AN INTEGRAL RISK ASSESSMENT MODEL FOR HAZARDOUS WASTES

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ABSTRACT

The Systems Analysis of Waste Burial (SAWB) model is a comprehensive analytical computer model of the movement and biological uptake of buried wastes. The model was developed to analyze the disposal of low-level radioactive wastes. SAWB has been adapted to the modeling of hazardous waste burial by the use of analogy. The model calculates the concentration and the total amount of contaminant at the surface and underlying aquifer as a function of sixteen or more parameters. The waste movement mechanisms are groundwater movement, dispersion in groundwater, diffusion, erosion and waste disturbance by man. The pathways are; drinking of well water, consumption of vegetables, meat and milk from irrigated or nonirrigated land, and the inhalation of contaminated dust. When the model is used for radioactive wastes, direct gamma radiation exposures and inhalation of radon are also included. SAWB is used to perform sensitivity analyses, calculate allowable concentrations for buried wastes and to calculate the integrated biological hazard (dose) for a single waste or a mixture of wastes. SAWB is based on closely coupled analytical solutions to heat transfer in solids and electrical impedance problems and can be readily modified to accommodate a wide variety of burial configurations and address a multitude of questions. The results for a nominal disposal system and four representative wastes are discussed. The response of the disposal system to incremental changes in parameters are provided.

INTRODUCTION

There are many nontechnical reasons for treating the disposal of radioactive wastes and other hazardous wastes as separate problems. However, from a technical viewpoint, the disposal of radioactive wastes is simply a special case of hazardous waste disposal. The analogy between the disposal of radioactive wastes and hazardous wastes is very strong. The principal technical differences between the disposal of the two wastes is the ability to measure and mathematically describe the properties of the wastes. There are less than twenty-six radioactive isotopes which are commonly found in radioactive wastes and which pose a potential hazard after disposal. The presence of these isotopes are comparatively easy to detect and their physical, chemical and biological properties are well known. In comparison, the list of potential nonradioactive hazardous wastes is extensive and only a fraction of the wastes have been identified. The properties of many of these waste have not been established.

In the past few years the analyses of radioactive waste disposal has changed greatly. This change is not the result of new understandings of the properties of the waste, but rather, an improved understanding of waste disposal itself. For example, past radioactive waste disposal analyses were based exclusively on the contamination of water supplies and water used for such purposes as irrigation.[1] More recent analyses has focused on the more direct pathways, particularly those which could occur on (or near) the disposal site after control of the site has been relinquished.[2,3,4] This concern for potential on-site exposures is reflected in a recent proposed regulation.[5] Likewise, new understandings are being gained as to the importance of such factors as container life, leach rates, length of site control and the time over which the calculations are performed. These improved analyses have been possible because of the rigorous mathematical manner in which radioactive waste disposal can be modeled. Since there is a strong analogy between radioactive waste disposal and hazardous waste disposal the modeling techniques used for radioactive waste can also be applied to hazardous waste. These modeling techniques can provide important insights into hazardous waste disposal even though, because of the lack of well defined parameters, they can not yet be used to predict in an accurate manner the consequences of hazardous waste disposal. The following discussion will illustrate the use of one such model, System Analyses of Waste Burial (SAWB).

ANALOGIES BETWEEN RADIOACTIVE AND HAZARDOUS WASTES

For nearly every parameter used in radioactive waste disposal modeling there is an analogy which applies to nonradioactive hazardous wastes. The list of analogies which follows is not complete but is sufficient to illustrate the use of such analogies.

Radioactive Decay

By definition, radioactive wastes decay. The rate at which the radioactive atoms decay is proportional to its decay constant. While some hazardous wastes are stable (e.g., metallic lead) others are not (e.g., organic compounds). Stable materials can be modeled by assigning them a zero decay constant. Materials which decay from one form to another can be modeled by assigning them a decay constant or half-life which represents the best estimate of the rate at which they will decay. (Half-life = ln(2)/decay constant.) While radioactive decay constants are not effected by the physical and chemical environment, the decay constants which would be used for hazardous wastes do depend on the external environment. Decay constants for use with hazardous wastes may have to be developed for different environments.

