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A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides

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Charles F. Baes III

Prepared for the U.S. Nuclear Regulatory Commission
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HEALTH AND SAFETY RESEARCH DIVISION
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A STATISTICAL ANALYSIS OF SELECTED PARAMETERS FOR PREDICTING FOOD CHAIN TRANSPORT AND INTERNAL DOSE OF RADIONUCLIDES

Final Report

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Summary

Approximately 200 references are reviewed in an attempt to quantify the uncertainty associated with selected input parameters incorporated into the food chain pathway models described in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.109 (Revision 1). An uncertainty analysis is also performed for the multiplicative chain models used to predict the pasture-cow-milk transport of ^{131}I and the subsequent dose to an infant's thyroid. This analysis indicates that for a given deposition rate of ^{131}I, the estimated annual mean dose is approximately a factor of six greater than the estimated most probable dose. The thyroid dose calculated using the generic default values provided in Regulatory Guide 1.109 exceeds the estimated 99*th* percentile and is a factor of approximately nine greater than the mean.

The assumptions of critical importance to the results are that:

1. the available data for input parameters are representative of the true populations of parameter values,
2. the model parameters are statistically independent, and
3. the structure of the model is an appropriate simulation of reality.

The validity of these assumptions remains to be verified; therefore, the results of this study may not accurately represent the true uncertainty associated with the parameters and pathways selected for investigation.

A reduction in model output uncertainty is expected when site-specific information is acquired for those input parameters for which such information is readily available. Testing of the complete model with field measurements will be necessary to improve the overall estimate of the uncertainty associated with model predictions.

Tables A and B, respectively, summarize the results for lognormally and normally distributed parameters. In these tables, values of the most probable, median, mean, and 99*th* percentile are provided for purposes of describing the estimated distribution for each parameter. Tabulation of these values, however, does not constitute a recommendation for their use in radiological assessments.

Table A. Summary table for lognormally distributed parameters including estimates of the most probable (X_p), median (X_m), mean ($\overline{X}$), and 99*th* percentile (X_{99}) for each parameter, the NRC generic default value, and the range of reported values

Parameter	μ[a]	σ[b]	n[c]	X_p	X_m	$\overline{X}$	X_{99}	NRC	Range
Ratio of the interception fraction to forage density, r/Y_v						m^2/kg (dry wt)			
	0.61	0.44	10	1.5 (0.33)[d]	1.8 (0.50)	2.0 (0.59)	5.1 (0.99)	1.1[e] (0.12)	1.0 to 4.0
Reciprocal of vegetation density, $1/Y_v$						m^2/kg (dry wt)			
forage	1.1	0.59	527	2.1 (0.28)	3.0 (0.50)	3.6 (0.62)	12 (0.99)	5.71 (0.86)	0.63 to 25
feed grain	1.7	0.78	315	3.0 (0.22)	5.5 (0.50)	7.4 (0.65)	34 (0.99)	5.71 (0.52)	1.12 to 33.3
silage	0.31	0.37	86	1.2 (0.36)	1.4 (0.50)	1.5 (0.57)	3.2 (0.99)	5.71 (1.0)	0.60 to 2.86
						m^2/kg (fresh wt)			
leafy vegetables	-0.73	0.46	112	0.39 (0.32)	0.48 (0.50)	0.54 (0.59)	1.4 (0.99)	0.5 (0.53)	0.19 to 2.78
Environmental half-time of materials deposited on vegetation, T_w						days			
particulates	2.7	0.26	9	13.9[f] (0.40)	14.9 (0.50)	15.4 (0.55)	27.2 (0.99)	14 (0.41)	10.5 to 27
iodines	2.3	0.31	10	9.06[f] (0.38)	9.97 (0.50)	10.5 (0.56)	20.5 (0.99)	14 (0.86)	6.5 to 13
Effective half-life of ^{131}I on grasses, T_{eff}						days			
	1.5	0.14	10	4.39[f] (0.44)	4.48 (0.50)	4.53 (0.53)	6.21 (0.99)	5.1 (0.82)	3.8 to 5

Table A (continued)

Parameter	μ[a]	σ[b]	n[c]	X_p	X_m	$\bar{X}$	X_{99}	NRC	Range
Milk transfer factor for dairy cows, F_m						days/liter			
iodine	-4.6	0.55	20	7.4E-3[g] (0.29)	1.0E-2 (0.50)	1.2E-2 (0.61)	3.6E-2 (0.99)	6.0E-3 (0.17)	2.7E-3 to 3.5E-2
strontium	-6.7	0.53	19	9.3E-4 (0.30)	1.2E-3 (0.50)	1.4E-3 (0.60)	4.2E-3 (0.99)	8.0E-4 (0.21)	6.4E-4 to 4.5E-3
cesium	-5.0	0.58	27	4.8E-3 (0.28)	6.7E-3 (0.50)	8.0E-3 (0.61)	2.6E-2 (0.99)	1.2E-2 (0.84)	2.5E-3 to 1.6E-2
Milk transfer factor for dairy goats, F_m						days/liter			
iodine	-1.1	0.73	10	0.20 (0.28)	0.33 (0.50)	0.43 (0.64)	1.8 (0.99)	0.06 (0.01)	0.06 to 0.65
Beef transfer factor, F_f						days/kg			
cesium	-4.5	0.81	24	5.8E-3 (0.21)	1.1E-2 (0.50)	1.5E-2 (0.66)	7.3E-2 (0.99)	4.0E-3 (0.10)	4.7E-3 to 9.7E-2
Freshwater finfish bioaccumulation factor, B_{ip}						liter/kg			
iodine	3.5	0.61	13	23 (0.27)	33 (0.50)	40 (0.62)	140 (0.99)	15 (0.10)	10 to 132
strontium	2.4	1.8	9	0.43 (0.04)	11 (0.50)	56 (0.82)	730 (0.99)	30 (0.71)	0.82 to 198
cesium	7.2	0.86	8	640 (0.19)	1300 (0.50)	1900 (0.67)	9900 (0.99)	2000 (0.68)	281 to 4850
Annual consumption of milk by infants, U^M_{ap}						liters/year			
age 0-4 months	5.6	0.13	100	266[f] (0.45)	270 (0.50)	273 (0.53)	366 (0.99)	330[h] (0.94)	199 to 388

Table A (continued)

Parameter	μ[a]	σ[b]	n[c]	X_p	X_m	$\bar{X}$	X_{99}	NRC	Range
age 4-6 months	5.7	0.20	45	287[f] (0.42)	299 (0.50)	305 (0.54)	476 (0.99)	330[h] (0.69)	175 to 431
Thyroid dose conversion factor for ^{131}I ingested by infants, D[i]	rem/μCi								
newborn	3.6	0.80		19 (0.21)	37 (0.50)	50 (0.66)	240 (0.99)	13.9 (0.11)	
age 0.5 to 1.5 years	2.4	0.70		6.8 (0.24)	11 (0.50)	14 (0.64)	56 (0.99)	13.9 (0.63)	
Analysis of the pasture-cow-milk pathway for ^{131}I[i]									
Ratio of milk to vegetation concentration (per mass vegetation), C_m/C_v	kg (dry wt)/liter								
	-2.8	0.61		4.2E-2 (0.27)	6.1E-2 (0.50)	7.3E-2 (0.62)	0.25 (0.99)	7.5E-2[j] (0.63)	
Ratio of milk to vegetation concentration (per unit ground area), C_m/C_p	m^2/liter								
	-1.7	0.85		8.9E-2 (0.20)	0.18 (0.50)	0.26 (0.66)	1.3 (0.99)	0.43[j] (0.84)	
Ratio of milk concentration to areal deposition, C_m/C_d	m^2/liter								
	-2.1	0.75		7.0E-2 (0.23)	0.12 (0.50)	0.16 (0.65)	0.70 (0.99)	0.43[j] (0.95)	
Ratio of milk to air concentration for $^{131}I_2$, C_m/χ	m^3/liter								
	8.3	0.62		2700 (0.27)	4000 (0.50)	4900 (0.62)	1.7E4 (0.99)	1900[jk] (0.11)	

Table A (continued)

Parameter	μ[a]	σ[b]	n[c]	X_p	X_m	$\overline{X}$	X_{99}	NRC	Range
Ratio of thyroid dose to $^{131}I_2$ concentration in air, R/χ	mrem·m³/pCi·year								
	8.5	1.0		1800 (0.16)	4900 (0.50)	8100 (0.69)	5.0E4 (0.99)	8600[j,k,l] (0.71)	
Ratio of thyroid dose to a daily deposition rate of ^{131}I, R/d	mrem·m²·day/pCi·year								
	-0.12	1.1		0.26 (0.14)	0.89 (0.50)	1.6 (0.71)	12 (0.99)	15.0[j,l,m] (>0.99)	

[a]μ = mean of the logarithms of observations.

[b]σ = standard deviation of the logarithms of observations.

[c]n = number of observations considered in the analysis.

[d]Values in parentheses represent cumulative probabilities $P(X \leq X_u)$.

[e]NRC values are 5.71 for iodines, 1.39 for wet deposition, and 1.11 for dry deposition.

[f]Three significant figures given for purposes of clarity.

[g]The notation 1.0E-1 equals 1.0×10^{-1}.

[h]NRC value represents the maximum exposed individual.

[i]Number of observations and ranges are not given for these parameters because the statistical properties have been generated through calculations combining the uncertainties of several subparameters.

[j]NRC value calculated assuming 100% of the cow's diet is fresh forage.

[k]NRC value calculated using a deposition velocity of 0.68×10^{-2} m/sec derived from NRC Regulatory Guide 1.111 (1977b).

[l]NRC value calculated assuming cows are on pasture throughout an entire year.

[m]NRC value calculated assuming 5.71 for r/Y_v.

Table B. Summary table for normally distributed parameters including estimates of the mean ($\overline{X}$), standard deviation (S.D.), and 99*th* percentile (X_{99}) for each parameter, the NRC generic default value, and the range of reported values

Parameter	n	$\overline{X}$	S.D.	X_{99}	NRC	Range
		----unitless----				
Interception fraction, r for forage grasses	10	0.47 (0.50)	0.30	1.0 (0.99)	0.20 (0.17)	0.02 to 0.82
		----kg(dry wt)per cow per day----				
Average daily intake of total dry matter by herds of dairy cows, Q_F^T	2927[a]	16 (0.50)[b]	2.6	22 (0.99)	12.5 (0.10)	6 to 25
Average daily intake of succulents by herds of dairy cows, Q_F^S	2927[a]	6.8 (0.50)	2.1	12 (0.99)		3 to 13
Average daily intake of succulents and hay by herds of dairy cows, Q_F^{S+H}	2927[a]	9.7 (0.50)	2.3	15 (0.99)		4 to 18
Average daily intake of concentrates by herds of dairy cows, Q_F^C	2927[a]	6.2 (0.50)	1.5	9.7 (0.99)		1.6 to 11
		----unitless----				
Fraction of total daily dry matter intake composed of fresh pasture forage,[c] f_s	2927[a]	0.43 (0.50)	0.13	0.73 (0.99)		0.1 to 0.8
Fraction of the year in which fresh forage is utilized by dairy cows, f_p	11468	0.40 (0.50)	0.22	0.91 (0.99)		0 to 1.0

[a] n is the number of herds of dairy cows considered in the analysis.

[b] Values in parentheses are cumulative probabilities, $P(X \leq X_{\mu})$.

[c] Estimated on the basis of succulent intake.

A STATISTICAL ANALYSIS OF SELECTED PARAMETERS FOR PREDICTING FOOD CHAIN TRANSPORT AND INTERNAL DOSE OF RADIONUCLIDES

F. Owen Hoffman, Charles F. Baes III, Donald E. Dunning, Jr., David E. Fields, Craig A. Little, Charles W. Miller, Thomas H. Orton, Elizabeth M. Rupp, D. Lynn Shaeffer and Roberta W. Shor

ABSTRACT

Compliance with environmental radiological standards promulgated to limit routine releases from nuclear facilities is usually determined through the use of mathematical models which are subject to considerable uncertainty. One way of estimating the uncertainty associated with model predictions is through an analysis of the statistical properties of their input parameters. This report presents results of such analyses for parameters incorporated in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.109. Approximately 200 references are reviewed and the distribution of values associated with input parameters is quantified. The results are used to estimate the uncertainty in dose prediction resulting from a given concentration of $^{131}I_2$ in air transported over the pasture-cow-milk pathway. The NRC recommended generic default values are compared with the statistical distribution of the selected parameters, and the probability of the default values not being exceeded is estimated. The results reported herein provide an estimation of actual uncertainties to be expected under real-world conditions in lieu of validation experiments. The relevance of these results to the true uncertainties associated with the parameters and models analyzed in this report is limited because of the qualifying assumptions and the quality of data. However, methods of taking results from these analyses into account when determining compliance with regulatory statutes are discussed.

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1. INTRODUCTION

Radiological assessments rely heavily on the use of mathematical models to predict the dose to man resulting from the environmental transport and subsequent human intake of radionuclides released from nuclear facilities. However, because all models are only approximations of reality and because of the inherent variability of input parameters used in these models, their predictions are subject to uncertainty. In the past, compensation for uncertainties in radiological assessment models has been accomplished through the use of conservative assumptions designed to produce an overestimate of actual doses received by members of the general public. This practice was considered acceptable as long as these intentionally conservative estimates of dose were only fractions of statutory limits. Currently an emphasis is being placed on removing the conservatism in model predictions in order to improve the "realism" of dose estimation in determining compliance with standards which specify that dose limits be "as low as is reasonably achievable" (USNRC 1975, USEPA 1977). However, improving the "realism" in model predictions should be based on reducing the uncertainty in model output, because the removal of conservative assumptions without a concurrent reduction in the model uncertainty can result in an increasing potential for a model to underpredict actual doses.

The uncertainty associated with model predictions is best determined through model validation experiments. These are experiments specifically designed to test the accuracy and precision of model predictions under the variety of conditions for which the model was intended (Hoffman et al. 1978; Shaeffer 1978a). Furthermore, validation experiments should be conducted to obtain time-averaged data appropriate for meaningful comparison with model predictions, because radiation protection standards are usually concerned with annual doses or dose commitments received as the result of a one-year chronic exposure. Unfortunately, model validation experiments usually are not feasible because of the necessary time and financial resources which must be committed and because of the difficulty in detecting low environmental concentrations of radionuclides. In the absence of specific tests of the uncertainty in model predictions, estimation of the uncertainties in dose prediction will be limited to an analysis of data available for input parameters (Shaeffer 1978a). This alternative approach to uncertainty estimation is dependent on the assumptions that the model is an appropriate representation of reality (i.e., correct input will produce correct output) and that the available data for input parameters are representative of the true distribution of parameter values.

