DEVELOPMENT OF A LOW-LEVEL WASTE RISK METHODOLOGY

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ABSTRACT

A probabilistic risk assessment method is presented for performance evaluation of low-level waste disposal facilities. The associated program package calculates the risk associated with postulated radionuclide release and transport scenarios. Risk is computed as the mathematical product of two statistical variables: the dose consequence of a given release scenario, and its occurrence probability. A sample risk calculation is included which demonstrates the method. This PRA method will facilitate evaluation of facility performance, including identification of high risk scenarios and their mitigation via optimization of site parameters. The method is a intended to be used in facility licensing as a demonstration of compliance with the performance objectives set forth in 10 CFR Part 61, or in corresponding state regulations. The Low-Level Waste Risk Methodology is being developed under sponsorship of the Nuclear Regulatory Commission.

BACKGROUND

In April 1982, the authors received funding from the Nuclear Regulatory Commission to create a computer program package for calculating the radiological risk associated with low-level waste disposal.[a] This computer program package has been called the Low-Level Waste (LLW) Risk Methodology. The methodology is a computational technique for calculating the probable dose commitment arising from hypothetical release scenarios at a near-surface disposal facility. In this technique, a mathematical model is used to calculate the consequence of the release scenario. An occurrence probability is assigned to each scenario to keep the relative likelihood of the consequences in perspective. Risk is then defined as the mathematical product of the occurrence probability and the consequence.

Development of the methodology[1] involved the conversion of an existing deterministic dose consequence model, System Analysis of Shallow Land Burial,[2] into the statistical version, BURYIT, and the adaptation of an existing uncertainty analysis program, ANALYZ,[3] to perform the probabilistic risk assessment (PRA) based on the results of BURYIT calculations and on the occurrence probability assigned to the release scenario.

Program Description

The program package for the LLW Risk Methodology quantifies radiological risk using two computer programs, named BURYIT and ANALYZ. BURYIT calculates the dose consequence resulting from radionuclide transport through six possible pathways. The pathways include air, soil (plant, animal uptake), groundwater, wind erosion, direct contact (puncture wounds), and direct radiation. Radionuclide release is modeled by selecting a release scenario and a waste inventory. BURYIT contains 302 release scenarios for the user to select from and has the capability for the user to add additional release scenarios. Release scenarios include operational events, such as ruptured containers and chronic occupational exposure, and post-closure events, such as intruders accessing the waste material and trench subsidence. Six waste inventories corresponding to institutional, industrial, and reactor waste streams are defined in terms of average specific activity of 44 radionuclides. The fraction of waste released to a pathway is specific to the release scenario and waste inventory selected.

ANALYZ is an uncertainty analysis package. It reads the responses from multiple BURYIT calculations (the BURYIT parameters are assumed to be random variables) and uses the response surface method of uncertainty analysis to calculate a statistical limit (or consequence level) for radiation exposure for a given release scenario.

ANALYZ then calculates the scenario risk using the statistical representations of the consequence level and the scenario occurrence probability. The method accounts for uncertainties in the inputs to BURYIT, in the BURYIT pathway models, and in the estimated occurrence probability.

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The output from the LLW Risk Methodology may be summarized as:

1. a sensitivity analysis yielding the rate of change of dose commitment with respect to a parameter change
2. the identification of those parameters contributing the most to the uncertainty in the response
3. tabulations and plots for the probability density function of dose commitment uncertainty
4. tabulations and plots for the probability density function of risk uncertainty.

METHODOLOGY DESCRIPTION

The LLW Risk Methodology is a PRA method which accounts for parameter uncertainties. The method is logically divided into two parts: the calculation of the dose commitment, or consequence, resulting from the occurrence of the postulated scenario, and the calculation of the risk, which is the product of the consequence and the scenario occurrence probability. Figure 1 is a diagram of the PRA method, illustrating the sequence of calculation. The two parts of the PRA method are explained in the following discussion.

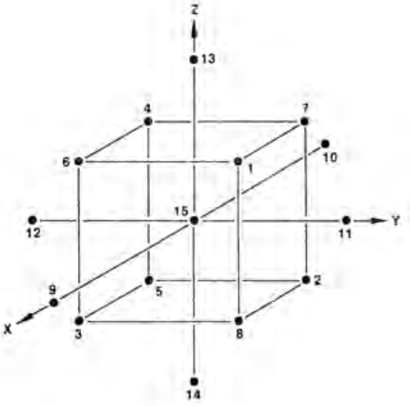
The method for obtaining the statistical representation of the scenario consequence is called the response surface method of uncertainty analysis. In this method, the dose consequence model is replaced by a polynomial response surface equation that approximates the dose consequence model response over the ranges of the uncertainties of the input variables. Statistical moments, calculated for the replacement equation, are then used to obtain the approximate probability density, or statistical distribution, of scenario consequence. The response surface method is outlined in the following steps and explained in the subsequent discussion:

- o identify the influential input and model parameters, and estimate the mean value and the uncertainty for each one
- o choose an experimental design and assign each parameter to a column of the design matrix
- o exercise the dose consequence model with the input and model parameters perturbed according to the design
- o fit the response surface equation (RSE) to the responses of the dose consequence model
- o calculate the statistical moments of the RSE
- o match a probability density function to the moments of the RSE.