Radioactive Decay Chains

Some radioactive isotopes decay to radioactive daughters. The radioactive decay of some isotopes result in a long chain of radioactive daughters. The physical properties, such as, toxicity and mobility, of these decay chains change with time. Likewise, chemical compounds, with time, can change from one form to another. As the parent compounds and their daughters go through a chain of chemical reactions, the physical and chemical properties will change. Thus, the toxicity and mobility of a chemical compound and its daughters may change with time. The same mathematical techniques used to model radioactive decay chains can also be used to model chemical reaction chains.

Dose Conversion Factors

Most modeling of radioactive waste disposal uses dose conversion factors which relate the amount of material ingested or inhaled to a radiological dose. Dose conversion factors provide the bases for estimating biological response. The units of the dose conversion factor are: unit of exposure/unit of intake (e.g., mrem/pCi ingested). The "Dose Unit" (DU) is suggest here as an analogous measure. The DU is defined as the greatest amount of a given material, which, if ingested or inhaled annually will produce a stochastic response. That is, a DU is the largest annual dose of a material which if ingested or inhaled for many years will not produce a statistically significant biological response. (The ingestion DU and the inhalation DU for the same substance will be different. For the illustrative analysis which follows, no distinction was made between the ingestion and the inhalation DU.)

Current regulatory standards may not provide good bases for DU's since many of these standards are based on achievable levels (for the purpose of the regulation) and are not consistent, objective measures of toxicity. Possibly a good starting point for developing the DU's is to review the literature which documents industrial workers' response to various materials.

Integrated Biological Response

The modeling of radioactive disposal is customarily intended to deal with chronic, low-level exposures. At these exposure levels, it is generally assumed that the response to variations in exposure levels is linear and that the response to multiple exposures is accumulative. With this formulation, as long as the exposure to any individual is stochastic (e.g., does not exceed 5 rem/yr) it is the total exposure to the entire population which is important and not the exposure to any one individual. Recent literature[6] indicates that the same questions which apply to the evaluation of the biological response to radiation also apply to the evaluation of biological response to hazardous materials. Specifically, if the exposure level is stochastic, the relationship between dose levels and duration of exposure to the biological response is poorly understood. Thus, provided no one individual received more than one DU/yr exposure, the use of the linear response as used with radiation exposure seems reasonable. That is, the total exposure of a population, measured in DU's, is a reasonable predictor of the total integrated biological response.

Retardation

Retardation is the ratio of the velocity of groundwater to the velocity of a contaminant in that groundwater. (Retardation is distinct from K_d which is a measure of sorption. Sorption is one of many phenomena which contribute to retardation.) Retardation is not a true constant, but rather is a function of many parameters, including time. Because of the difficulty in determining the dependency of retardation on other parameters, it is normally assigned a single value. Since retardation does not depend on the radiological properties of wastes, the treatment of retardation should be the same for both radioactive and non-radioactive wastes. However, the chemical forms of radioactive wastes are not as diverse as those of hazardous wastes and the evaluation of the retardation of radioactive wastes may be a simpler task. There are listings of retardation factors for various elements in various soils.[4,7] For many wastes it may be necessary to approximate their mobility. For example, the movement of many organic compounds may have a retardation close to that of carbon (which readily forms compounds).

Biological Uptake

Biological uptake includes the bioaccumulation in plants, meat and milk, and the contamination of air and water. Biological uptake also includes the rates at which man consumes air, water, plants, meat and milk. (The uptake of wastes through the consumption of fish and poultry may also be included.) For radioactive waste there is also direct exposure to gamma radiation. This direct exposure may have an analogy in hazardous waste in exposure through skin contact. These various uptake factors have been evaluated for various elements.[8] Like retardation, the available values are for elements and not compounds. Some judgment is required to compare the uptake of elements to the uptake of compounds.

Other Parameters

There are many other parameters which are used in the modeling of waste disposal (e.g., package life and leach rates). However these parameters are much the same regardless of whether radioactive or hazardous waste disposal is being modeled.