The uncertainty analyses performed in this study are a statistical analysis of data applicable to the parameters used as input to the models incorporated by the U.S. Nuclear Regulatory Commission (NRC) within Regulatory Guide 1.109, Revision 1 (USNRC 1977a). The specific pathways of concern which incorporate these parameters are given below.

Inhalation Pathway

(a) Organ dose via inhalation of radionuclides in air

Terrestrial Pathways

(a) Radionuclide concentrations in produce and leafy vegetables
(b) Radionuclide concentrations in animal feeds and forage
(c) Radionuclide concentrations in milk
(d) Radionuclide concentrations in beef
(e) Organ dose from ingestion of atmospherically released radionuclides in food.

Aquatic Pathways

(a) Organ dose from potable water
(b) Organ dose from aquatic foods

The generalized conceptual formulation of these models is:

$$R_{aipj} = C_{ip} U_{ap} D_{aipj} , \tag{1.1}$$

where

R_{aipj} = the annual dose to organ j of an individual of age group a from nuclide i via pathway p in mrem/year;

C_{ip} = the concentration of nuclide i in the medium of pathway p. For example: for nuclide i, C_{im} = concentration in milk (pCi/liter), C_{iv} = concentration in forage (pCi/kg), C_{ip} and C_{id} = concentration in pasture area, and deposition, respectively (pCi/m^2);

U_{ap} = the intake rate (usage) associated with pathway p for age group a in m^3/year, liter/year, or kg/year (as appropriate);

D_{aipj} = the dose factor, specific to age group a, radionuclide i, pathway p, and organ j. This factor is from the intake of a radionuclide (mrem/pCi).

Most of the parameters analyzed in this study are used to calculate C_{ip}. The specific parameters selected for detailed analysis are identified in Table 1.1. The contribution of these parameters to the total uncertainty associated with the pasture-cow-milk pathway for ^{131}I is considered separately because of the importance of this pathway in compliance with regulatory requirements (Sect. 4).

The models incorporated in Regulatory Guide 1.109 were originally implemented at Battelle Northwest Laboratories for use in the computer code HERMES (Fletcher and Dotson 1971, Soldat 1971, Soldat et al. 1974) and later adapted by the NRC as a guide for determining compliance with Title 10, U.S. *Code of Federal Regulations*, Part 50 (10 CFR 50), Appendix I (USNRC 1975) through incorporation in Regulatory Guide 1.109 Revision 1 by the U.S. Nuclear Regulatory Commission (1977a). The U.S. Environmental Protection Agency (EPA) (1977) has also considered this model for use in implementing Title 40, U.S. *Code of Federal Regulations*, Part 190 (40 CFR 190). Similar versions of this model are in use for regulatory assessments in other countries (BMI 1977a,b).

Site-specific information is usually recommended for this model whenever it is available because of the potentially large variability of many of the transfer coefficients and factors directly related to the calculation of dose. However, in lieu of site-specific information, generic default values are used for input. The data sources which have been used most extensively for the derivation of these generic default values are the documents by Ng et al. (1968) and Garner (1971) for terrestrial transfer coefficients; Thompson et al. (1972) and Freke (1967), respectively, for freshwater and salt water bioaccumulation factors; and the International Commission on Radiological Protection (ICRP) Publication II (1959) for values used in the calculation of dose conversion factors. The degree to which these generic default

Table 1.1. Model parameters defined and incorporated within Regulatory Guide 1.109, Revision 1 and selected for statistical analysis

Symbol	Description	Units
Terrestrial transport factors		
r	Fractional interception of depositing materials by the above ground edible portions of terrestrial vegetation	
Y_v	The standing crop biomass of forage and food crops at time of harvest	kg/m^2
λ_w	Environmental loss constant of materials deposited on the surfaces of terrestrial vegetation	day^{-1}
Q_F	Average quantities of pasture forage and stored feed consumed by a grazing animal	kg/day
f_p	Fraction of the year dairy cows graze on or are fed fresh pasture vegetation	
f_s	Fraction of the total feed intake that is composed of fresh pasture vegetation	
F_m	Animal intake-to-milk transfer coefficients for the elements iodine, strontium, and cesium	day/liter
F_f	Animal intake-to-meat transfer coefficients for selected long-lived nuclides	day/kg
$\lambda_{s\ell}$[a]	Soil loss constant for iodine, cesium, strontium, plutonium, and technetium	$year^{-1}$
B_{iv}	Concentration ratio of elements, vegetation to soil	
Aquatic transport factor		
B_{ip}	Bioaccumulation factors (concentration ratios), freshwater fish-to-water for cesium, strontium, and iodine	liter/kg
Human dietary and behavioral factor		
U_{ap}	Inhalation rates of air and consumption rates of milk, water, fish, and other solid foods for infants, children, teenagers, and adults	m^3/year, kg/year, or liter/year
Dose conversion factor		
D_{aipj}	Thyroid dose conversion factor from the ingestion of ^{131}I by infants and small children	mrem/pCi

[a]Parameter not included in Regulatory Guide 1.109, Rev. 1 (USNRC 1977a).

values affect the "realism" or "conservatism" of model predictions must be investigated when compliance with regulations is in question.

2. STATISTICAL APPROACH

(D. Lynn Shaeffer and F. Owen Hoffman)

2.1 The Use of Lognormal Statistics

Because of the lack of data from model validation experiments, a quantitative analysis of uncertainties in model predictions must rely upon a statistical analysis of values for input parameters. In a multiplicative chain model, uncertainties can be determined from analytically derived formulae if parameters are lognormally distributed and statistically independent. If the parameters are not lognormal or statistically independent, uncertainties must be determined numerically, generally by computer simulation. Therefore, the literature values chosen for analysis were plotted on lognormal probability paper to examine the assumption of lognormality. If a straight line reasonably fit the plotted data, the assumption of a lognormal distribution was determined to be feasible. This graphical method is the easiest and a commonly used technique for determining the appropriateness of a particular probability density function (p.d.f.) to describe a set of data (Aitchison and Brown 1969; Speer and Waite 1975). If lognormality was assumed, the data were log-transformed to produce a normal distribution having a population mean value μ and standard deviation σ, where the estimates, $\hat{\mu}$ and $\hat{\sigma}$, of μ and σ, respectively, are given by:

$$\hat{\mu} = \sum_i \ln X_i / n \ , \tag{2.1}$$

$$\hat{\sigma} = \sqrt{\frac{\sum_i (\ln X_i)^2 - \frac{(\sum_i \ln X_i)^2}{n}}{n - 1}} \ , \tag{2.2}$$

where

$\ln X_i$ = logarithm of i^{th} observation and

n = number of observations.

For a variable that is normally distributed, the mean ($\overline{X}$), median (X_m), and most probable (X_p) values are all equal. For a lognormal distribution all three values are different. The formulae for the corresponding values of a variable, X, which is lognormally distributed are as follows (Aitchison and Brown 1969):

$$X_p = \exp(\mu - \sigma^2) \ , \tag{2.3}$$

$$X_m = \exp(\mu) \ , \text{ and} \tag{2.4}$$

$$\overline{X} = \exp(\mu + \sigma^2/2) \ . \tag{2.5}$$

Estimates of these three quantities (X_p, X_m, and $\overline{X}$) are obtained by substituting $\hat{\mu}$ and $\hat{\sigma}$ for μ and σ, respectively.

The probability $P(X \leq X_u)$ of a given value, X_u, not being exceeded by X is:

$$P(X \leq X_u) = \int_0^{X_u} f(X)\, dX \ , \tag{2.6}$$

where f(X) is the p.d.f. for the parameter. This probability [$P(X \leq X_u)$] is referred to in this report as the cumulative probability. We sometimes refer to the cumulative probability in percent (e.g., A%) as the A^{th} percentile.

For a parameter that is lognormally distributed, f(X) is defined in terms of μ and σ by:

$$f(X) = \frac{1}{\sigma X \sqrt{2\pi}} \exp\left\{ - \frac{(\ln X - \mu)^2}{2\sigma^2} \right\} . \tag{2.7}$$

Substitution of Eq. (2.7) into Eq. (2.6) gives:

$$P(X \leq X_u) = 1/2(1 + \text{erf } t_u) \ , \tag{2.8}$$

where

$$t_u = \frac{1}{\sigma\sqrt{2}} (\ln X_u - \mu) \ , \tag{2.9}$$

and erf is the error function (Abramowitz and Stegun 1972).

By substituting X_p, X_m, and $\overline{X}$ from Eqs. (2.3) through (2.5) for X_u in Eqs. (2.8) and (2.9), the probability that values of X_p, X_m, and $\overline{X}$ will not be exceeded can be calculated as follows:

$$P(X \leq X_p) = \frac{1}{2} \left\{ 1 - \text{erf} \frac{\sigma}{\sqrt{2}} \right\} \ , \tag{2.10}$$

$$P(X \leq X_m) = \frac{1}{2} \ , \text{ and} \tag{2.11}$$

$$P(X \leq \overline{X}) = \frac{1}{2} \left\{ 1 + \text{erf} \frac{\sigma}{2\sqrt{2}} \right\} \ . \tag{2.12}$$

It is evident that the probability of X_p and $\overline{X}$ not being exceeded is entirely dependent on the standard deviation of the logarithms, σ.

To estimate a parameter value (X_A) corresponding to a desired percentile A, the median value (X_m) is multiplied by exp ($Z\sigma$), or:

$$X_A = \exp(\mu + Z\sigma) \ , \tag{2.13}$$

where Z is a factor corresponding to the *Ath* percentile for a standard normal distribution. Values of Z are provided in most statistical texts, with typical values being 1.0 for the 84*th* percentile, 1.645 for the 95*th* percentile, and 2.326 for the 99*th* percentile (Neter et al. 1978). In this report the 99*th* percentile (X_{99}) is estimated along with values of X_p, X_m, and $\overline{X}$ for the purpose of describing the estimated distribution for each parameter assumed to be lognormal. The mean ($\overline{X}$), standard deviation (S.D.) and 99*th* percentile (X_{99}) are presented for those parameters assumed to be normally distributed.

2.2 The Statistical Analysis of Model Predictions

In a multiplicative chain model of the form:

$$R = X_1 X_2 X_3 \dots (1/Y)_4 (1/Y)_5 (1/Y)_6 \dots \tag{2.14}$$

the predicted quantity R will be lognormally distributed if all of the input parameters are lognormally distributed and statistically independent (Aitchison and Brown 1969). The log-transformed distribution of the model output will have a mean value, μ_R, and a standard deviation, σ_R, values of which can be calculated knowing the values of μ and σ for the logarithms of each multiplicative parameter. In the model it follows that:

$$\mu_R = \sum_j \mu_j , \tag{2.15}$$

and

$$\sigma_R^2 = \sum_j \sigma_j^2 , \tag{2.16}$$

where the subscript j refers to the variables X_j and $(1/Y)_j$ of the model described by Eq. (2.14). If the statistical properties of $(1/Y)_j$ are derived from observations of Y, then it is necessary to change the sign of $\hat{\mu}$ (corresponding to the mean of ln Y) in Eqs. (2.3) through (2.13) [the reader should note that values for $(1/Y)_p$, $(\overline{1/Y})$, and $(1/Y)_{99}$ will not be equal to $1/Y_p$, $1/\overline{Y}$, and $1/Y_{99}$]. Values of μ_R and σ_R for the model output can be used in Eq. (2.3) through (2.13) to calculate the most probable value (R_p), median (R_m), mean ($\overline{R}$), and 99*th* percentile (R_{99}) for the output along with their associated cumulative probabilities. In a multiplicative chain model composed of lognormally distributed, statistically independent parameters, the contribution of the uncertainty in a given input parameter to the uncertainty in the model output can be estimated by dividing σ_j^2 by σ_R^2.

The statistical methodology presented here and used throughout this report has been developed by Shaeffer (1979) for the purpose of quantifying uncertainties associated with lognormally distributed parameters and the related uncertainties associated with the predictions of multiplicative chain models. The key assumptions in this analysis are (1) the model is correct; therefore, correct input values will give correct output, (2) the parameters are statistically independent and therefore not correlated, and (3) the available data represent the true distribution of parameter values.

2.3 Procedures Used in Lieu of Lognormal Statistics

If the assumption of a lognormal distribution of parameter values did not appear feasible, an analysis of the data available for the parameter was performed assuming a normal distribution. In those cases where neither the assumption of a lognormal nor a normal distribution of data is made, only a mean value and a range are reported. When the quality of the data for a parameter is particularly questionable, estimates are made of upper-limit or worst-case default values.

2.4 Interpretation of Probability Plots

The solid lines in the probability plots presented in the following sections represent the theoretical distribution of the parameter. Generally, these lines were drawn through two points located at the 50*th* and 99*th* percentile. The 50*th* percentile was determined at [exp $(\hat{\mu})$] for lognormal probability plots and at the arithmetic mean $(\overline{X})$ for normal probability plots. The 99*th* percentile was determined at [exp $(\hat{\mu} + 2.326\ \hat{\sigma})$] for lognormal plots and at [$\overline{X}$ + 2.326 one standard deviation (S. D.)] for normal plots. Values of $\hat{\mu}$ and $\hat{\sigma}$ are calculated using Eqs. (2.1) and (2.2), respectively.

For a few parameters (Q_F^T, f_s, and f_p) a theoretical lognormal distribution was produced for normally distributed data by visually fitting a straight line to the data plotted on lognormal probability paper. Usually, a straight line would reasonably fit such data above the 20*th* percentile. The adoption of this theoretical distribution was for the purpose of analyzing the uncertainties of the pasture-cow-milk multiplicative chain model (Sect. 4). This procedure would only be expected to produce errors in the lower ($\leq$ 20%) percentiles.

The data points presented in the probability plots do not necessarily represent one literature value. Thus, the theoretical distribution (solid line) may not appear to agree with the data. A data point may be representative of many individual literature values which coincide or may represent only one literature value. Thus, the points should not be weighted equally. Generally, in figures which have many data points, the points occurring in the extreme high or low cumulative probabilities may be weighted less than points in the midrange of the distribution because points in the midrange may represent more than one literature value. The figures involving large numbers of observations are produced using an approximative technique whereby the cumulative frequency of the data is calculated by the expression (i/n). For data sets involving fewer than 30 observations the expression (i - 0.375)/(n + 0.25) is used (Goslee and Mitchell 1972). In these expressions i is the rank order of observations and n is the number of observations. All calculations of the uncertainty in the parameters analyzed in this report are based on the theoretical distribution of observed data.

