formation or Fault Movement