THE SAWB MODEL

The System Analysis of Waste Burial model (SAWB) is not a single model but a modeling framework upon which many modeling components can be arranged. As the need to answer new questions arise, new components are developed and some old components may be discarded. The flexibility of SAWB derives from the use of analytical solutions of heat transfer and electrical impedance equations which can be closely coupled.

SAWB is the continuation of the modeling of intermediate depth burial at arid sites.[9] The question which was being addressed at that time was how thick should the cover be for intermediate depth burial. Previous work had shown that if a thick cover were used, considerably higher concentrations of wastes could be safely buried.[2,3] The question of how thick such a cover should be had not been addressed through modeling. An important consideration was, the thicker the cover, the closer to the aquifer the wastes would be and the greater the contamination of the aquifer.

Because the sites being considered were arid, normal hydrological modeling would be difficult. To address the trade-off of thickness of cover vs. thickness of soil between the waste and aquifer, an electrical impedance model was used. The impedance per meter of soil was assumed to be the same for both the cover and the soil under the wastes. An impedance was assigned to the uptake at the surface (breathing of contaminated dust and consumption of food grown on site) and the aquifer (drinking of well water). A low-level radioactive waste source term was representative as an electrical charge. By varying the thickness of the cover, it was possible to determine a thickness of cover such that the current through the surface pathways was the same as that for the well water pathway. This model used the same starting partial differential equation as had been used for other models.[2,3,6] The major difference between SAWB and these other models is the use of an infinite distorted medium as the boundary condition. The use of such boundary conditions provides for flexibility.

New questions were asked, and new features were added to the model.[5] For example, one question was: how much waste could be buried at various depths of burial? The question was no longer that of optimizing the thickness of cover, but actually stating what amount of a waste could be safely buried. To answer this question, new considerations were introduced. What if, over the time of consideration, the hydrologic conditions at the site would change or someone drilled into the waste while seeking water or other resources? To address these new factors, bulk movement of waste by groundwater movement and the drilling scenario were added. Bulk movement of wastes was incorporated by using a moving source term. The drilling scenario was accommodated by using a high impedance shunt directly to the surface. The model has continued to evolve and new features have been added. Examples of the new features are, accommodation of heat generating wastes, calculation of concentrations at the surface and aquifer as a function of time, and the calculation of total population exposures.

SAWB PARAMETERS

Vertical Ground Water Velocity, Dispersion and Diffusion

The usual period of concern used for the calculations is ten thousand years. The calculational period is normally limited to ten thousand years, since longer periods of time are likely to involve events which will disrupt the disposal site, such as, an ice age. Over such a length of time, the hydrologic conditions at a given disposal site can not be predicted with certitude. Therefore, four different vertical groundwater velocities are used which range from five meters per year (humid site) to no groundwater movement (arid site). There is always diffusive movement (random molecular movement). There is also dispersion due to "agitation" caused by ground water movement through a porous medium. The dispersion is proportional to the groundwater velocity. Hence, for the arid site there is no dispersion.

Package Life and Leach Rate

The package life refers to the time during which the package integrity is maintained and no waste is released from the container. The leach rate refers to the rate at which the waste is released from the package after the package fails. SAWB is unique in that it does not use a leach constant. The rate at which the waste is leached from the container is dependent upon the concentration gradient both inside and outside of the package.

Erosion Rate and Drilling Rate

The rate at which the waste arrives at the surface can be effected by the rate at which the cover over the waste is eroded and the rate at which the waste is disturbed by man. Erosion is treated as a uniform rate. Disturbance by man is simulated by the drilling scenario in which it is assumed that the rate of disturbance is inversely proportional to the depth of the wastes. Wastes which, because of bulk groundwater movement, dispersion and diffusion, have moved below the depth of the drilling are not available to the drilling scenario.