3. ANALYSIS OF THE PARAMETERS

The following sections present a statistical analysis of selected parameters which are used as input to the models incorporated in NRC Regulatory Guide 1.109 (1977a).

3.1 Productivity of Agricultural Crops and Forage, Y_v

(Charles F. Baes III and Thomas H. Orton)

3.1.1 Description of the parameter

In NRC Regulatory Guide 1.109, estimates of radiation dose to man via the pasture-cow-milk pathway and via direct ingestion of produce or leafy vegetables is inversely dependent on values of agricultural productivity, Y_v, when the primary route of foliar contamination is direct deposition from the atmosphere. The default values recommended by the NRC used in lieu of site-specific data are 0.7 kg/m^2 (fresh weight) for pasture forage and 2.0 kg/m^2 (fresh weight) for produce consumed by man.

In this report, the parameter Y_v for pasture forages and animal feeds is estimated on a dry weight basis to minimize weighing errors which are particularly evident when feeds desiccate during storage. The water content of stored feed and silage varies with desiccation which may be dependent on many factors including farming practices, climate, and time of storage. Conversion of fresh weight estimates of Y_v for animal feeds to dry weight standardizes these estimates and minimizes uncertainty. Assuming that fresh forage is 25% dry matter, the NRC default value of 0.7 kg/m^2 (fresh weight) converts to 0.175 kg/m^2 (dry weight).

In this study, wet weight estimates of Y_v for fresh produce are considered appropriate because packaging and refrigeration techniques are designed to reduce water loss and present a product which is nearly identical to its condition at harvesting. Also, dietary consumption data are expressed in fresh weight.

In NRC Regulatory Guide 1.109, the default value of 2.0 kg/m^2 for produce applies to all vegetables, fruits, and grains. However, we have subdivided produce into six categories: (1) leafy vegetables, (2) non-leafy vegetables, (3) below-ground vegetables, (4) fruits, (5) nuts, and (6) food grains.

Animal feeds are subdivided into three categories: (1) forage grasses, (2) feed grains, and (3) silage.

The specific types of vegetation considered in these categories are presented in Table 3.1.

3.1.2 Description of the data base

Forage grasses. One estimate of forage grass productivity was determined from selected state and total U.S. averages for 1962-1966, 1969, and 1970 (Heath et al. 1973). Local variation by field, farm, and county is not reflected in these data. In addition, only a fraction of the total variation among states is represented, because only the top ten states leading in forage grass production are reported in Heath's data. The values of Y_v derived from this reference are representative of standing crop biomass *at harvest*.

Forage grass productivity was also estimated from various data obtained from field experiments (Archer and Decker 1977; Balasko 1977; Hart et al. 1977; Jones et al. 1977; Kroth et al. 1977; Lundberg et al. 1977; Ocumpaugh and Matches 1977; Ream et al. 1977; and Ryerson et al. 1977). These data are perhaps more complete and reliable than the data based on state averages because local variations in productivity as a response to soil fertility, nutrient status, herbicide application, mechanical disturbance, and farming technique are included in the data. Values of Y_v derived from these references are based on standing crop biomass at harvest. Generally, annually averaged Y_v values representative of standing crop biomass throughout the entire growing season are unavailable.

Feed grains, silage, vegetables, and food grains. Productivity estimates for feed grains, silage, below-ground vegetables, leafy vegetables, non-leafy vegetables, and food grains were determined from 1974 state averages (USDA 1976). Additionally, estimates for feed grains and silage were determined from experimental data (Alessi and Power 1977; Brewster et al. 1977; Escalada and Plucknett 1977; Frank et al. 1977; Harvey et al. 1977; Larson and Maranville 1977; Maranville and Clegg 1977; Mock and Erbach 1977; Ream et al. 1977; Ryerson et al. 1977; Stivers et al. 1977; and Unger 1977). State averaged productivity values are often based on sample surveys of farmers and businessmen, and the accuracy of the reported data is questionable. In states where more than a single harvest occurred, each harvest was recorded individually. Thus, Y_v estimates for feed grains, silage, vegetables, and food grains are in kg/m^2 per harvest. As for forage grasses Y_v values derived from the above sources represent standing crop biomass at harvest.

Fruits and nuts. Productivity estimates for fruits and nuts were determined from 1974 state averages (USDC 1977) which included farms having annual sales of $2500 or more. Productivity was estimated from the data in the following manner:

$$Y_v = \frac{\text{Quantity harvested}}{(\text{Acreage allotted for all trees})\left(\frac{\text{"bearing" trees}}{\text{Total trees}}\right)} \qquad (3.1)$$

"Bearing" and "non-bearing" trees were assumed to be distinct and exclusive classes, and both "bearing" and "non-bearing" trees were assumed to be growing at the same relative density.

3.1.3 Results

Animal feeds. Appropriate conversion factors from Morrison (1956) and the National Academy of Sciences (1971) were used to convert animal feeds Y_v data from wet to dry weight (Table 3.2). Lognormal probability plots of the Y_v estimates suggest that a lognormal distribution is appropriate for animal feeds (Figs. 3.1 and 3.2). The differences in the data averaged for each state and the data obtained from experimental studies reflect plant plasticity responses to environmental stimuli and suggest that the experimental data are more indicative of the variability in Y_v than are the data obtained from state averages.

Because the parameter Y_v appears in the denominator of the NRC Regulatory Guide 1.109 terrestrial food-chain pathway model, the statistical analysis is performed for the reciprocal ($1/Y_v$) as described in Sect. 2.2. The results are obtained from Eqs. (2.1) through (2.13) and are shown in Table 3.3. The cumulative probabilities $P(X \leq X_u)$ are given only for the experimental data.

Produce ingested by man. Lognormal probability plots for the various produce ingested directly by man suggest a lognormal distribution (Figs. 3.3 and 3.4), with the exception of the distribution for fruits, which appears to be more normally distributed (Fig. 3.5). However, because of the high degree of uncertainty associated with estimates of state productivity averages for fruits and nuts, a lognormal distribution was assumed for fruits and appropriate statistics were employed in determination of $1/Y_v$ (Table 3.4) for consistency and because of the relatively minor importance of fruits and nuts in the human diet.

3.1.4 Correlations of Y_v with other parameters

There is a correlation between forage vegetation density and deposition (Chamberlain 1970). This correlation is discussed further in Sect. 3.2. Correlation between Y_v for other vegetation types and deposition estimates is expected, but quantification of this relationship is not available. Values of the interception fraction r for non-leafy vegetables, fruits, nuts, and grains are expected to be lower than values of r for forage grasses and leafy vegetables, since there is a correlation between r and foliage surface area (Fig. 3.6). The values of Y_v for these vegetation types could result in considerable over-estimates of contamination if used in concert with values of deposition which are specific for leafy vegetables or forage grasses.

Other unquantified correlations are suspected between values of Y_v and the environmental removal constant (λ_w), between Y_v and the daily quantity of animal feed ingested (Q_F) Koranda (1965), and thus between Y_v and the milk transfer coefficient (F_m). Evidence for influences of Y_v on F_m is associated mainly with various forage types (Black et al. 1975). These correlations would be quantified most effectively as an integral part of a model validation study. However, until such quantification is available, Y_v, λ_w, Q_F, and F_m are treated as being statistically independent.

Table 3.1. Animal feeds and produce used in the estimation of Y_v

Forage grasses		Feed grains		Silage	
State av	Experimental	State av	Experimental	State av	Experimental
Alfalfa[a]	Alfalfa				
Clover[b]	Alfalfa-Bromegrass	Barley	Corn	Corn	Corn
Hay[c]	Birdsfoot Trefoil	Corn	Oats	Sorghum	Sorghum
Lespedeza	Bromegrass	Oats	Sorghum		
	Clover[a]	Sorghum	Wheat		
	Crownvetch[a]				
	Fescue				
	Kentucky Bluegrass				
	Orchardgrass				
	Soft Chess				

Vegetables					
Below-Ground	Leafy	Non-leafy	Fruits	Nuts	Food grains
		Broccoli	Apples[d]	Almonds	Barley
Carrots	Cabbage	Cauliflower	Oranges[e]	Filberts	Rye
Onions	Lettuce	Green peas	Peaches[f]	Hazelnuts	Wheat
Potatoes	Spinach	Lima beans	Pears[g]	Pecans[h]	
		Sweet corn		Pistachios	
				Walnuts[i]	

[a]Also mixtures.
[b]Clover and Timothy and mixtures of clover and grass.
[c]Many types.
[d]Dwarf, semi-dwarf, and standard.
[e]Valencia, navel, temple and others.
[f]Clingstone and freestone.
[g]Bartlett and others.
[h]Improved and wild.
[i]Black, English, and Persian.

Table 3.2. Dry weight conversion factors for animal feeds (data averaged by state)[a]

Feed	Conversion factor	Reference
Alfalfa	0.898	1,2
Barley grain	0.890	1
Corn grain	0.890	1,2
Corn silage	0.341	1,2
Clover	0.891	1,2
Wild hay	0.896	1,2
Lespedeza	0.906	1,2
Oat grain	0.913	1,2
Sorghum grain	0.599	1,2
Sorghum silage	0.259	1,2

[a]Agricultural Statistics (1976) data is given in semi-dry rather than fresh weight. Conversion factors transform semi-dry to dry weight. The conversion factors from fresh to dry weight range roughly between 0.20 and 0.35.

References: National Academy of Sciences (1971).
Morrison (1956).

Table 3.3. Statistical analysis of $1/Y_v$ for forage grasses, feed grains, and silage

	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Reported range
				m²/kg, dry wt					
Forage grasses									
State averages	1.1	0.35	162	2.7	3.0	3.2	6.8	5.7	1.56-7.14
Experimental	1.1	0.59	527	2.1	3.0	3.6	12	5.7	0.63-25
				(0.28)[a]	(0.50)	(0.62)	(0.99)	(0.86)	
Feed grains									
State averages	1.5	0.51	139	3.5	4.5	5.1	15	5.7	1.30-11.1
Experimental	1.7	0.78	315	3.0	5.5	7.4	34	5.7	1.12-33.3
				(0.22)	(0.50)	(0.65)	(0.99)	(0.52)	
Silage									
State averages	0.18	0.35	70	1.1	1.2	1.3	2.7	5.7	0.67-3.23
Experimental	0.31	0.37	86	1.2	1.4	1.5	3.2	5.7	0.60-2.86
				(0.36)	(0.50)	(0.57)	(0.99)	(1.0)	

[a]Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

Note: The NRC value of $1/Y_v$ recommended in lieu of site-specific information is 5.7 m^2/kg for pasture forage. The cumulative probabilities for the NRC values are (0.86) for pasture grasses, (0.52) for feed grains, and (1.0) for silage.

Table 3.4. Statistical analysis of $1/Y_v$ for produce ingested directly by man[a]

Produce type	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Reported range
Vegetables				----------	----------	m^2/kg, fresh wt	----------	----------	----------
Below-ground	-1.01	0.39	97	0.31 (0.35)[b]	0.36 (0.50)	0.39 (0.58)	0.90 (0.99)	0.5 (0.79)	0.18-1.27
Leafy	-0.73	0.46	112	0.39 (0.32)	0.48 (0.50)	0.54 (0.59)	1.4 (0.99)	0.5 (0.53)	0.19-2.78
Non-leafy	0.43	0.52	82	1.18 (0.30)	1.54 (0.50)	1.75 (0.60)	5.26 (0.99)	0.5 (0.02)	0.62-5.88
Fruits	0.44	1.2	238	0.37 (0.12)	1.6 (0.50)	3.2 (0.73)	25 (0.99)	0.5 (0.17)	0.30-100
Nuts	3.5	1.0	50	12 (0.16)	33 (0.50)	55 (0.69)	340 (0.99)	0.5 (0.0)	3.57-100
Food grains	1.7	0.35	106	4.8 (0.36)	5.5 (0.50)	5.8 (0.57)	12 (0.99)	0.5 (0.0)	2.27-20

[a]Analysis based on data derived from reported averaged by state.

[b]Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

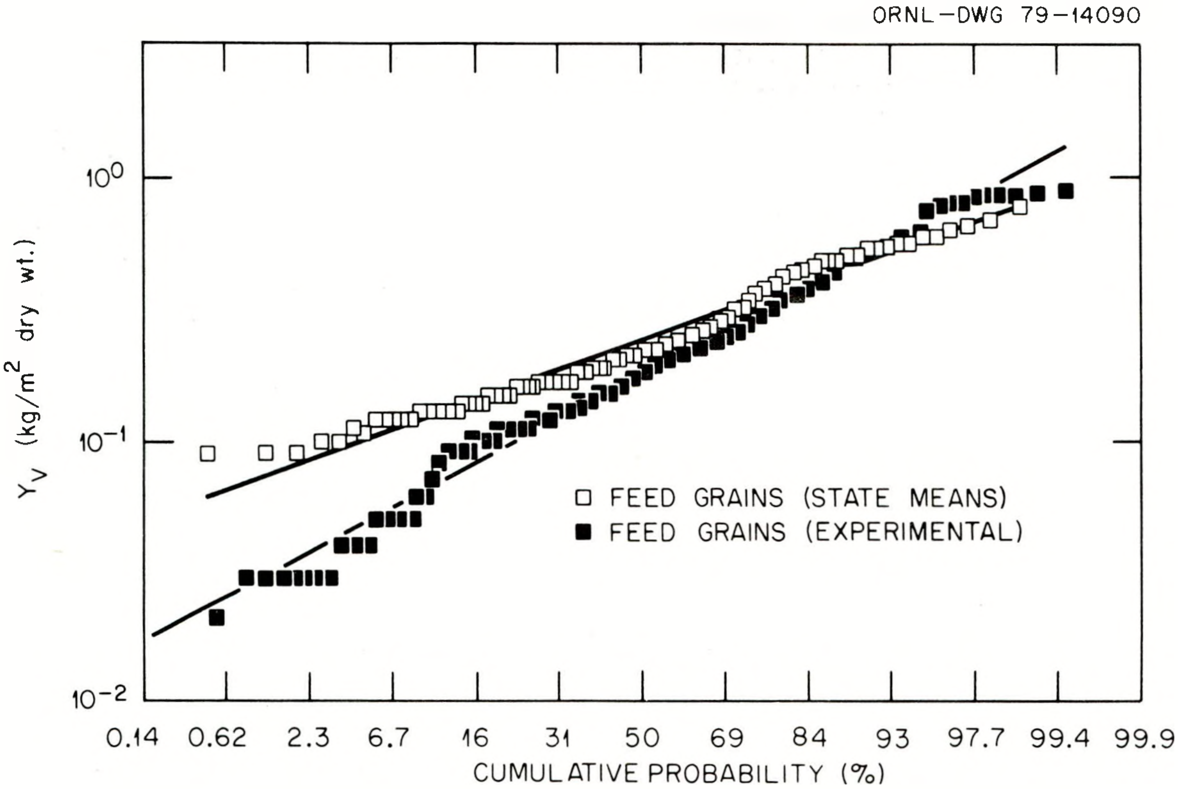

Fig. 3.1. Lognormal probability plots of agricultural productivity Y_v (standing crop biomass at harvest) for feed grains based on annual state averages and experimental data.