The identification of influential parameters usually involves a sensitivity study, to pare the number of input and model parameters to those which actually influence dose commitment. A dose consequence model calculation is made with each candidate variable perturbed to its limiting value. These limiting values are usually taken to be three standard deviation above and below the nominal value ($\mu \pm 3\sigma$). Two runs are done for each candidate, one for each limiting value. These runs are called the star points of the design; star points for the influential variables are used for estimating the quadratic terms of the RSE.

An experimental design is a pattern, or schedule, for perturbing the input parameters in an efficient manner so that the coefficients of the RSE can be estimated in as few computer runs as possible. Figure 2 shows a sample experimental design for three parameters: x, y, and z. The linear runs are made

Runs	Variables X	Y	Z
1	1	1	1
2	−1	1	−1
3	1	−1	−1
4	−1	−1	1
5	−1	−1	−1
6	1	−1	1
7	−1	1	1
8	1	1	−1
9	S	0	0
10	−S	0	0
11	0	S	0
12	0	−S	0
13	0	0	S
14	0	0	S
15	0	0	0



NOTES:

1. Three input variables X, Y, and Z
2. Runs 1-8 are with variables perturbed simultaneously to 1 σ above or below nominal
3. Runs 9-14 are star points of the design. Variables are perturbed to S σ above or below nominal. Typically S = 3
4. Run 15 is with all variables at nominal values

Fig. 2. Experimental design for three input variables.

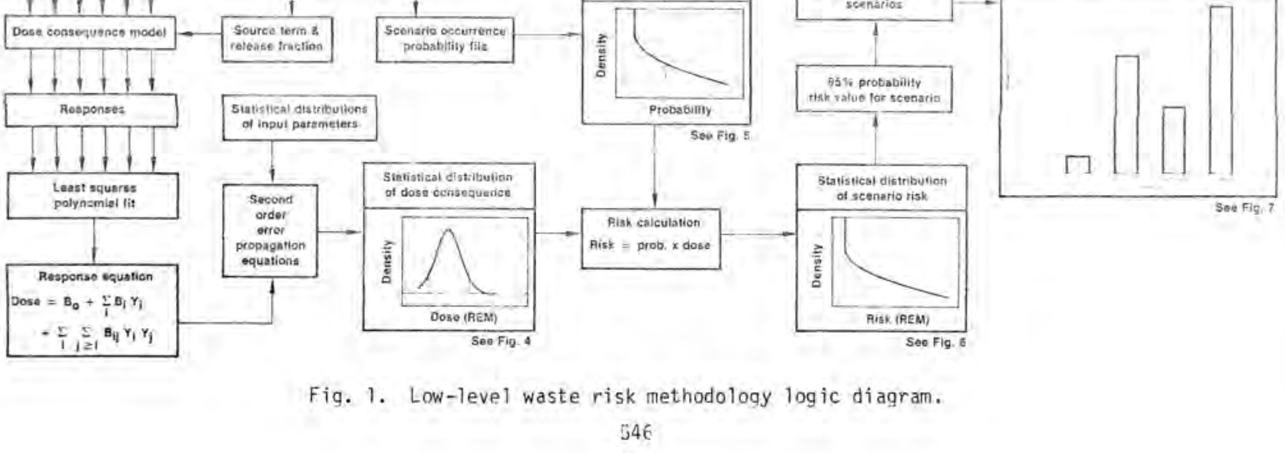


Fig. 1. Low-level waste risk methodology logic diagram.

with the parameters perturbed simultaneously to 1σ above or below nominal ($\mu \pm 1$), and are used to estimate the linear and two-factor, or interaction, terms of the RSE. The star points are obtained with the parameters perturbed individually, and are used to estimate curvature of the response surface. In its present form, BURYIT has the capability to perform all the runs required by an experimental design in a single step. The user specifies the variable parameters and their nominal and uncertainty values. The supervisory programming within BURYIT chooses the design, assigns the input parameters to the design in the user-specified order, calls the dose consequence model for each run of the design with the input parameters perturbed to their specified uncertainty values, and collects the dose commitment responses for all the runs. Figure 3 shows the operation of the supervisory program and the dose consequence model of BURYIT.