Administrative Control and Buffer Zone

For many wastes, the toxicity decreases with time. Administrative control of the disposal site can decrease the potential impacts of waste disposal by prohibiting man's access to disposal sites for a period of time. The effectiveness of the administrative control may depend on the amount of land (buffer zone) immediately outside the disposal area which is also under administrative control.

Perforated Well Casing Length

Waste reaching the aquifer will be diluted by the water flowing through the aquifer. The degree of this dilution will depend on the length of the perforated well casing and the flow rate of the aquifer. If the casing is long, then the amount of uncontaminated aquifer water entering the well will be large and the concentration of the contaminants in the well water will be lower.

Irrigation and Mass Conservation

The concentration of the contaminant at the surface can be increased by using well water from the aquifer below the site to irrigate the site. The irrigation scenario is treated as one pass irrigation since it is considered highly unlikely that the same water could pass through the same small horizontal cross section more than once. The waste which moves in the aquifer away from the site is accounted for by "mass conservation". The waste which escapes down the aquifer is assumed to be distributed in the biosphere in the same manner as that waste which remains at the site. Waste included in the mass conservation fraction are not added to the concentrations on site. Thus the use of mass conservations does not add to the maximum concentrations upon which the Surface Area Inventory Limits (SAIL) are based. The mass conservation fraction is accounted for when calculating accumulated exposures.

ILLUSTRATIVE ANALYSIS

The following illustrate analysis demonstrates the utility of models such as SAWB in the analyses of hazardous waste disposal. For this demonstration SAWB was used to calculate Surface Inventory Limits (SAIL), population exposures and to perform a sensitivity analysis.

SAWB is used to perform sensitivity analyses by calculating the partial differentials of the outputs with respect to the inputs. That is, SAWB calculates the sensitivity of the results to the various input parameters. Such a sensitivity analysis points to those parameters which most greatly influence the results. With this information it is possible to identify those parameters which can be improved with the greatest resulting advantage.

Table I lists the base line parameters which were used. The partial differentials of four different performance measures with respect to these parameters were calculated and are shown in Tables III through VI. Also included in those tables are the changes in the performance measures when "irrigation" and "mass conservation" are not included. (As used here, performance measure means some calculated output which reflects the ability of a disposal system to mitigate the environmental impacts resulting from buried wastes.)

Table II shows the base line performance measurements which were calculated. Four different wastes (Type A through D) were used. The SAIL values are based on peak exposure rates while the population dosage is based on average (over 10,000 years) exposure rates. The time at which the peak exposure rates would occur are also shown along with the SAIL's. Table II is read as follows:

> The Humid SAIL times the surface area of the site (in square meters) is that amount of wastes, measured in Dose Units (DU), which could be buried in a humid disposal site, with a

TABLE I

BASE LINE PARAMETRIC VALUES

Thickness of Cover Over The Wastes	5.0 m
Distance from Waste to Aquifer	5.0 m
Buffer Zone (during Administrative Control)	200.0 m
Dispersion (groundwater velocity dependent)	20.0 m
Diffusion (groundwater velocity independent)	0.1 m^2/yr
Duration of Administrative Control	100.0 yrs
Waste Package Life	100.0 yrs
Retardation Modifier	1.0
Leach Rate Modifier	1.0
Calculational Period	10000.0 yrs
Cover Erosion Rate	0.001 m/yr
Drilling Rate (divided by the depth to waste)	0.00001 m^2/yr
Perforated Well Casing Length	5.0 m

TABLE II

BASE LINE PERFORMANCE MEASUREMENTS

Waste Type[a]	Humid SAIL[b]	Arid SAIL[c]	Population Dosage[d]
	(DU/m^2)	(DU/m^2)	(DU/p/km^2)
A	1.1×10^3/101[e]	6.8×10^3/105	3.3×10^{-8}
B	9.5×10^4/120	1.2×10^9/140	2.5×10^{-11}
C	2.2×10^4/10000[f]	4.0×10^4/10000[f]	5.0×10^{-7}
D	3.0×10^3/101	4.2×10^3/890	1.8×10^{-6}

DU (Dose Unit) is the measure of the amount of a wastes which is deemed to be the maximum acceptable annual uptake (ingestion or inhalation) by a single individual.