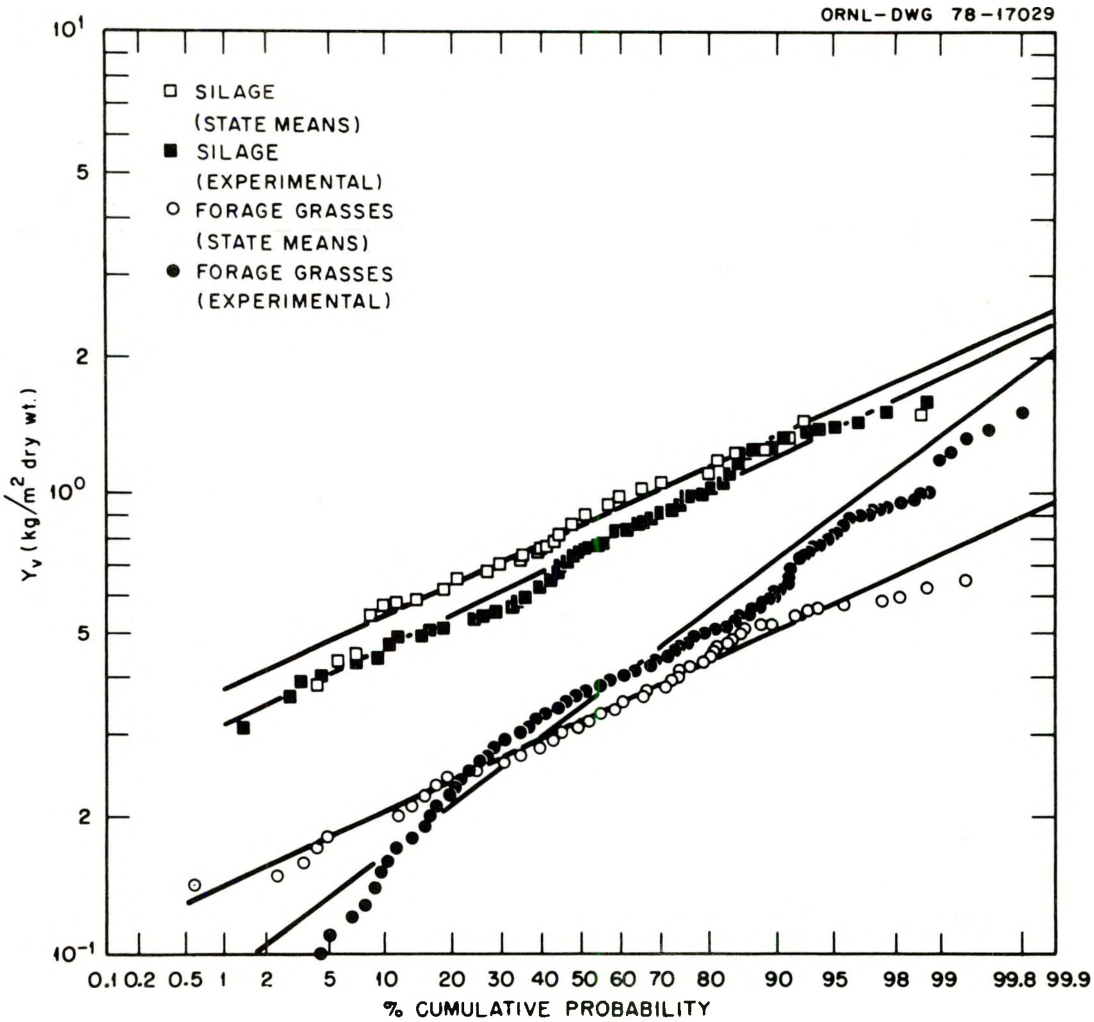

Fig. 3.2. Lognormal probability plots of agricultural productivity Y_v (standing crop biomass at harvest) for silage and forage grasses based on annual state averages and experimental data.

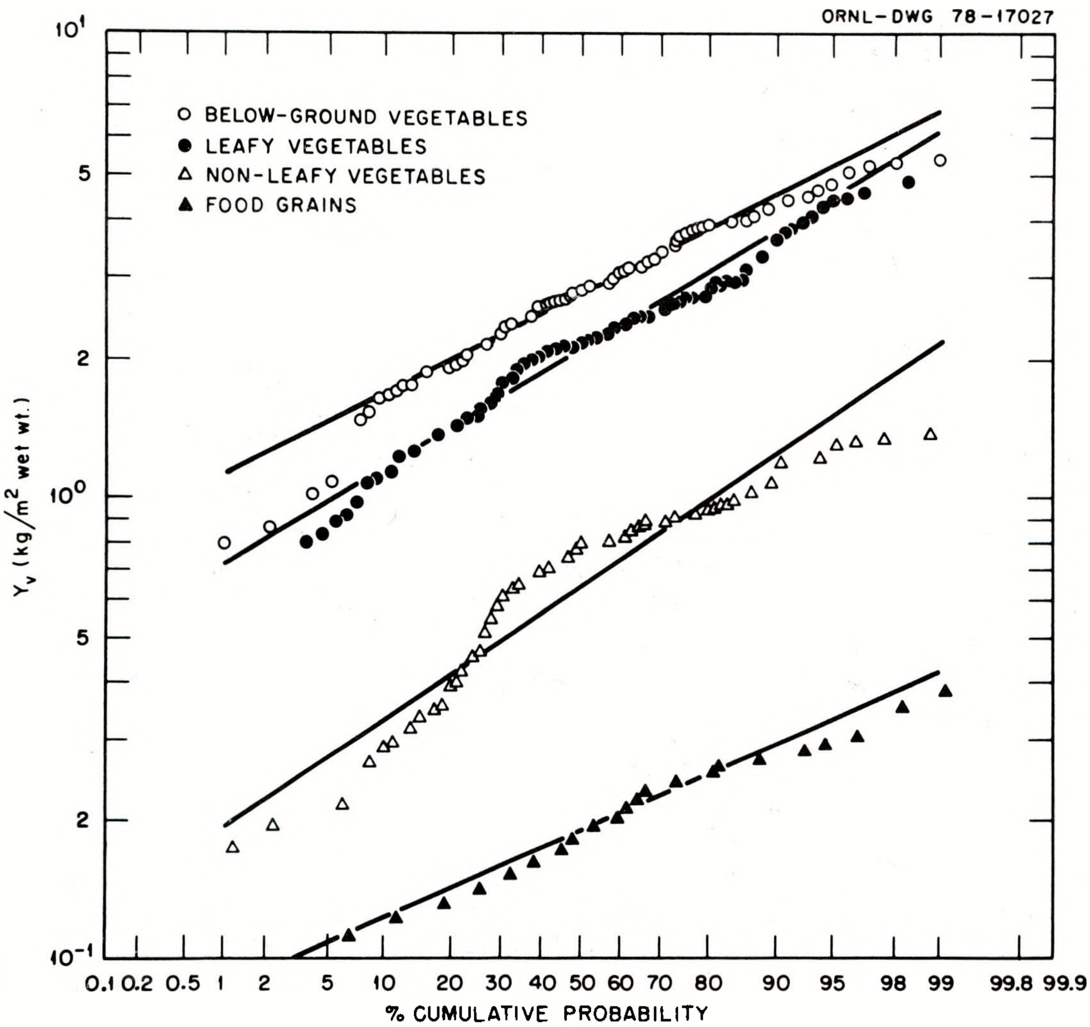

Fig. 3.3. Lognormal probability plots of agricultural productivity Y_v (standing crop biomass at harvest) for various fresh produce ingested by man.

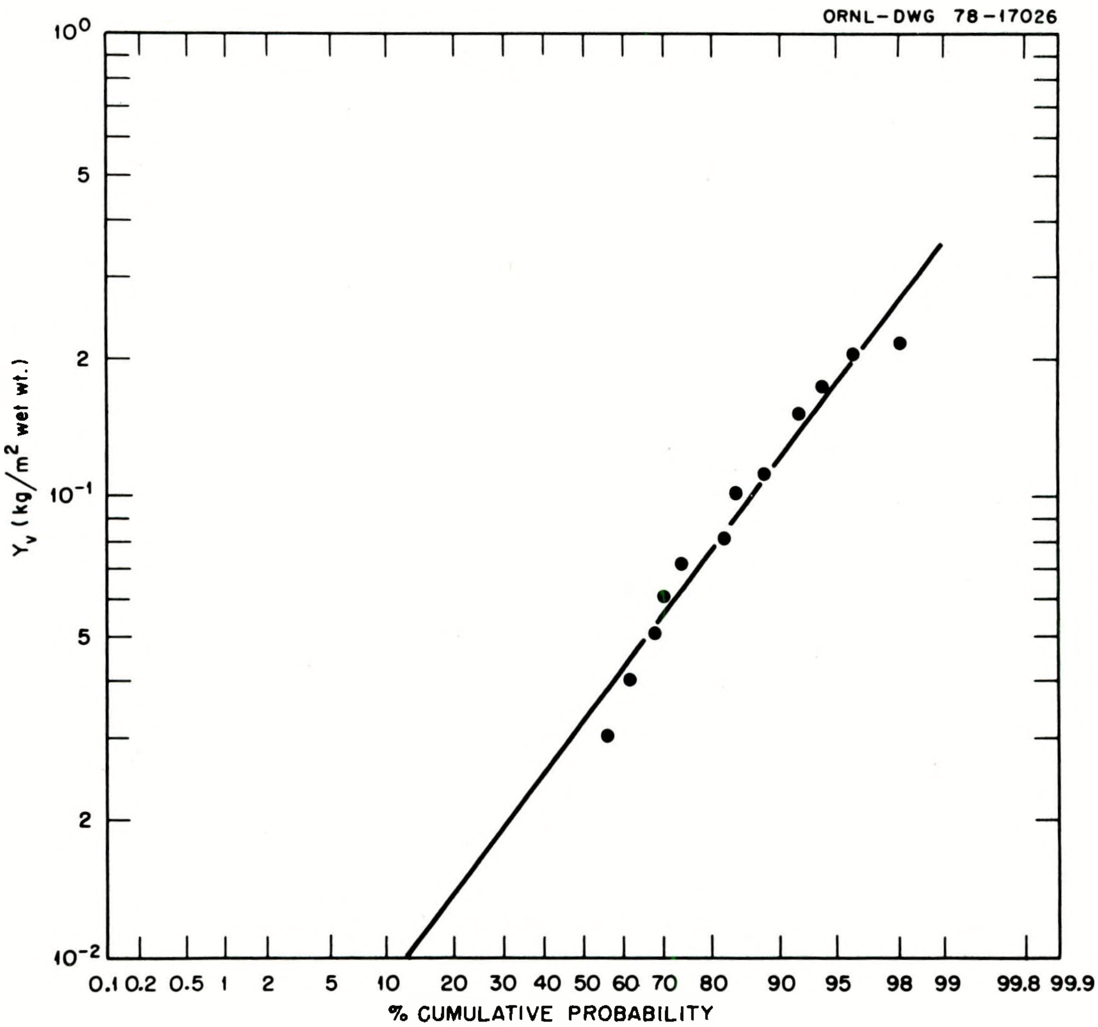

Fig. 3.4. Lognormal probability plot of agricultural productivity Y_V (standing crop biomass at harvest) for nuts.

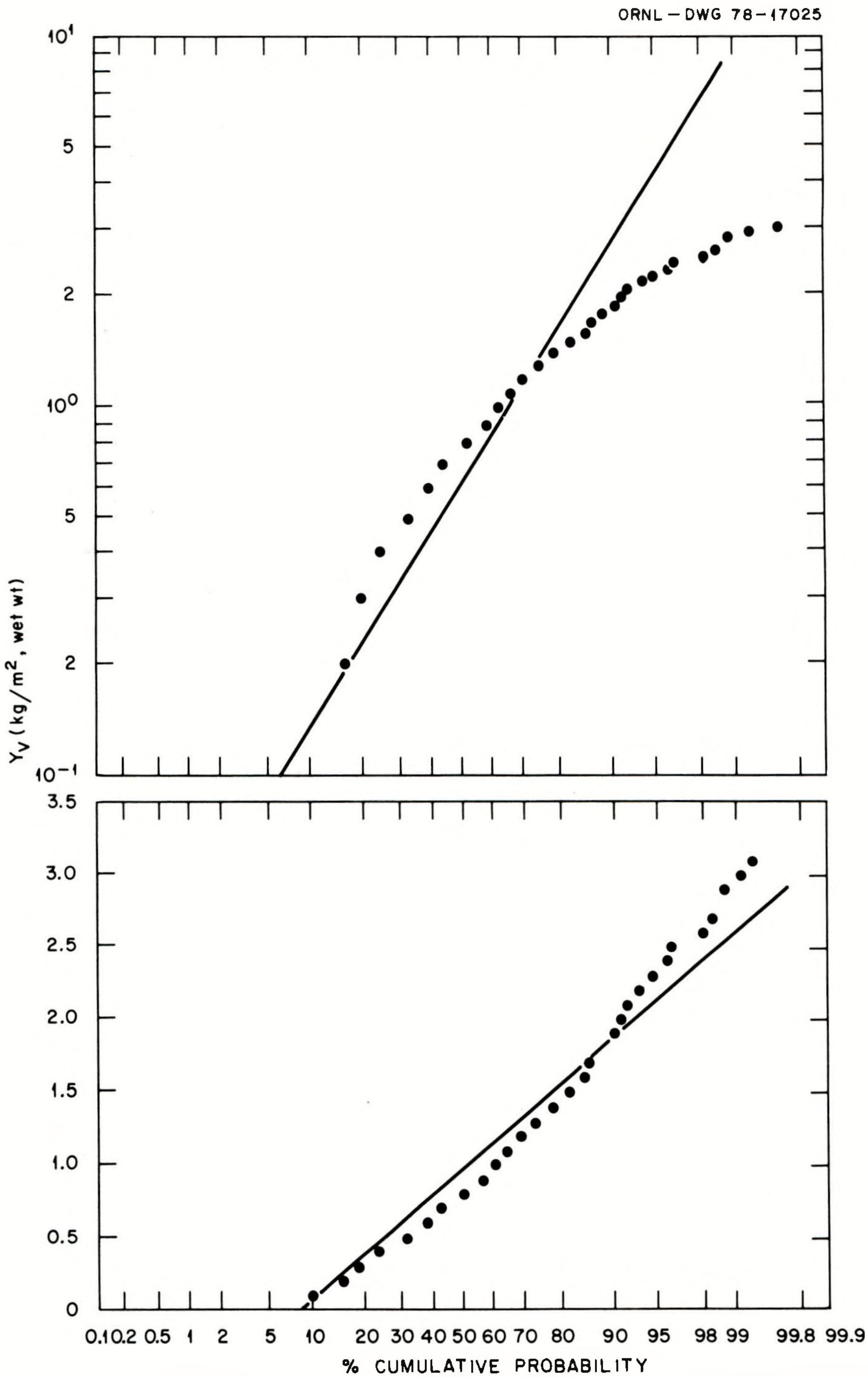

Fig. 3.5. Lognormal and normal probability plots of agricultural productivity Y_v (standing crop biomass at harvest) for fruits.