The dose commitment responses are fitted to a second-order polynomial equation, the RSE. This equation is equivalent to a second-order Taylor's series expansion about a base value, that is:

$$Y = b_o + \sum_i b_i x_i + \sum_i \sum_{j \geq i} b_{ij} x_i x_j \qquad (1)$$

where

Y = response variable (dose commitment)

x_i = i^{th} input variable, in standard form (i.e. μ=o, σ=1)

b_o = intercept coefficient

h_i = linear coefficient of the i^{th} input variable

b_{ii} = quadratic coefficient of the i^{th} input variable (i=j)

b_{ij} = interaction coefficient (i>j)

Rigorous second-order error propagation[4] is then used to estimate the lower four statistical moments of the response probability density. The method used solves the equations for the statistical moments of a Taylor's series expansion that is truncated after second-order terms. It produces exact estimates of the lower four moments of the RSE, which are then matched to those of a Pearson probability density function.[5] This approximate dose commitment probability density is then used to estimate the consequence of the scenario at a specified probability value. Usually the consequence is estimated at the 95% probability value; hence, 95% of all the possible combinations of input and model parameter values result in a dose commitment less than or equal to the consequence estimated at the 95% probability value. Conversely, less than 5% of all the possible input and model parameter combinations could result in a dose commitment which exceeds the estimated consequence.

The statistical method described above is implemented in the code ANALYZ. This program reads the responses calculated by BURYIT, performs the least-squares RSE fit in the subcode ANYOLS,[6] calculates the RSE statistical moments in the subcode SOERP,[4] and matches these moments to those of an appropriate distribution in the subcode PDFPLOT.[7] In addition, ANALYZ calculates the scenario risk, as described in the following section, and has the capability for plotting statistical distributions for consequence, occurrence probability, and risk; and for plotting a bar chart comparison of the risks calculated for all scenarios analyzed.

The risk associated with the scenario is the product of scenario consequence and scenario occurrence probability. Since the risk calculation again involves error propagation, the method for estimating the probability density of risk is similar to that of estimating the density of consequence. Again, the statistical moments are calculated for the Taylor's series expansion, which, for risk, is based on the following equation:

$$Y = X_1 \cdot X_2 \qquad (2)$$

where

Y = risk

X_1 = consequence

X_2 = occurrence probability

The coefficients of the Taylor's series are, in the notation of Equation 1:

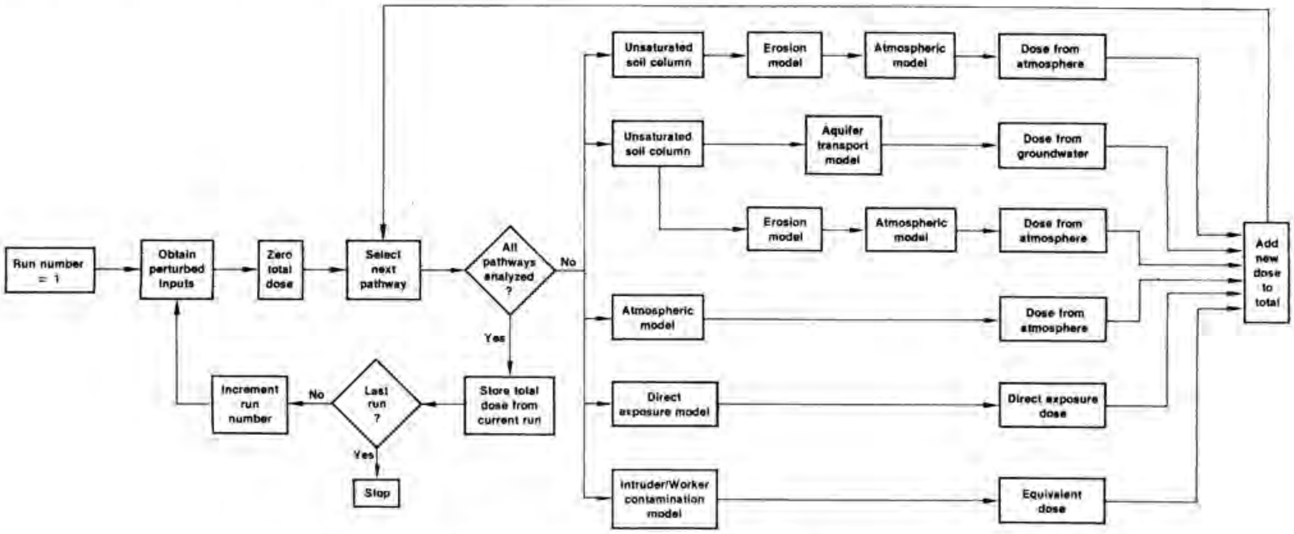


Fig. 3. Dose consequence model.

