PROBABILITY OF INTRUSION EVENTS AT RADIOACTIVE WASTE DISPOSAL FACILITIES

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ABSTRACT

A probabilistic model and data set are established to estimate radiation risks to future land reclaimers groups (CPG) from radioactive low level waste (LLW) sites following cessation of surveillance and institutional control. These radiation risks are defined as the product of the consequence dose and the probability of occurrence of the exposure event to the reclaimer group.

For radiological risk assessment the probability that at least one or more radiological events will occur is of primary interest. The entire event space in which radiological events can transpire has dependence in both space and time. The spatial distribution function is associated with the selection of land area sites for various uses (e.g., residencies, farms, grazing land, etc.). The temporal distribution function is associated with the time interval in which the event might occur. Although low level radioactive waste is stored in various locations through the world, focus is made upon the LLW sites at the Idaho National Engineering Laboratory (INEL) and the Savannah River Plant (SRP).

The major land use fractions for principal pathways by which future reclaimers might be exposed to radiation for the LLW sites at INEL and SRP are determined. Data are given for the U.S., the appropriate agricultural regions and the states hosting these two sites and future projections of land use fractions are made for the INEL and SRP sites. Changes of land use over the past 24 years (1959 to 1982) are determined to assess future trends. The probable occurrence of at least one radiological exposure event is tabulated for cropland, pasture and residency at the INEL and SRP sites following loss of site control. Cropland siting at the INEL and SRP sites approaches unity within 5000 years. Pasture and grazing use approaches unity within 1000 years at INEL and 10,000 years at SRP. Residency use at both sites approaches unit only after about 100,000 years or more.

INTRODUCTION

The purpose of this study is to develop a satisfactory probabilistic exposure model with a data set to estimate the expected doses that uncontrolled reclaimers might receive from LLW disposal sites in the future. An arid site and humid site are selected as examples of the methodology. Site specific data for the U.S. Idaho National Engineering Laboratory (INEL-the arid site) and the Savannah River Plant (SRP-the humid site) are used as examples.

THEORY AND PROBABILISTIC MODEL

Let p_i be the probability that a given intrusion event, e_i, with radiological consequences (viz., external exposure, inhalation, or ingestion) will occur in the time interval T_i. Assume that a sequential series of time periods, T_1, T_2, ..., T_n, occurs and the radiological event probabilities within each time interval are independent of the outcome or occurrence of events in other time periods. Then the probability distribution function for n sequential time periods is given be the multinomial distribution function M(e,p,n)

$$M(e,p,n) = \prod_{i=1}^{n} (q_i + p_i) = 1 \quad (1)$$

where

q_i = $1 - p_i$

p_i = the probability of occurrence of the radiological event e_i during the time period T_i

The term M(e,p,n) is equal to unity since M is the total probability distribution function which accounts for all possible outcomes in n trials and therefore has a probability of unity. The distribution function M may be expanded to give the following individual terms

$$M(e,p,n) = q_1q_2 \cdots q_n + q_1q_2q_3 \cdots q_n + \cdots + p_1p_2 \cdots p_n \quad (2)$$

Each of the terms in Eq. 2 may be interpreted as the probability of the occurrence of a particular set of radiological events in a series of n time intervals. For example, the probability for no occurrence of a radiological event during any of the n time periods is given by M(e = 0,p,n) where

$$(M0,p,n) = q_1q_2 \cdots q_n = (1 - p_1)(1 - p_2) \cdots (1 - p_n)$$

The probability of one occurrence of the radiological event e_i during the time period T_i is given by $M_i(e_i=1,p,n)$ where

$$M_i(1,p,n) = p_iq_1q_2 \cdots q_{i-1}q_{i+1} \cdots q_n$$

$$= p_i(1 - p_1) \cdots (1 - p_{i-1})(1 - p_{i+1}) \cdots (1 - p_n)$$

Now the multinomial probability distribution function can be considerably simplified if it can be assumed that the probability p_i for the ith time interval is identical for all time periods so that p_i=p for all i. Under appropriate conditions such an assumption is justified. Then the probability distribution function becomes the familiar bionomial distribution function given by

$$B(e,p,n) = \sum_{r=0}^{n} \frac{n!p^r q^{n-r}}{r!(n-r)!} \quad (3)$$

The general term (with $q = 1 - p$) may be interpreted as the probability of the occurrence of the radiological event e, r times during the time period spanning n time intervals. Also, it should be noted that for this particular event set for the occurrence of r radiological events, there are $n!/r!(n-r)!$ different or independent ways such an event set can occur and each has a probability of $p^r(1-p)^{n-r}$.