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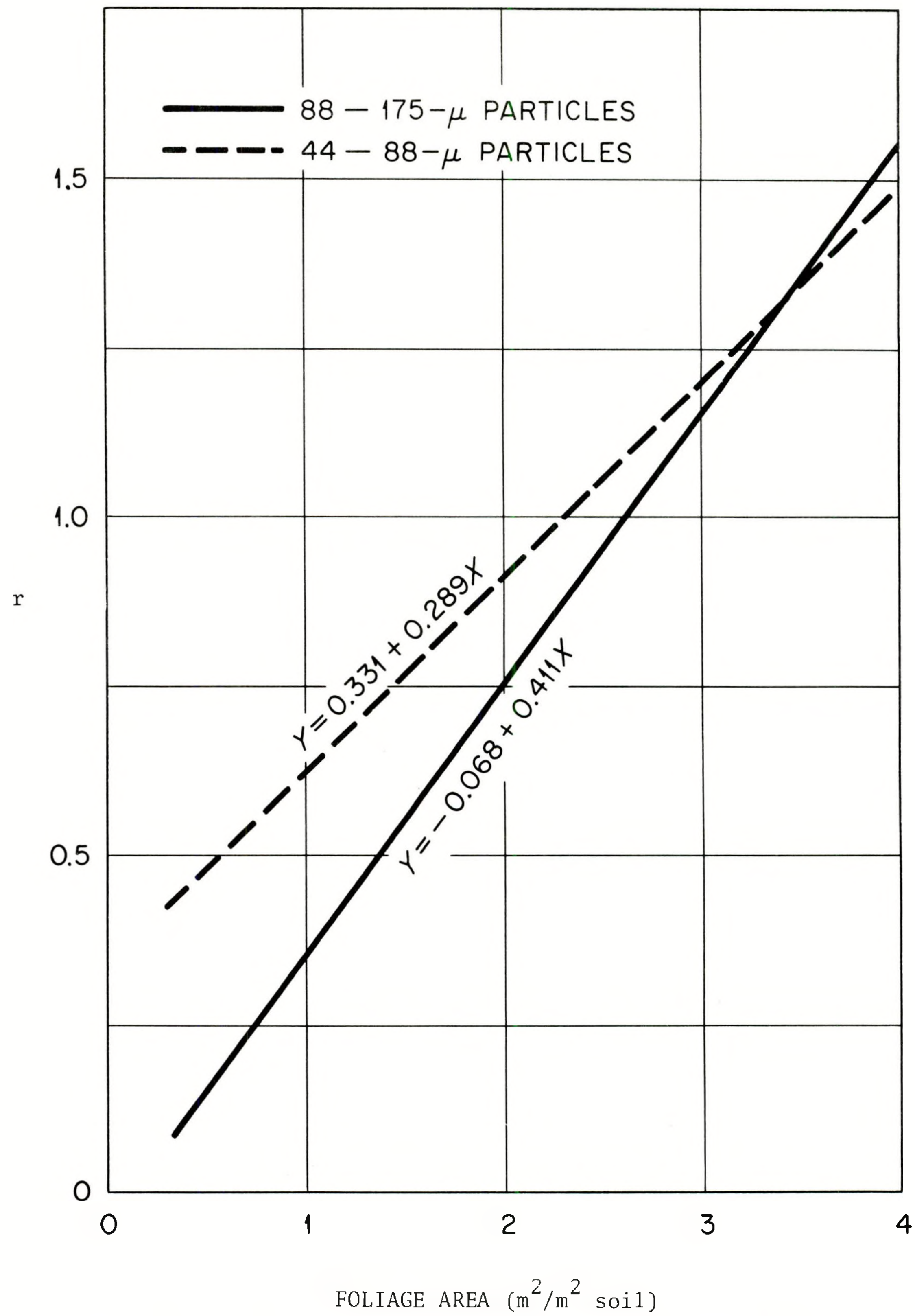

Fig. 3.6. Linear regression of the interception fraction r and foliage area (after Witherspoon and Taylor 1970).

3.2 The Interception Fraction
(Charles W. Miller)

3.2.1 Description of the parameter

The interception fraction r is a parameter that represents the fraction of the total radioactivity being deposited from the atmosphere that is retained on aerial portions of crops, leafy vegetables, or pasture grasses. Deposition may be due to wet processes, dry processes, or a combination of both. The NRC currently recommends the following values for use in lieu of site-specific information (USNRC 1977b):

1. deposition for all radionuclides from irrigation spray = 0.25,
2. dry and wet deposition for radioiodine = 1.0,
3. dry and wet deposition for particulates = 0.2.

No explanation is given as to why a separate value of r is given for irrigation spray. One might expect r to be the same for irrigation spray as for other wet deposition processes.

3.2.2 Description of the data base

Measured values of r found in the literature for forage grasses are summarized in Table 3.5. A similar summary for vegetation other than grass is found in Table 3.6. Other measurements of aerosol deposition on vegetation can be found in the literature, for example Miller (1967) and Aarkrog (1969). The experimental techniques used in these studies, however, are not compatible with the definition of r as used by the NRC, because of artifically high vegetation densities and/or failure to specify the total quantity of material deposited. Only average values of r for each report are shown in Tables 3.5 and 3.6 since the value of r contained in NRC Regulatory Guide 1.109 should be an average value for the entire growing season.

A serious limitation of this data base is its small size. This is especially true for vegetation other than grasses (Table 3.6), where only a few species of vegetation are represented and at most three average measurements for any one species is available. The lack of data for leafy vegetables and many other garden crops is readily apparent.

Table 3.5 contains a mixture of results from both dry and wet deposition processes.

Chamberlain (1970) reviewed the first four experiments listed in Table 3.5. From these data, Chamberlain derived a relationship between r and the grass density Y_v as follows:

$$r = 1 - \exp(-\gamma Y_v) \; . \tag{3.2}$$

The constant γ was found to range between 2.3 and 3.3 m^2/kg (dry wt) when Y_v has the units kg/m^2 (dry wt). If Y_v is less than about 0.3 kg/m^2, Eq. (3.1) may be approximated by using a Maclaurin's series and retaining only the first term. This results in

$$r = \gamma Y_v \; . \tag{3.3}$$

Such a direct relationship between r and Y_v [Eq. (3.3)] has been used for both wet and dry deposition estimates in other studies (Pelletier and Voillequé 1971). The model represented by Eq. (3.2) has been verified using the other data contained in Table 3.5 and the sorghum data contained in Table 3.6 (Miller 1979).

3.2.3 Results

The p.d.f. of observed r values for forage grasses (Table 3.5) more nearly approximated a normal rather than a lognormal distribution (Fig. 3.7). These data have a mean value of 0.47 with a standard deviation of 0.30. A similar analysis was not performed for the data in Table 3.6 because of the limitations in the data set as discussed above.

It is generally assumed that the parameters used in the dose assessment model are statistically independent of one another. Equation (3.2) indicates, however, that r and Y_v are not independent of one another. Because of this high correlation, and because r and Y_v appear in the dose assessment model as the ratio r/Y_v, the variability of the ratio r/Y_v for forage grasses was also determined.

The p.d.f. of this ratio more nearly approximated a lognormal rather than a normal distribution (Fig. 3.8). As a result, the statistical parameters for estimating the uncertainty in r/Y_v shown in Table 3.7 were calculated using Eqs. (2.1) through (2.13). About a factor 2.8 separates the median value of r/Y_v from the 99*th* percentile.

As mentioned earlier, the values of r recommended by the NRC are 0.25 for irrigation spray, 0.2 for deposition of particulates, and 1.0 for deposition of radioiodine. The NRC-recommended default value of Y_v for the grass-cow-milk-man pathway is approximately 0.175 kg/m^2, dry weight, assuming that fresh grass is 25% dry matter. Using these values of r and Y_v results in $r/Y_v = 1.4$ for irrigation spray, $r/Y_v = 1.1$ for particulates, and $r/Y_v = 5.7$ for radioiodine.

It has been suggested that values of r for assessment purposes can be generated using Eq. (3.2) and values of Y_v (Garten 1978; Miller 1979). In Sect. 3.1 of this report, a statistical analysis of Y_v for various agricultural products is presented. Experimental values from this data base for forage grasses and silage (corn and sorghum) were used in Eq. (3.2) to generate values of r. A γ value of 2.8 was used (Garten 1978).

Shown in Table 3.7 for comparison purposes are the statistical parameters for estimating the uncertainty in r/Y_v as generated by Eq. (3.2). The p.d.f.'s of r/Y_v for both forage grasses and silage appear lognormally distributed (Fig. 3.9). If these values of r and Y_v had been derived from independent measurements of r and Y_v, and if r and Y_v are assumed to be lognormally distributed, the variance of the ratio between them, σ^2_{r/Y_v}, would then be given by Bevington (1969):*

$$\sigma^2_{r/Y_v} = \sigma^2_r + \sigma^2_{Y_v} - 2\,\rho\sigma_r\sigma_{Y_v} \qquad (3.4)$$

where ρ = the correlation coefficient between r and Y_v .

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*Because r and Y_v are assumed to be lognormally distributed, the formula for σ^2_{r/Y_v} is that of a difference not a quotient.

Since this is clearly not the case for these generated data, Eqs. (2.1) through (2.13) were again used to calculate the appropriate statistical parameters. The value of σ (0.22) was found to be a factor of 2 less than the σ associated with measured data (Table 3.7).

The values of Y_v for pasture grasses used in the model are not the most appropriate values which could be used to generate r values, because these values of Y_v represent standing crop biomass at harvest. Measured values of Y_v (standing crop biomass) for pasture vegetation actively being grazed by cattle would be more appropriate for generation of r for pasture vegetation.

3.2.4 Limitations

More measured values of r on forage grasses are needed. Because of the small size of the data set used in this study the addition of more data could markedly affect the statistical results reported herein. These measurements could also be used to validate further Eq. (3.2). Also, more measurements of r specific for the edible portions of other crops and leafy vegetables are needed to estimate the uncertainty associated with r for these items.

The use of r in estimating the dose to man assumes that the total amount of material deposited within a specified area has been determined. This is the assumption incorporated in NRC Regulatory Guide 1.111 (1977b) from which deposition rates are calculated and input to NRC Regulatory Guide 1.109 (1977a). However, the values for the deposition velocities applied to the methodologies incorporated within NRC Regulatory Guide 1.111 were taken from measurements of ^{131}I deposition at Idaho Falls, Idaho (Markee 1967). These are measurements of deposition onto grass above a specified area of ground and not the total deposition onto that ground area (Pelletier and Zimbrick 1970). As a result, it is appropriate to use a value of r = 1.0 for radioiodine vapor. For other radionuclides and other physicochemical forms of iodine, the grass-specific deposition velocity for iodine vapor used to produce values of deposition rate in NRC Regulatory Guide 1.111 (1977b) may not be an appropriate transfer factor for total deposition (Miller et al. 1978, Hoffman 1977). To utilize values of $r < 1$, properly, deposition velocities representative of total deposition for each depositing substance of concern must be used in the calculation of a deposition rate from a given air concentration. Alternatively, deposition velocities specific for each substance and foliage surface (grass, vegetables, etc.) could be used with $r = 1.0$.

Table 3.5. Summary of experimental measurements of r and r/Y_v for forage grasses

Reference	Depositing material	Depositing surface	r	Y_v (kg/m^2, dry wt)	r/Y_v (m^2/kg, dry wt)
Milbourn and Taylor 1965	Time spray of water droplets containing ^{89}Sr in solution	Variety of pasture species, including both grasses and clover	0.23	0.094	2.93
Chadwick and Chamberlain 1970	Spray of droplets containing ^{89}Sr, ^{51}Cr, and ^{210}Pb in solution; suspension of 1-μm-diam polystyrene particles tagged with ^{51}Cr	Mixture of grasses, including a little clover and many weeds	0.38	0.166	2.36
Chamberlain 1967 as cited in Chamberlain 1970	30-μm-diam Lycopodium spores tagged with ^{131}I	Long established grassland	0.44	0.200	2.34
Chamberlain and Chadwick 1966 as cited in Chamberlain 1970	Elemental ^{131}I vapor	Mixture of grasses and broad leafs such as dandelion, clover, and vetch	0.50	0.291	1.97

Witherspoon and Taylor 1970	44-88-μm-diam particles	Lespedeza	0.02	0.020	1.00
	88-175-μm-diam particles	Lespedeza	0.08	0.020	4.00
Peters and Witherspoon 1972	44-88-μm-diam particles	Fescue	0.69	0.44	1.57
		Bluegrass	0.79	0.57	1.39
		Bermuda	0.82	0.52	1.58
		Zoysia	0.77	0.75	1.03

Table 3.6. Summary of experimental measurements of r and r/Y_V for above ground portions of vegetation other than grasses

Reference	Diameter of depositing particles (μm)	Vegetation	r	Y_V (kg/m^2, dry wt)	r/Y_V (m^2/kg, dry wt)
Witherspoon and Taylor 1970	44-88	Squash plants	0.89	0.069	12.9
		Soybean	1.2[a]	0.12	10.0
		Sorghum	0.11	0.058	1.9
		Peanut plants	0.06	0.048	1.25
	88-175	Squash plants	1.2[a]	0.069	17.4
		Soybean	1.0	0.12	8.3
		Sorghum	0.49	0.058	8.5
		Peanut plants	0.10	0.048	2.1
Witherspoon and Taylor 1971	1-44	Soybean			
		Leaves	0.32	0.14	2.3
		Stem	0.07	0.10	0.7
		Total	0.40	0.25	1.6
		Sorghum			
		Leaves	0.09	0.06	1.5
		Stem	0.004	0.07	0.06
		Axil	0.29	0.004	72.5
		Total	0.38	0.14	2.7

[a]Values of $r > 1$ due to bush-like form of the plants in combination with the experimental methods.