SAIL (Surface Area Inventory Limit) is the limit on the amount of waste (DU's) which can be buried per square meter of disposal facility surface, such that, the exposure of any individual will not exceed one DU.

[a] Waste Type A decays 99% in 100 years, has a retardation of 1 and the biological uptake of water.

Waste Type B decays 90% in 100 years, has a retardation of 100 and the biological uptake of calcium.

Waste Type C does not decay, has a retardation of 10,000 and the biological uptake of a heavy metal.

Waste Type D is an arbitrary mixture of 25 separate wastes.

[b] Humid SAIL is based on the movement of waste by bulk groundwater movement, dispersion, diffusion and drilling activities.

[c] Arid Sail is based on the movement of waste by diffusion and drilling activities.

[d] Population Dosage is the total exposure to a population over 10,000 years, measured in DU exposure per DU buried per person per square kilometer.

[e] Years after burial at which the maximum exposure rate occurs.

[f] Constrained by the calculational period of 10,000 years.

TABLE III

Performance Measurement Differentials for a 15 year half-life, high mobility waste with a biological accumulation similar to water.

NORMALIZED PARTIAL DIFFERENTIALS - WASTE TYPE A

Variable	Humid SAIL	Arid SAIL	Pop Dosage	Geo-Mean
Admin Control	34.0	0.0002	1.9	6.0
Mass Conservation[a]	-	-	-5.8	-5.9
Package Life	5.4	5.3	3.4	5.4
Irrigation[a]	-6.2	-0.86	-3.0	-3.8
Cover Thickness	0.15	2.8	0.42	0.91
Aquifer Depth	0.20	0.70	0.89	0.70
Diffusion	0.0002	-1.17	-0.28	-0.44
Leach Rate	-0.18	-0.097	-0.19	-0.16
Well Casing Length[b]	0.050	0.93	0.067	0.070
Erosion Rate	-0.0049	-0.084	-0.028	-0.036
Dispersion	0.20	-	-0.035	0.031
Drilling Rate[b]	0.0000	0.0010	0.0000	0.0000
Buffer Zone[c]	-	-	-	-
Retardation	0.0000	0.0000	0.0000	0.0000
Years[b]	0.0000	0.0000	0.0000	0.0000

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[a] Step function rather than a differential and not a controllable parameter.

[b] Not a controllable parameter.

[c] May be an inportant parameter if the system fails to perform as expected (e.g., early package failure).

TABLE IV

Performance Measurement Differentials for a 30 year half-life, moderate mobility waste with a biological accumulation similar to calcium.

NORMALIZED PARTIAL DIFFERENTIALS - WASTE TYPE B

Variable	Humid SAIL	Arid SAIL	Pop Dosage	Geo-Mean
Cover Thickness	0.27	2.0	1.7	1.6
Package Life	2.48	-0.018	1.5	1.5
Years[b]	0.000	0.0000	0.0000	0.0000
Admin Control	0.0001	2.4	0.60	0.89
Retardation	0.50	0.0000	0.98	0.66
Aquifer Depth	0.81	0.0000	0.63	0.54
Mass Conservation[a]	-	-	-0.96	-0.52
Dispersion	-0.18	-	0.84	-0.44
Drilling Rate[b]	0.0000	-0.84	-0.23	-0.33
Well Casing Length[b]	0.18	0.0000	0.082	0.086
Erosion Rate	-0.017	-0.053	-0.12	-0.076
Diffusion	-0.0002	0.0000	-0.066	-0.033
Leach Rate	-0.0250	0.0000	-0.013	-0.0130
Irrigation[a]	-0.026	0.0000	-0.014	-0.013
Buffer Zone[c]	-	-	-	-

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[a] Step function rather than a differential and not a controllable parameter.

[b] Not a controllable parameter.

[c] May be an inportant parameter if the system fails to perform as expected (e.g., early package failure).

TABLE V

Performance Measurement Differentials for a stable, low mobility waste with a biological accumulation similar to most heavy metals.