$b_0 = \mu_1 \cdot \mu_2$

$b_1 = \mu_2$

$b_2 = \mu_1$

$b_{12} = 1$

where

μ_1 = mean value of consequence

μ_2 = mean value of occurrence probability.

The risk statistical moments are matched to those of a Pearson density, as were the consequence RSE moments, and this density is used to estimate risk at a specified probability value. As shown in Fig. 7, the risk for the current scenario can be compared with the risks for previously analyzed scenarios, in bar chart format.

SAMPLE RISK CALCULATION

A sample risk calculation was done for a scenario involving the atmospheric pathway of the dose consequence model. Scenario 136 models large volume release of a high specific activity waste to the atmosphere. The radioactive cloud results in direct exposure dose (shine) and inhalation dose. The radioactive material transported by the cloud is also deposited on crops and grassland and thus into the human food chain. An ingestion dose results from consumption of crops, beef cattle, and milk. Table I is a list of influential parameters for the sample calculation.

TABLE I. INFLUENTIAL PARAMETERS IN SAMPLE PROBLEM

Input Parameter	Nominal Value	Uncertainty	Distribution Type
Weather frequency array	Average annual conditions	$+1\sigma$ – average summer conditions -1σ – average winter conditions	Normal
Release height	5 m	1.6 m	Normal
Annual rainfall	0.2 m/yr	0.02 m/yr	Normal
Breathing volume	Child: 8320 m^3/yr Teen: 12160 m^3/yr Adult: 10160 m^3/yr	1930 m^3/yr 3150 m^3/yr 2070 m^3/yr	Normal
Milk consumption	Child: 330 liters/yr Teen: 400 liters/yr Adult: 310 liters/yr	40 liters/yr 70 liters/yr 40 liters/yr	Normal
Meat consumption	Child: 65 kg/yr Teen: 140 kg/yr Adult: 210 kg/yr	6.5 kg/yr 14 kg/hr 21 kg/yr	Normal
Areal grass density	Median = 0.082 kg/m^2	Error factor = 2.6	Log normal
Crop deposition fraction	0.47	0.30	Normal
Plume model lack-of-fit	Calculated result from Gaussian Plume Rise Model	70%	Normal

The coefficients of the RSE are shown in Table II. The relative importance of each influential parameter is also listed in Table II. The important pathways for the source term used were the inhalation of resuspended Pu 242 (43% of the total dose) and the ingestion of beef cattle and milk from isotopes Cs 137 (29%) and Cs 134 (27%). Direct exposure from the cloud and direct inhalation of radioactive particles were very small, 10^{-5}% and 0.02%, respectively. As shown in Fig. 4, the mean and 95% probability values of dose consequence were 0.18 rem and 0.32 rem, respectively.

TABLE II. RESPONSE SURFACE EQUATION FOR SAMPLE PROBLEM

Parameter	Coefficient	Contribution to Response Variance (%)
Weather frequency	– 0.024	8.4
Release height	0.010	1.3
Annual rainfall	0.015	3.3
Breathing volume	0.010	1.4
Milk consumption	– 0.018	4.5
Meat consumption	0.008	0.9
Areal grass density	– 0.026	10.0
Crop deposition fraction	0.058	49.2
Plume model lack-of-fit	0.015	3.1
(Areal grass density) X (Crop deposition fraction)	– 0.024	8.0
(Milk consumption) X (Crop deposition fraction)	– 0.019	5.1
(Weather frequency) X (Crop deposition fraction)	– 0.012	2.2
(Milk consumption) X (Areal grass density)	0.012	2.1
$(\text{Breathing volume})^2$	0.004	0.4

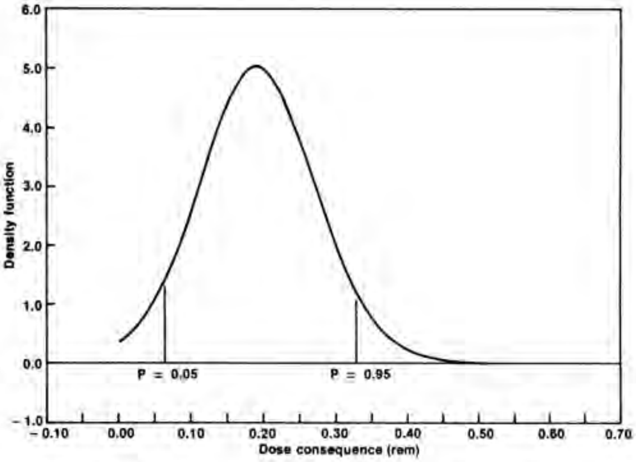


Fig. 4. Statistical distribution of scenario consequence.