Note: Values of Y_V and r in this table are representative of the entire above-ground portion of the plant. Values of Y_V in this table are not comparable with Y_V values in Table 3.4 because the latter Y_V values are specific only to the *edible* portion of the plant.

Table 3.7. Estimation of uncertainties associated with r/Y_v [a]

Vegetation type	μ	σ	n[b]	m^2/kg, dry wt							
				X_p	X_m	$\bar{X}$	X_{99}	NRC			Range of observed values
Forage[c,d] grasses, experimental	0.61	0.44	10	1.52 (0.33)[e]	1.84 (0.50)	2.03 (0.59)	5.12 (0.99)	1.1 (0.13)	1.4 (0.26)	5.7 (0.99)	1.0 — 4.0
Forage[c,f] grasses, modeled	0.55	0.22		1.65 (0.41)	1.73 (0.50)	1.78 (0.54)	2.89 (0.99)	1.1 (0.02)	1.4 (0.16)	5.7 (1.0)	
Silage[c,f] modeled	0.14	0.27		1.07 (0.39)	1.15 (0.50)	1.19 (0.55)	2.16 (0.99)	1.1 (0.45)	1.4 (0.76)	5.7 (1.0)	

[a]All estimates of r/Y_v based on lognormal statistics.

[b]n = number of observed values.

[c]Values accurate to two significant figures; three are shown for clarity.

[d]Experimental data from Table 3.5.

[e]Values in parenthesis indicate cumulative probability, $P(X \leq X_u)$.

[f]Modeled data are based on experimental values of Y_v and Eq. 3.2 using a value of $\gamma = 2.8$.

Note: The NRC default values are 5.7 for radioiodines, 1.4 for irrigation spray, and 1.1 for particulates.

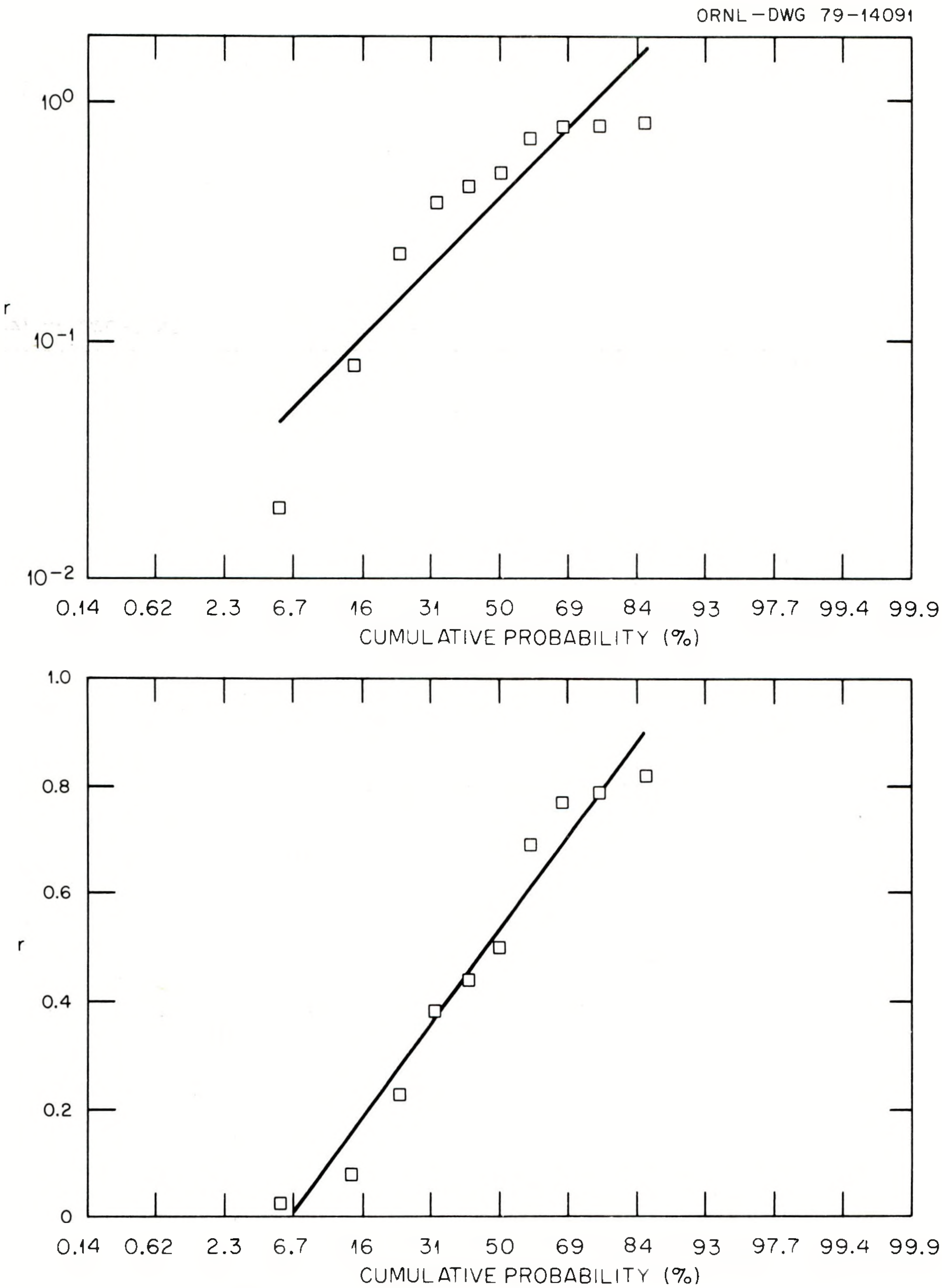

Fig. 3.7. Lognormal and normal probability plots of measured values of the interception fraction r for forage grasses.

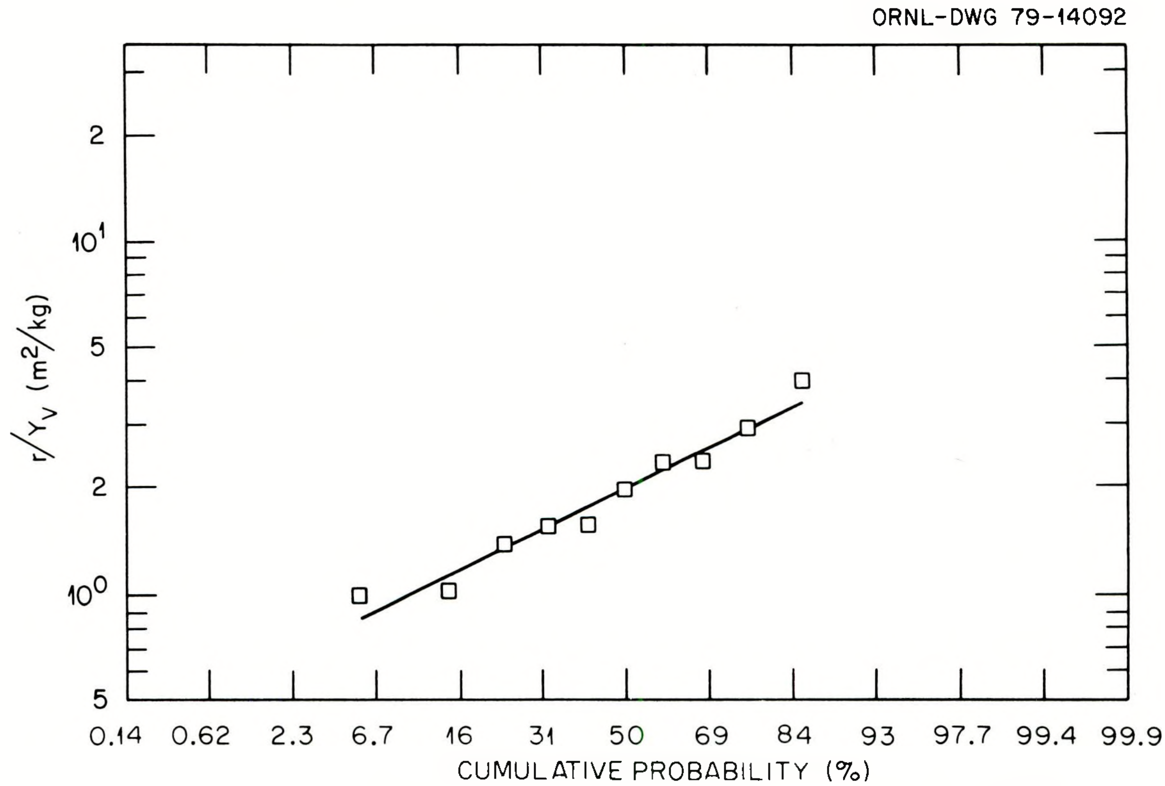

Fig. 3.8. Lognormal probability plot of measured values of r/Y_V for forage grasses.

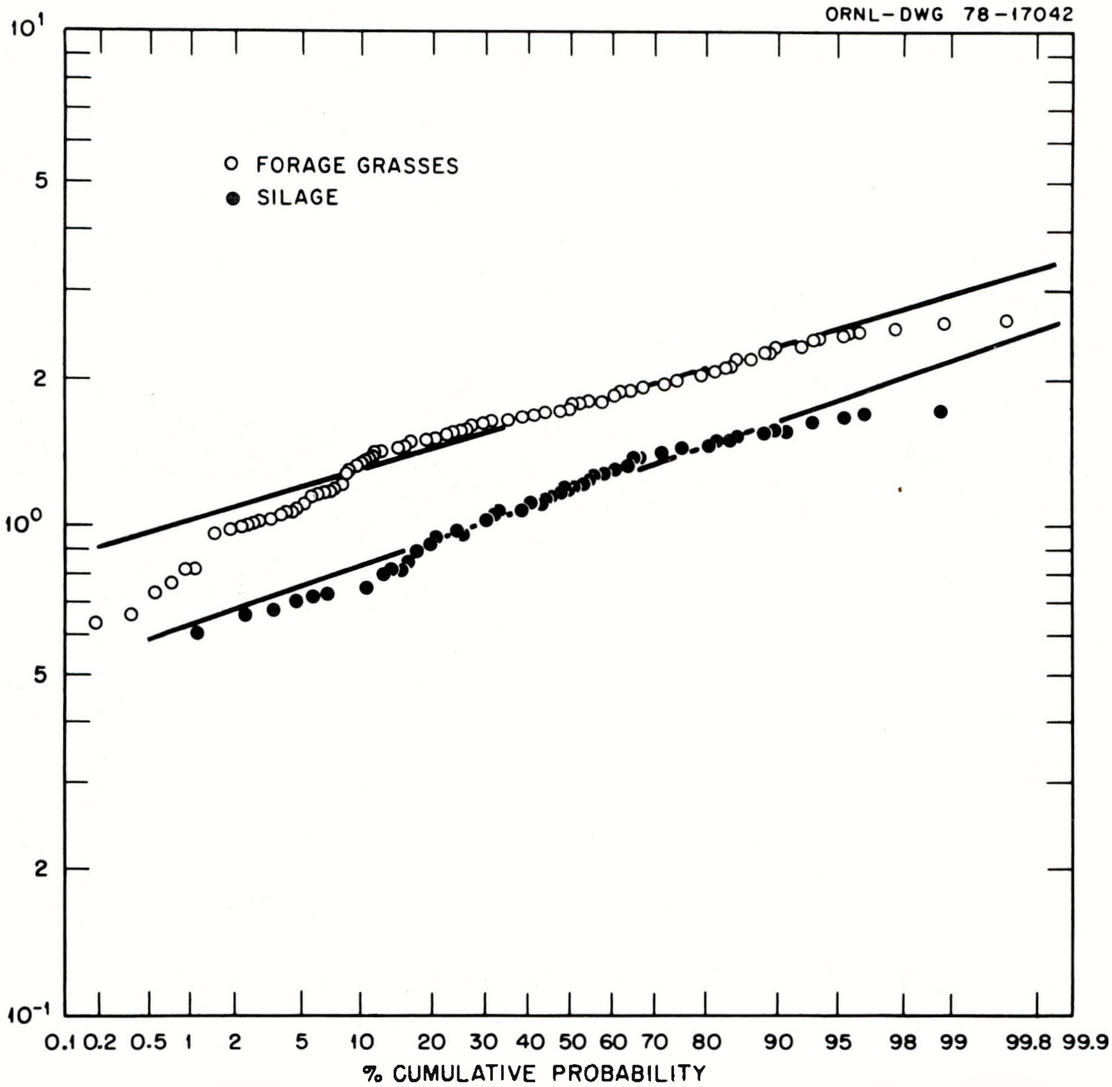

Fig. 3.9. Lognormal probability plots of r/Y_v for forage grasses and silage based on estimated values of the interception fraction r derived from Chamberlain's model (1970) and measured values of agricultural productivity, Y_v.

3.3 The Environmental Loss Constant for Radionuclides Deposited on the Surfaces of Vegetation, λ_w

(Charles W. Miller and F. Owen Hoffman)

3.3.1 Description of the parameter

After radionuclides are deposited on the surfaces of vegetation, environmental removal processes will combine with radioactive decay to reduce the quantity of initial contamination on the vegetation surface (Chamberlain 1970). The time necessary for one-half of the radioactivity to be removed by environmental processes is referred to as the environmental half-time, T_w. This parameter is related to the environmental loss constant λ_w as follows:

$$\lambda_w = \frac{\ln 2}{T_w} . \qquad (3.5)$$

In NRC Regulatory Guide 1.109 (1977a), λ_w appears in the denominator of the model. The reciprocal of λ_w is the equivalent of $T_w/\ln 2$. The default value recommended by the NRC is T_w = 14 days, or $\lambda_w = 5 \times 10^{-2}$ day^{-1}.