For radiological assesment work it is often of particular significance to determine the probability that at least one or more radiological events will occur during the time period 0 to t which spans n time intervals. If the probability of occurence in each time interval is p and is the same for all time intervals than the probability of one or more occurrences is given by $B(e>1,p,n)$ where

$$B(e>1,p,n) = (p + q)^n - q^n = 1 - (1 - p)^n$$

The number of time intervals n can be expressed explicitly in time ($n = t/T$) where T is the mean time interval during which the radiological event can possibly occur and t is the total time period during which such events are considered.

The derivative of $B(e>1,p,n)$ or equivalently $B(e\underline{>}1,p,t)$ with respect to the number of event intervals or time provides the expected probability of one or more radiological events occurring per unit time interval. Letting $P = B(e\underline{>}1,p,t)$ then the derivative of P with respect to $n = t/T$ is given by

$$\frac{dP}{d(t/T)} = -(1 - p)^{t/T} \ Ln \ (1 - p) \quad (4)$$

or equivalently

$$\frac{dP}{d(t/T)} = p^* \exp(-p^* \ t/T) \quad (5)$$

where

$$p^* = - Ln \ (1 - p).$$

Often the probability p for the occurrence of a radiological event will be small ($p<<1$) so that $p^*=p$. Furthermore, if the mean value (which is given by pn for a binomial distribution) for the number of occurrences of a radiological event in time periods (i.e., $pn = pt/T = p^* \ t/T$) is also small so that $p^*t/T<<1$ then Eq. 5 becomes

$$\frac{dP}{d(t/T)} = p \exp \ (-pt/T) = p$$

This provides the interesting result that the probability of one or more radiological occurrences in time per unit time interval is simply equal to the probability p for the occurrence in any single time interval if p is small and the total number of time intervals t/T is small compared to 1/p. When these conditions are not satisfied then Eq. 4 provides the probability of one or more radiological events occurring per unit time.

A useful expansion of the exposure model is the incorporation of event probabilities that are time dependent. Returning to Eq. 1 for the probability p_i (i.e., the probability of occurrence of the radiological event e_i during the time period T_i), it it is reasonable to assume that these probabilities will change with time. A reasonable mathematical model for this time dependence is the standard exponential growth equation where

$$p_i = p_o \ (1 + F)^{t/T} \quad (6)$$

where

- p_o = the probability of occurrence of the radiological event e_o during the mean time period t=o
- F = the fractional growth rate per mean time interval T
- T = the mean time interval
- t = calendar time

Observe that the probability of non occurrence of the event e_i is given by $q_i = 1 - p_i$ where p_i is defined by Eq. 6. The use of Eq. 6 for the probability results in rather complex expressions for the probability density function defined by Eqs. 1 or 3. Observe that the binomial distribution given by Eq. 3 is valid for time varying probabilities defined by Eq. 6. A somewhat simple distribution function results if it can be assumed that the growth rate F is small so that $Ft/T<<1$. Then yields the result that $p_i = p_o \ (1 + Ft/T)$ and the bionomial distribution function (see Eq. 3) becomes

$$B(e,p,n) = p_o \sum_{r=0}^{n} \frac{(t/T)!}{r! \ (t/T - r)!} (1 + Ft/T) \ X$$
$$[1 - p_o(1 + It/T)]^{t/T-r}$$

The general term in the sum may be interpreted, as before, as the occurrence of the radiological event r times during the time period t.

The event space in which the occurrence of radiological events can transpire is a joint probability space with a spatial probability distribution function associated with the selection of land area sites for various activities with possible radiological consequences (e.g., residences, farms, commercial buildings, etc.) and a temporal probability distribution function associated with the time at which an event might occur and the time duration or interval over which the event would extend.

DEVELOPMENT OF MODEL DATA BASE

To develop credible estimates of future radiation exposures to individuals from LLW sites in the absence of control at an arid (e.g., INEL) and humid (e.g., SRP) sites it is necessary to establish a data base on pertinent area populations, land usage patterns and reasonable trends expected in the future for these data. Low level radioactive waste is stored in numerous locations throughout the world.