NORMALIZED PARTIAL DIFFERENTIALS - WASTE TYPE C

Variable	Humid SAIL	Arid SAIL	Pop Dosage	Geo-Mean
Years[b]	0.0000	-3.5	-4.7	-1.8
Mass Conservation[a]	-	-	-1.5	-0.85
Diffusion	0.0003	-1.3	-0.27	-0.46
Cover Thickness	0.61	0.0000	0.43	0.37
Retardation	-0.35	1.3	0.21	0.32
Drilling Rate[b]	-0.10	-0.52	-0.21	-0.26
Aquifer Depth	0.038	0.0000	0.31	0.17
Erosion Rate	-0.20	0.0000	-0.19	-0.14
Dispersion	0.29	-	0.0072	0.068
Package Life	-0.0026	-0.0070	-0.0097	-0.0072
Admin Control	0.0026	0.0070	0.0037	0.0042
Well Casing Length[b]	0.0093	0.0000	0.0024	0.0035
Leach Rate	-0.0009	-0.0021	-0.0024	-0.002
Irrigation[a]	0.0003	0.0000	-0.0001	0.0001
Buffer Zone[c]	-	-	-	-

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[a] Step function rather than a differential and not a controllable parameter.

[b] Not a controllable parameter.

[c] May be an inportant parameter if the system fails to perform as expected (e.g., early package failure).

Performance Measurement Differentials for an arbitrary mix of wastes.

NORMALIZED PARTIAL DIFFERENTIALS - WASTE TYPE D

Variable	Humid SAIL	Arid SAIL	Pop Dosage	Geo-Mean
Mass Conservation[a]	-	-	-8.6	-26.0
Admin Control	13.0	0.0001	0.015	2.3
Irrigation[a]	-4.1	-0.26	-0.52	-1.3
Package Life	3.6	0.56	0.018	0.96
Aquifer Depth	0.18	0.15	0.89	0.56
Years[b]	0.0000	-0.0006	-1.58	0.34
Cover Thickness	0.26	1.09	-0.45	0.3
Drilling Rate[b]	0.0000	-0.0006	-0.27	-0.13
Erosion Rate	-0.0084	-0.19	-0.12	-0.11
Leach Rate	-0.17	-0.025	-0.080	-0.089
Diffusion	0.0001	-0.16	-0.19	-0.049
Dispersion	0.14	-	-0.12	-0.025
Well Casing Length[b]	0.045	0.026	0.0037	0.020
Retardation	0.0010	-0.085	0.040	-0.0013
Buffer Zone[c]	-	-	-	-

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[a] Step function rather than a differential and not a controllable parameter.

[b] Not a controllable parameter.

[c] May be an inportant parameter if the system fails to perform as expected (e.g., early package failure).

high degree of assurance that no individual would receive more than one DU per year.

The Arid SAIL is for the case when there is no net vertical groundwater movement.

The Population Dosage is based on a combination of humid and arid conditions. This value, when multiplied by the amount of waste buried and by the population density (persons per square kilometer) is the total exposure of the population in ten thousand years. Both the amount of waste buried and the exposures are measured in DU's. (Because of the difficulty in predicting hydrological conditions over 10,000 years the average of arid and humid conditions was used for the illustration.)

Tables III through VI show the normalized partial differentails. To calculate the absolute differential, the normalized differential is multiplied by base line SAIL or divided by the Population Dosage from Table II as appropriate. It is important to recall that these differentials are calculated using a given base line. The use of another base line can result in significantly different results.

Table II shows that for the base line case analyzed, the Humid SAIL can vary by at least two orders of magnitude, depending on the decay rate of the wastes and their mobility. The Arid SAIL can vary by more than five orders of magnitude. Still, it is interesting to note that for only one of the wastes (Type B) is there a great difference between the Humid and Arid SAIL's.