Considering radioactive decay with environmental loss processes, an effective half-life T_{eff} or loss constant λ_{eff} can be calculated as follows:

$$T_{eff} = \frac{T_w \cdot T_r}{T_w + T_r} \text{ and} \qquad (3.6)$$

$$\lambda_{eff} = \lambda_w + \lambda_r , \qquad (3.7)$$

where

T_r = radiological half-life,

λ_r = radiological decay constant.

3.3.2 Description of the data base

The data base used in this analysis is summarized in Tables 3.8 and 3.9. Table 3.8 includes nine T_w values reported in the literature for particulates deposited on grasslands and six T_w values for particulates deposited on other types of vegetation. Table 3.9 summarizes ten T_w values for molecular and particulate iodines deposited on pasture grasses and lists calculated T_{eff} values appropriate for ^{131}I. Values of T_w may be expected to vary markedly depending on the growth of vegetation, climate, and season. Thus, only average values of T_w were incorporated into Tables 3.8 and 3.9. The values used in the NRC Regulatory Guide 1.109 should be a representative average of an entire growing season. One limitation of the data base listed in Table 3.8 is its small size. Further, Table 3.8 is a mixture of results obtained under both dry and wet conditions. However, the value of T_w for molecular iodine has not been shown to be influenced by variations in these conditions (Heinemann et al. 1976). Also, the values of T_w reported here are overall time-averaged T_w values representative of a single exponential decay process. Other investigators (Witherspoon and Taylor 1970, 1971; Peters and Witherspoon 1972) indicate, however, that retention curves should be divided into appropriate post-application time components for half-life analysis.

3.3.3 Results

A lognormal probability plot of T_w values for particulates on grasses (Fig. 3.10) and all T_w values (Fig. 3.11) from Table 3.8 were made. Only the summer value from Chadwick and Chamberlain (1970) was used in Fig. 3.10. Both plots illustrate variability in the measured values. The values in Table 3.9 are plotted in Fig. 3.10.

Figures 3.8 through 3.10 indicate that the assumption of a lognormal distribution is reasonable, and the results of the statistical analysis (Eqs. 2.3 through 2.13) are presented in Table 3.10. Corresponding values of λ_w or λ_{eff} can be obtained using Eq. (3.5).

Table 3.8. Measured values of T_W for particulates on vegetation

T_W (days)	Depositing material	Reference
12.5	^{89}Sr sprayed on grassland	Milbourn and Taylor (1965)
27 (summer) 71 (winter)	^{85}Sr sprayed as a solution of $SrCl_2$ on grassland	Chadwick and Chamberlain (1970)
10.5	^{137}Cs from Windscale accident on Seascale pasture	Booker (1958)
13.5	^{95}Zr from Windscale accident on Seascale pasture	Booker (1958)
13	^{131}I particulate fallout on pasture	Knapp (1963) as cited by Thompson (1965)
14	^{89}Sr sprayed on grass	Bryant (1964)
14	^{144}Ce sprayed on grass	Bryant (1964)
13.5	$^{103-106}Ru$ from Windscale accident on Seascale pasture	Booker (1958)
8.7	^{54}Mn, ^{89}Sr, ^{95}Zr, ^{106}Ru, ^{131}I, ^{137}Cs, and ^{144}Ce sprayed on young cabbage plants	Middleton and Squire (1961)
17	^{131}I particulate fallout on desert shrubs	Martin (1965)
28	^{89}Sr fallout on desert shrubs	Martin (1965)
13	^{131}I particulate fallout on desert shrubs	Martin (1964)
27	^{89}Sr fallout on desert shrubs	Martin (1964)
26	^{90}Sr fallout on desert shrubs	Martin (1964)

Table 3.9. Environmental half-time T_w reported for molecular and particulate iodines deposited on pasture forage and the corresponding effective half-life T_{eff} calculated for ^{131}I

T_w (days)	T_{eff} (days)	Comments	Reference
6.5	3.6	Average for growing pasture grasses	Markee (1967)
7.2	3.8	Average of seven experiments using stable $^{127}I_2$	Heinemann et al. (1976)
6.5	3.6	Derived from data on grass contamination near Monticello Nuclear Power Station	Weiss et al. (1975)
12.5	4.9	Values for growing grasses affected by Windscale release	Booker (1958)
13.2	5.0	Data summarized by Black and Barth, (1976)	James (1964)
12.5	4.9	Data summarized by Black and Barth, (1976)	Knapp (1963)
13.2	5.0	Data summarized by Black and Barth, (1976)	Comar et al. (1967)
13.2	5.0	Data summarized by Black and Barth, (1976)	Marter (1963)
8.0	4.0	Data summarized by Black and Barth, (1976)	Soldat (1965)
3.8	4.2	Pasture grasses sprayed with aerosol containing ^{131}I	Black and Barth (1976)

Table 3.10. Statistical analysis of T_W for particulates and iodines and T_{eff} for ^{131}I

Parameter	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Observed range
				days					
T_W, particulates on grasses[a]	2.7	0.26	9	13.9 (0.40)[b]	14.9 (0.50)	15.4 (0.55)	27.2 (0.99)	14 (0.41)	10.5-27
T_W, particulates on grasses and other vegetation	2.8	0.37	13	14 (0.36)	16 (0.50)	17 (0.57)	37 (0.99)	14 (0.33)	8.7-28
T_W, iodine on grasses[a]	2.3	0.31	10	9.06 (0.38)	10.0 (0.50)	10.4 (0.56)	20.5 (0.99)	14 (0.86)	6.5-13
T_{eff} for ^{131}I[a]	1.5	0.14	10	4.39 (0.44)	4.48 (0.50)	4.53 (0.53)	6.21 (0.99)	5.1 (0.82)	3.8-5

[a]Values accurate to 2 significant figures. Three are shown for clarity.

[b]Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

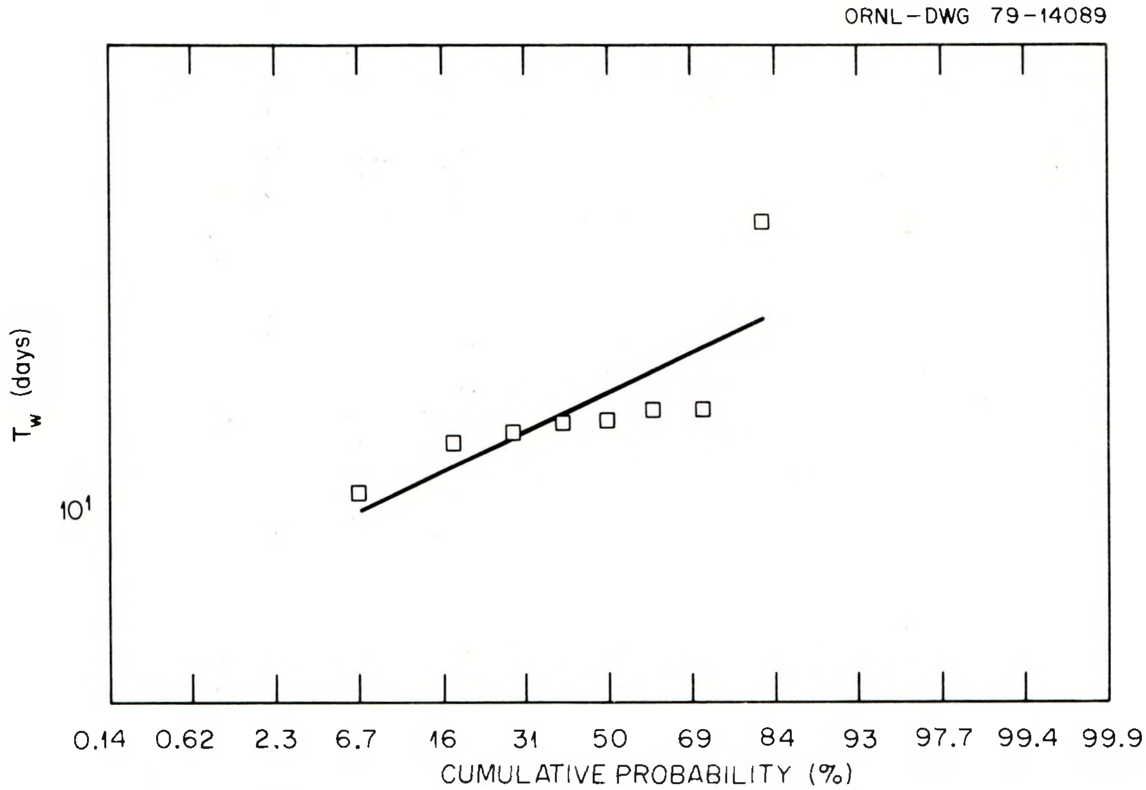

Fig. 3.10. Lognormal probability plot of the environmental half-time T_W for particulates on grasses.

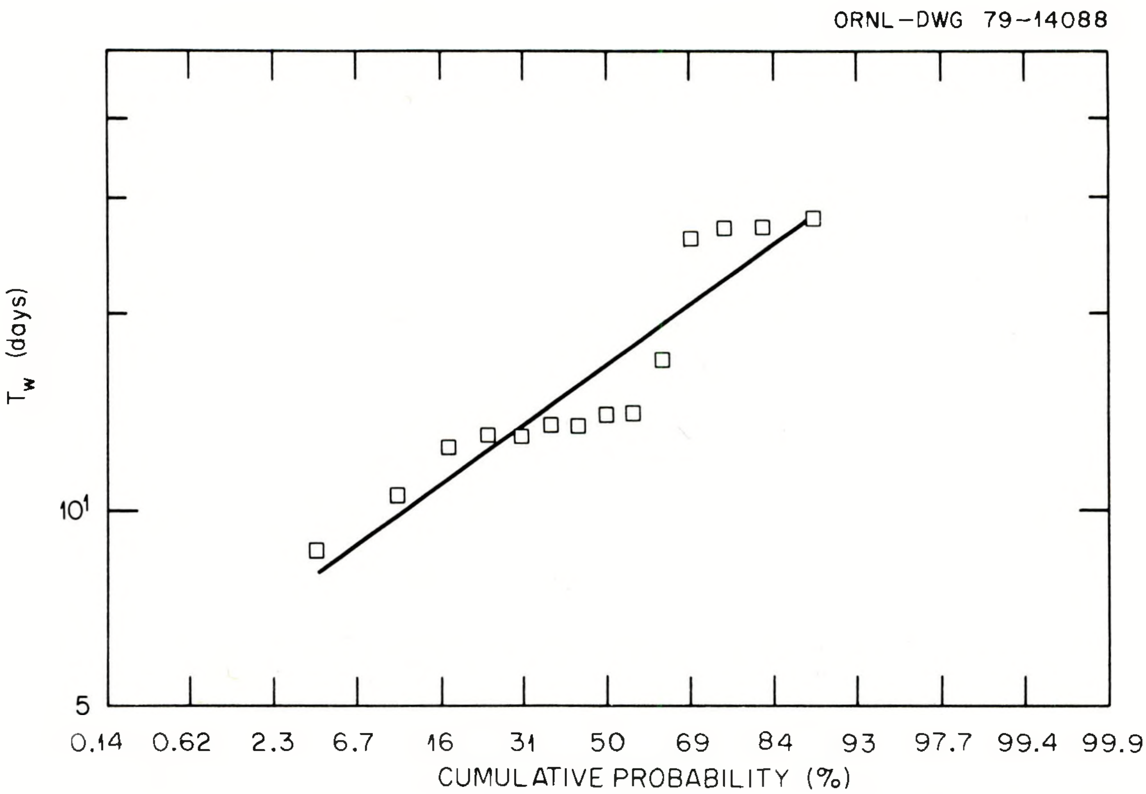

Fig. 3.11. Lognormal probability plot of the environmental half-time T_w for particulates and aerosols on grasses and other vegetation.

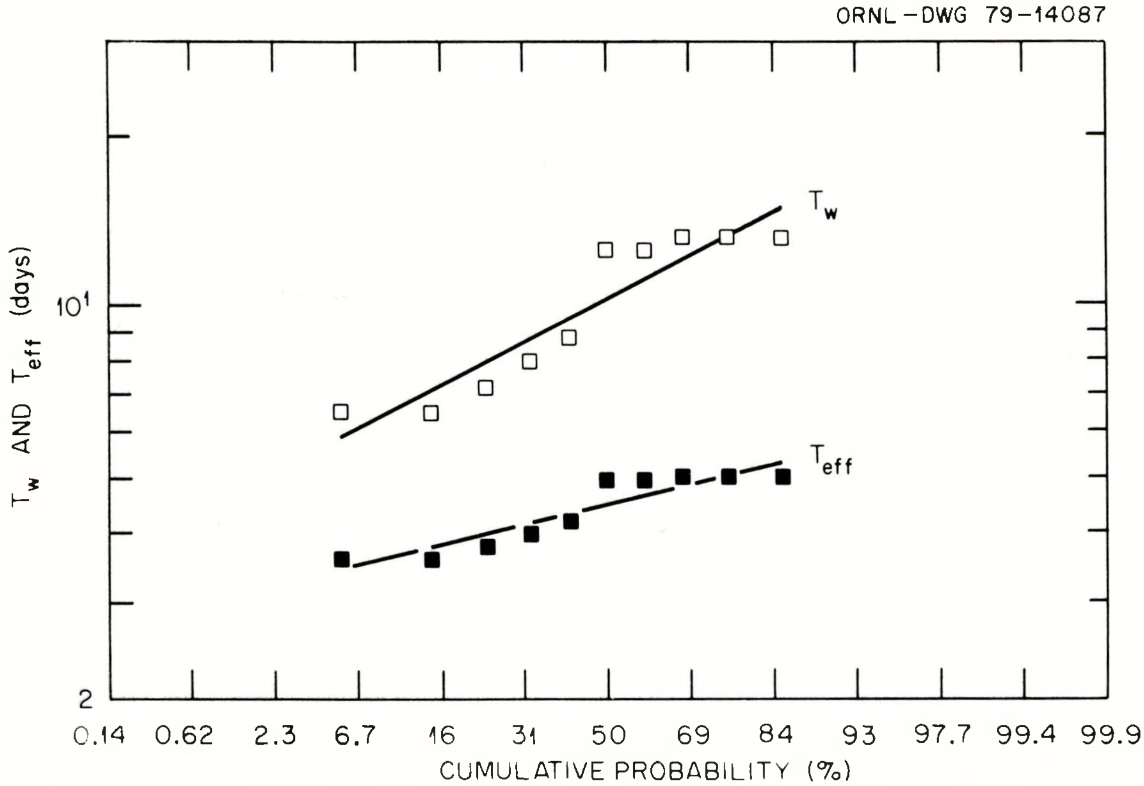

Fig. 3.12. Lognormal probability plots of the environmental half-time T_w for molecular and particulate iodines on pasture grasses and the corresponding effective half-life T_{eff} for ^{131}I on pasture grasses.