Table I provides the data base used to develop projections for residency probabilities at the SRP and INEL sites. With population, residency and land area data available from the official U.S. 1980 census(1), values for persons per residency and residencies per acre can be determined. Furthermore, by weighting the residency density values for the counties surrounding the SRP and INEL sites it is possible to project a residency per unit acre value for these sites in the absence of the existing restrictions and institutional control. For example, the SRP site occupies about 193,000 acres and if no restrictions existed the projected number of residences of the SRP site would by 9700 with about 7 of those residencies located on the LLW site. For the INEL site which covers a land area of 528,000 acres the projected number of residences with no control would be 3000 and about 0.4 of these residences would occur on the LLW site.

The U.S. Department of Agriculture(2,3,4) with support from individual state agencies and reporting services periodically provides data on major uses of land by regions within the United States. Figure 1 is a composite of land use data derived by dividing all U.S. land into one of the following four categories: 1) Cropland includes all land planted and harvested, held idle, used for pasture, sustained crop failure, cultivated summer fallow and used for soil improvement; 2) Pasture and grazing land used in open, permanent farm pasture for grazing and grassland range not in farms; 3) Forest land as reported by the U.S. Forest Service; and 4) Other land which includes land for all cities and towns of 1000 or more persons, highway and rail rights-of-way, airports, parks, wildlife refuges, wilderness areas, military lands, flood control areas, etc. These four categories coupled with human residency density data provide the data base required for estimating the probabilities associated with the various human activities that are related to pathways by which persons might be exposed to radiation from LLW sites.

Table II provides the major land use fractions for the four categories previously enumerated for selected regions in the U.S. Because primary interest is directed at accurately projecting estimates of land use that might prevail in the vicinity of the INEL and SRP sites, those regions which include these sites are given. Land use data for the Southeast region (includes that states of South Carolina, Georgia, Florida and Alabama) and Mountain region (includes the states of Idaho, Montana, Wyoming, Colorado, New Mexico, Arizona, Utah and Nevada). These two regions are designated by the U.S. Department of Agriculture as being representative of land use categories and agricultural activities pertinent to that region of the U.S. Land use data is then given for South Carolina and its two counties, Aiken and Barnwell which contain the SRP site. Also data for Idaho and the four counties (Bingham, Butte, Bonneville and Jefferson) associated with the INEL site are given. Finally U.S. average land use data are given, together with changes in land use experienced over the last 24 years (1959 to 1982). The annual reduction rate is -0.30 percent and an annual growth in other land use is 0.61 percent. Annual growth data for the other regions, states and counties can be similarly assessed.

RESULTS AND DISCUSSION

With the land use fractions given for specific land uses in Table II it is possible to estimate annual probabilities for those particular land use activities that might result in radiological exposures to future intruders at the SRP and INEL sites. The land use activities which have major potential for human exposure are cropland use through crops, pasture and grazing land through dairy crops and residency on the land area. Table III provides the annual probabilities estimated for cropland, pasture and residency use at the INEL and SRP sites as functions of time after loss of institutional control and radiological surveillance.

These annual probabilities are determined by assigning mean turnover time intervals of 100 years for cropland and pasture use and 50 years to residencies to obtain annual probability estimates. Using these derived annual probabilites as asymptotic values (i.e., p for the time range greater that 200 years), the annual probabilities for the time range 0 to 100 years were taken as p/10 and for the time range 100 years to 200 years as p/ 10. This is based upon the assumption that loss of these large facilities would

TABLE I

Residency Characteristics for Selected Regions

Item	U.S.	South Carolina	Counties: Aiken	Counties: Barnwell	SRP Site	Idaho	Counties: Butte	Counties: Bingham	Counties: Bonneville	Counties: Jefferson	INEL Site
Population (1980)	2.26E+8	3.12E+6	1.05E+5	1.99E+4	-	9.44E+5	3,342	3.65E+4	6.60E+4	1.53E+4	
Residences (1980)	2.12E+7	1.15E+6	3.96E+4	7,193	-	3.74E+5	1,280	1.21E+4	2.35E+4	4,994	
Land Area (Acres)	2.27E+9	1.93E+7	6.99E+6	3.57E+6	1.93E+5	5.27E+7	1.43E+6	1.34E+6	1.18E+6	7.00E+5	5.28E+5
Persons/ residency	10.7	2.71	2.67	2.76	-	2.52	2.61	3.02	2.81	3.06	-
Residences/ acre*	.0094	.0603	.0647	.0286	(.0503)	.0072	.0013	.0094	.0199	.0077	(.0057)
Residency weighting for site counties	-	-	.60	.40	1.00	-	.55	.20	.10	.15	1.00

* This is the net residency per acre after subtracting respective site area (SRP and INEL). Value for SRP and INEL region is the projected residency density in the absence of institutional control using the residency weighting given for appropriate site counties.