Using Tables III through V (differentials for Waste Types A, B, and C) it is difficult to draw clear conclusions as to which parameters are generally the most important. Since Table VI is for a mixture of wastes (Waste Type D) it provides a better indication of which parameters are important for the base line disposal configuration. Of the controllable parameters, Administrative Control, Package Life, Aquifer Depth and Cover Thickness have the greatest impact on the performance of the disposal system. Retardation, Dispersion, Diffusion and Leach Rate are the least important parameters. Again, it is important to remember that this ordering of parameters is based on a given base line configuration and mixture of wastes. If different base line parameters were used or a different source term were used, then significantly different results could result.

To help understand the importance of treating waste disposal as a system, consider the differential for the Buffer Zone. Tables III through VI show no response to changes in the size of the buffer zone. This is the result of the buffer zone not being maintained any longer than the period of administrative control and the package life being equal to the period of administrative control. Thus, during the period in which the buffer zone was maintained, there were no wastes available for movement in the biosphere. Table VII shows results which were obtained as a

TABLE VII

PERFORMANCE MEASUREMENTS AS A FUNCTION OF BUFFER ZONE SIZE[e]

BUFFER ZONE = 200 METERS / (BUFFER ZONE = 30 METERS)

Waste Type[a]	Humid SAIL[b] (DU/m^2)	Arid SAIL[c] (DU/m^2)	Population Dosage[d] (DU/p/km^2)
A	4.7×10^{1} (2.2×10^{1})	6.5×10^{2} (6.5×10^{2})	3.0×10^{-7} (8.0×10^{-7})
B	5.0×10^{4} (3.8×10^{4})	1.3×10^{9} (1.3×10^{9})	8.0×10^{-11} (9.0×10^{-11})
C	2.2×10^{4} (2.2×10^{4})	4.0×10^{4} (4.0×10^{4})	5.0×10^{-7} (5.0×10^{-7})
D	1.8×10^{2} (8.7×10^{1})	1.7×10^{3} (1.7×10^{3})	1.9×10^{-6} (2.0×10^{-6})

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[a] Waste Type A decays 99% in 100 years, has a retardation of 1 and the biological uptake of water.

Waste Type B decays 90% in 100 years, has a retardation of 100 and the biological uptake of calcium.

Waste Type C does not decay, has a retardation of 10,000 and the biological uptake of a heavy metal.

Waste Type D is an arbitrary mixture of 25 separate wastes.

[b] Humid SAIL is based on the movement of waste by bulk groundwater movement, dispersion, diffusion and drilling activities.

[c] Arid Sail is based on the movement of waste by diffusion and drilling activities.

[d] Population Dosage is the total exposure to a population over 10,000 years, measured in DU exposure per DU buried per person per square kilometer.

[e] Base line parameters are used execpt package life is zero and the buffer zones used are 200 and 30 meters.

function of the buffer zone size when the waste package life was set to zero. These results illustrate the importance of analyzing waste disposal as a system.

DISCUSSION

The disposal of radioactive waste is a special case of hazardous waste disposal. Because radioactive wastes are easily described in a qualitative manner, numerous mathematical models have been developed for the analyses of their disposal. Using the analogies described in this paper, it is possible to adapt many of these models for the analyses of the disposal of hazardous wastes. This is particularly true for models such as SAWB which use closely coupled analytical solutions. While models, such as SAWB, so adapted, can provide important insights into the nature of hazardous wastes disposal, it should not be expected that they can provide accurate predictive results. Before these models can be used in a true predictive mode, better definition of the parameters applying to hazardous wastes will be required.

Because SAWB is more a modeling framework rather than a model, the variety of possible applications of SAWB can not be briefly discussed. The simple illustration which has been given was intended to provide only a flavor of the possible uses of SAWB in analyzing the disposal of hazardous wastes.

One approach to using models such as SAWB to provide prompt useful results is to create a number of waste disposal categories based on a three dimensional matrix of waste decay constant, waste mobility, and waste uptake. This would be an expansion on Waste Types A, B, and C which were used in the illustrative analysis. The analyses of the disposal requirements for these various waste disposal categories could be conducted independently of which wastes would actually belong to any given category. As wastes are evaluated, they could be categorized as appropriate and the disposal requirements would have already been determined.

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