Occurrence probability is taken as a log-normal variant with a median of 0.001 and an error factor of 5 (Fig. 5). The risk, resulting from the combination of consequence and occurrence probability, is 0.001 rem at the 95% probability value, as shown in Fig. 6. Figure 7 displays a sample comparison among the risks of Scenario 136 and three other hypothetical scenarios.

CONCLUSIONS

The LLW Risk Methodology is advantageous for disposal site development. The method allows users to directly calculate the radiological performance of proposed or existing near-surface disposal facilities. It produces a simple result: a single value per release scenario that is both conservative for and representative of the true hazard. With this simple

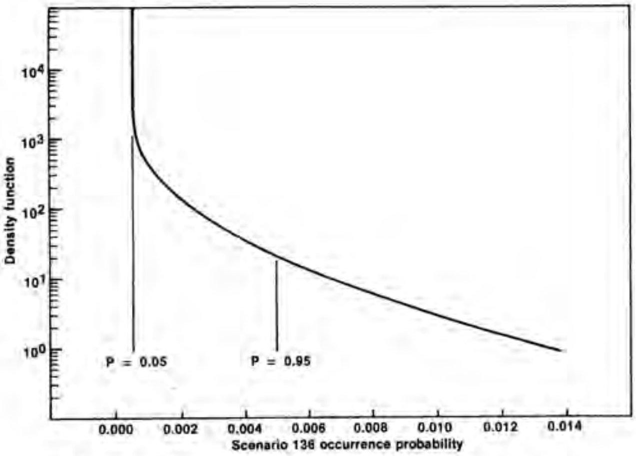


Fig. 5. Statistical distribution of scenario occurrence probability.

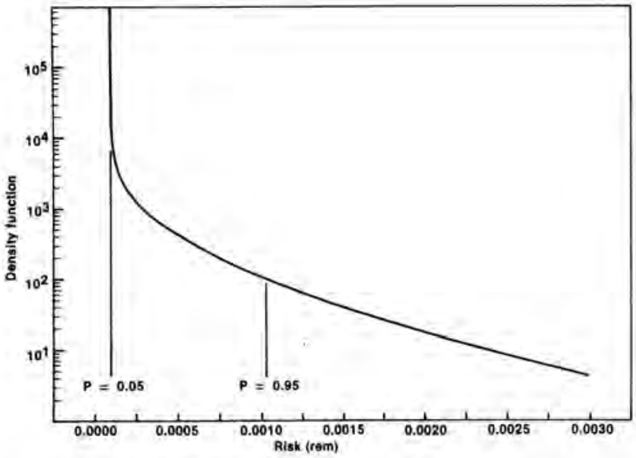


Fig. 6. Statistical distribution of scenario risk.

representation, the high risk scenarios can be readily identified. Detailed examination of these scenarios will permit the identification of influential parameters. Facility location, design, operations, waste inventory, and closure can then be optimized.

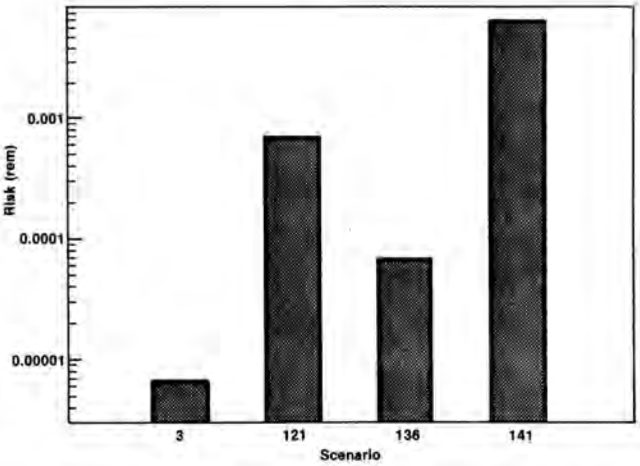


Fig. 7. Comparison of risks of sample scenarios.

Additionally, the evaluation can be used to establish monitoring requirements to ensure satisfactory radiological performance over the lifetime of the facility. The risk assessment method is intended for use in facility licensing as a demonstration of compliance with the performance objectives set forth in 10 CFR Part 61, or in corresponding state regulations.

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