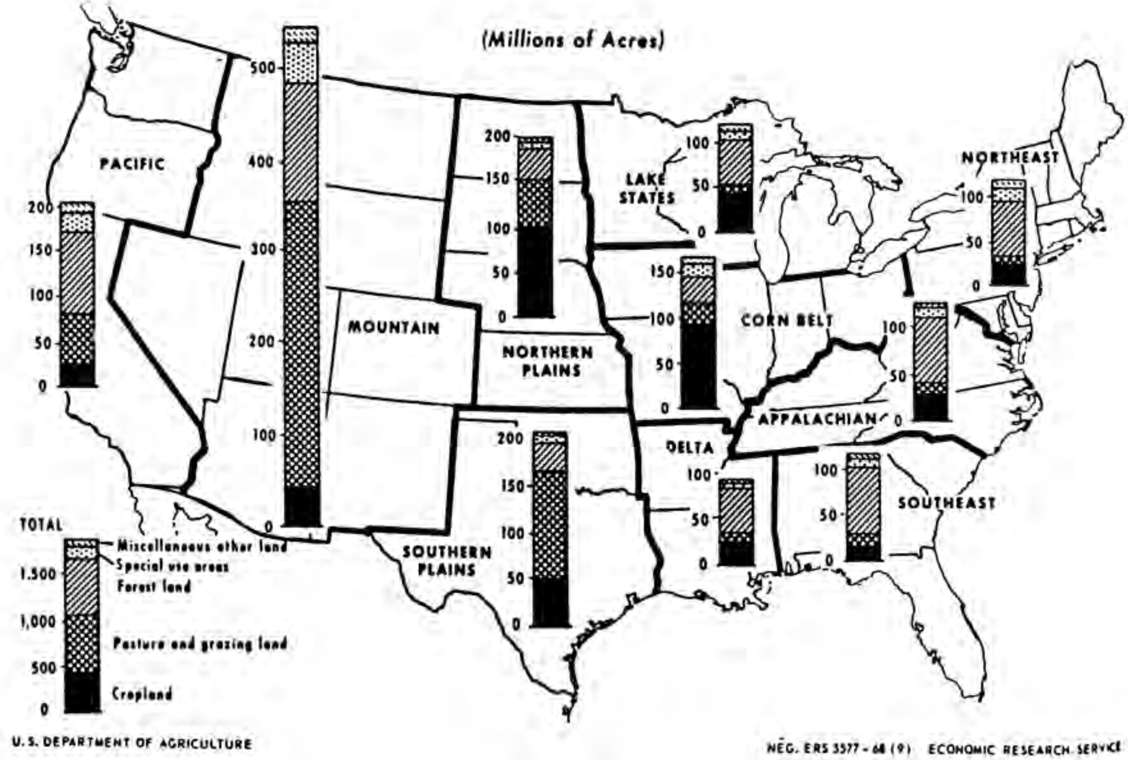

Fig. 1. Major Uses of All Land, by Regions, 48 States.

TABLE II

Estimates of Land Usage Fractions for 1982 Selected Regions

Specific Land Use	U.S.	South East(1)	South Carolina	SRP Site(2)	Mountain(3)	Idaho	INEL Site(4)
Crop Land	.21	.17	.18	.16	.08	.13	.23
Percent Change(5)	.15	-.02	-1.2	-2.6	.15	.57	.57
Pasture	.26	.09	.04	.08	.56	.38	.63
Percent Change(5)	-.28	1.3	-1.8	.46	-.13	-.41	-.41
Forest Land	.32	.60	.63	.61	.25	.41	.09
Percent Change	-.30	-.21	.05	.06	-.22	-.02	-.02
Other Land	.21	.14	.15	.15	.11	.08	.05
Percent Change(5)	.61	1.6	1.5	3.8	.90	1.0	1.0
Residences	7.0E-4	2.0E-3	4.5E-3	3.7E-3	1.8E-4	5.3E-4	4.3E-4

(1) Includes some or all of the states of SC, GA, FL, and AL.
(2) Projected values using the SC counties of Aiken and Barnwell.
(3) Includes all of the states of ID, MT, WY, CO, NM, AZ, UT, and NV.
(4) Projected values using the ID counties of Bingham, Butte, Bonneville, and Jefferson.
(5) Denotes the annual percent growth (or reduction) based upon land use change for the past quarter century.

TABLE III

Annual Probabilities Projections in Time for Selected Land Uses

	Annual Probabilities Over Time					
	Time Range					
	0 to 100 yrs		100 to 200 yrs		> 200 yrs	
Land Use	INEL	SRP	INEL	SRP	INEL	SRP
Cropland	2.3E-4	1.6E-4	7.3E-4	5.1E-4	2.3E-3	1.6E-3
Pasture & Grazing	6.3E-4	8.5E-5	2.0E-3	2.7E-4	6.3E-3	8.5E-4
Residency	8.6E-7	7.4E-6	2.7E-6	2.3E-5	8.6E-6	7.4E-5

significantly decrease new land occupation for residence and farming activities and that some human memory of LLW disposal activities at the INEL and SRP sites would restrain land use for the first two centuries.

The probability for the occurrence of one or more radiological events e for a given land use over the time t in years after loss of site control is given by P(e>1)

$$P(e>1) = \begin{cases} 1 - (1 - p/10)^{t};\ 0 < t < 100 \text{ years} \\ 1 - (1 - p/10)^{100}(1 - p/10)^{t-100}; \\ \quad 100 < t < 200 \text{ yrs} \\ 1 - (1 - p/10)^{100}(1 - p/10)^{100}(1 - p)^{t-200}; \\ \quad t > 200 \text{ yrs} \end{cases}$$

where p is the greater than 200 year annual probability given in Table III for the respective land use activity and site location.

Figure 2 displays the increase of P(e>1) over time for cropland, pasture and residency use at the LLW sites at INEL and SRP. The probable occurrence of at least one cropland siting at both the INEL and SRP sites approaches unity within 5000 years after loss of site control. Pasture use approaches unity within 1000 years at INEL and within 10,000 years at SRP. The occurrence of residency at both site approaches unity only after about 100,000 years or longer.

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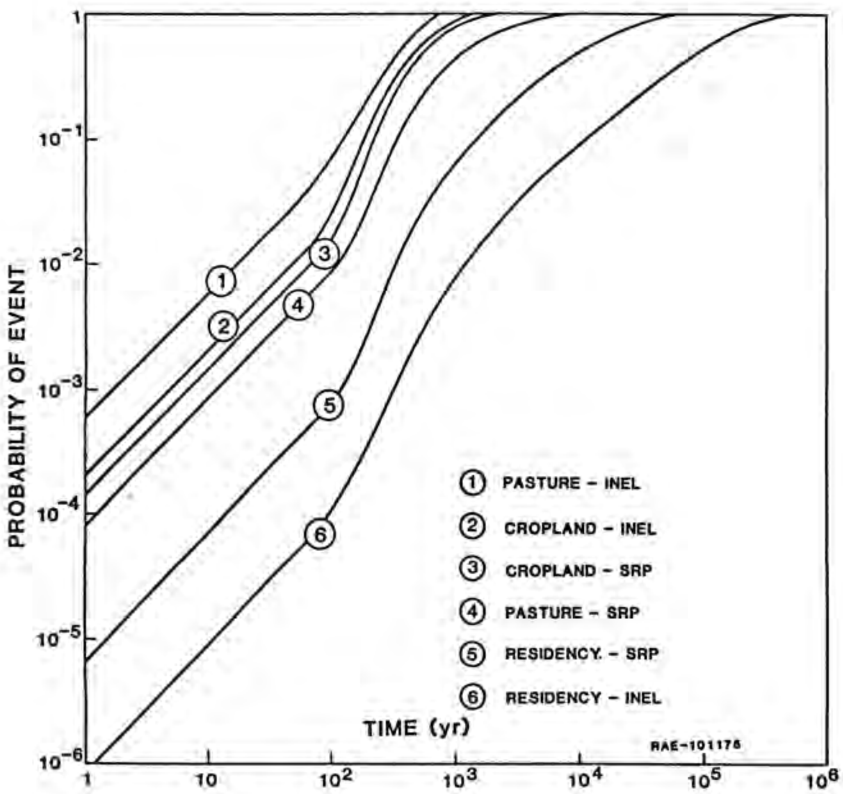

Fig. 2. Cumulative Probability for the Occurrence of Selected Radiological Events at INEL or SRP Sites.