3.4 Animal Feed Consumption Rate, Q_F

(Roberta W. Shor and David E. Fields)

3.4.1 Description of the parameter

The transfer of radionuclides to animal food products from contaminated vegetation is directly dependent on the quantity of vegetation ingested by the animal, Q_F. The value of Q_F recommended in NRC Regulatory Guide 1.109 (1977a) to be used in lieu of site-specific information is 50 kg per day per cow on a fresh weight basis. The equivalent value on a dry-matter basis is 12.5 kg per day per cow, assuming 25% dry matter. The parameter Q_F is considered in this study on a dry-matter basis because of the potential weighing errors caused by the variability in moisture content of fresh forage, as discussed in Sect. 3.1. An analysis of Q_F for dairy cows is made for total feed Q_F^T, succulents Q_F^S, succulents and hay Q_F^{S+H}, and concentrates Q_F^C. Succulents include silage and fresh cut pasture forage (green chop). Concentrates are composed mainly of feed grains.

3.4.2 Description of the data base and assumptions

Records obtained from the Dairy Herd Improvement Association (DHIA) provide data on about 3000 dry-lot dairy herds and about 11,500 partially pastured herds of dairy cows (Dickinson et al. 1978). About 11% of the entire U.S. dairy cow population is included in this data. The data, however, only represent values of Q_F averaged per herd of cows rather than among individual cows, so the analysis performed herein is only valid for among-herd variation.

Values of Q_F are given for succulents (silage and green chop), hay, and concentrates fed to dairy cows, but no values are reported for fresh pasture consumed by these animals. The 11,500 partially pastured herds of dairy cows could only be compared to the 3000 dry-lot herds to test for similarity of feeding habits. The data for Q_F, therefore, reflect only values derived from the 3000 dry-lot herds.

The conversion of feed quantities from weight reported "as fed" to the dry matter equivalent is necessary for the computation of total feed intake or for comparisons with experimental studies. The dry matter content of many feeds are listed in *Nutritional Requirements for Dairy Cattle* (National Academy of Sciences 1971) and in *Feeds and Feeding* (Morrison 1956). The factor used to convert dry forage and concentrates from "as fed" to dry matter is 0.9. A value of 0.3 is used for succulents. The most common feeds in each one of the three feed categories are corn grain for concentrates, alfalfa hay for hay, and corn silage and green chop for succulents. The dry matter content of these substances ranges from 86-93% for corn grain, 84-93% for alfalfa hay, and 28-43% for corn silage. Succulents, including corn silage and green chop, mostly range between 25-35% dry matter.

In evaluating the DHIA data, it should be noted that values reported for dry-matter intake may be slightly higher than for the entire U.S. cow population. A comparison of milk production of the DHIA herds with that of the average for the U.S. cow population indicates that the milk production is greater for the dry-lot DHIA herds, 5860 kg/year per cow, than for the entire U.S. population, 4951 kg/year per cow (USDA 1977). Therefore, the feed intake of the DHIA herds may be presumed to be larger by a proportional amount. A factor contributing to the larger milk production exhibited by the DHIA dry-lot herds is that about 90% of the cows were of the Holstein breed. Holsteins are larger, produce more milk, and eat more than other breeds in the United States (King et al. 1977). For this study, no correction is made to account for the fact that DHIA dairy herds are consuming more dry matter per day than the average for U.S. herds because of the lack of available feed statistics for U.S. herds. Therefore for this study Q_F values are representative for the Holstein breed.

3.4.3 Results

Dairy cows. The results presented for Q_F represent annual averages and reflect variability among herds, but they do not reflect variability among individual cows. Variability by year and by day is not inherent in the data. An examination of data for milk production indicates that average values of Q_F for total dry matter intake have been increasing over the years because of efforts to increase the volume of milk produced per cow (King et al. 1977).

Lognormal and normal probability plots of total average daily dry matter intake per cow Q_F^T, the average daily succulent intake per cow Q_F^S, the average daily succulent and hay intake per cow Q_F^{S+H}, and the average daily intake of concentrates per cow Q_F^C are presented in Figs. 3.13 through 3.16, respectively. These figures clearly indicate that the data more closely fit a normal than a lognormal distribution; although a lognormal fit does seem feasible for data occurring above the 10% cumulative probability level. The results in Table 3.11 are based on normal statistics. However, in the uncertainty analysis of the pasture-cow-milk pathway (Sect. 4), a lognormal distribution fit to Q_F^T values above the 10% cumulative percentile is used. Note: The solid lines in the lognormal plots in Figs. 3.13 through 3.16 were drawn to visually fit the data above the 10% cumulative probability.

Dairy goats. Few data are available for dairy goat feeding habits. A review of this subject by the chairman of the Subcommittee on Dairy Goat Nutrition of the National Research Council, National Academy of Sciences contains recommendations on feed consumption based on available experience (Haenlein 1978). These recommendations are as follows:

> A well managed doe of 40-50 kg body weight producing 2.5 ℓ/day of milk should eat about 2 kg/day, dry matter. This material may be composed of about 50% grass or leaves of bushes and trees. The remaining portion should be composed of stored feed.

This example is a good average for body weight and milk production according to the author. Because of the lack of data on Q_F for dairy goats, no statistical analysis is performed for this parameter.

Table 3.11. Statistical analysis of Q_F for herds of dairy cows

Parameter	Mean	Standard deviation	X_{99}	NRC	Range	Number of herds
	----------------------kg, dry wt per cow per day---------------					
Q_F^T [a]	16 (0.50)[b]	2.6	22 (0.99)	12.5 (0.10)	6-25	2927
Q_F^S [c]	6.8 (0.50)	2.1	12 (0.99)		3-13	2927
Q_F^{S+H} [d]	9.7 (0.50)	2.3	15 (0.99)		4-18	2927
Q_F^C [e]	6.2 (0.50)	1.5	9.7 (0.99)		1.6-11	2927

[a] Q_F^T is the average daily intake of total dry matter.

[b] Values in parentheses indicate the cumulative probability, $P(X \leq X_u)$.

[c] Q_F^S is the average daily intake of succulents.

[d] Q_F^{S+H} is the average daily intake of succulents and hay.

[e] Q_F^C is the average daily intake of concentrates.

Note: Above analysis based on normal statistics.

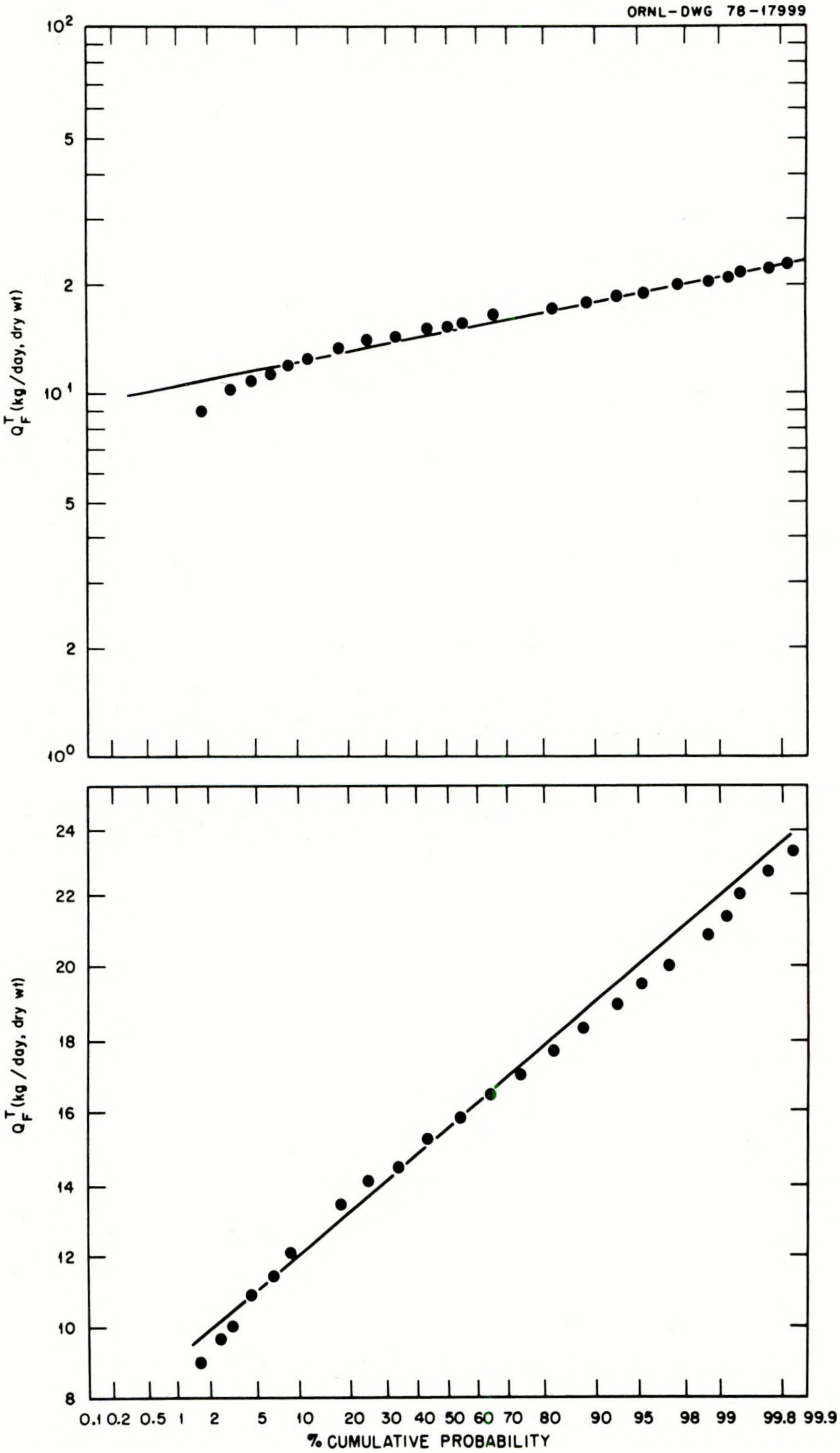

Fig. 3.13. Lognormal and normal probability plots of the average daily intake of toral dry matter Q_F^T by dairy cows.

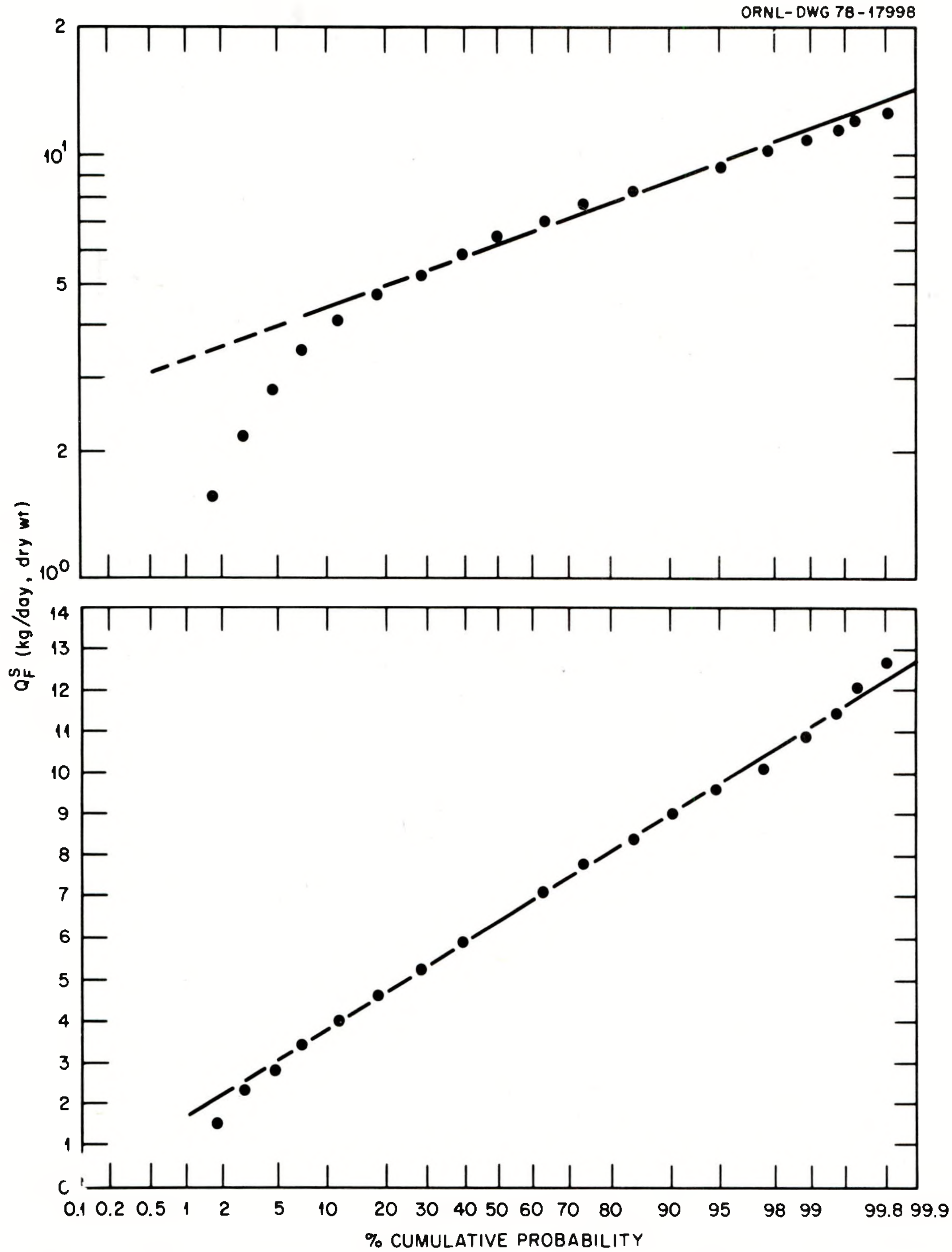

Fig. 3.14. Lognormal and normal probability plots of the average daily intake of succulents Q_F^S by dairy cows.

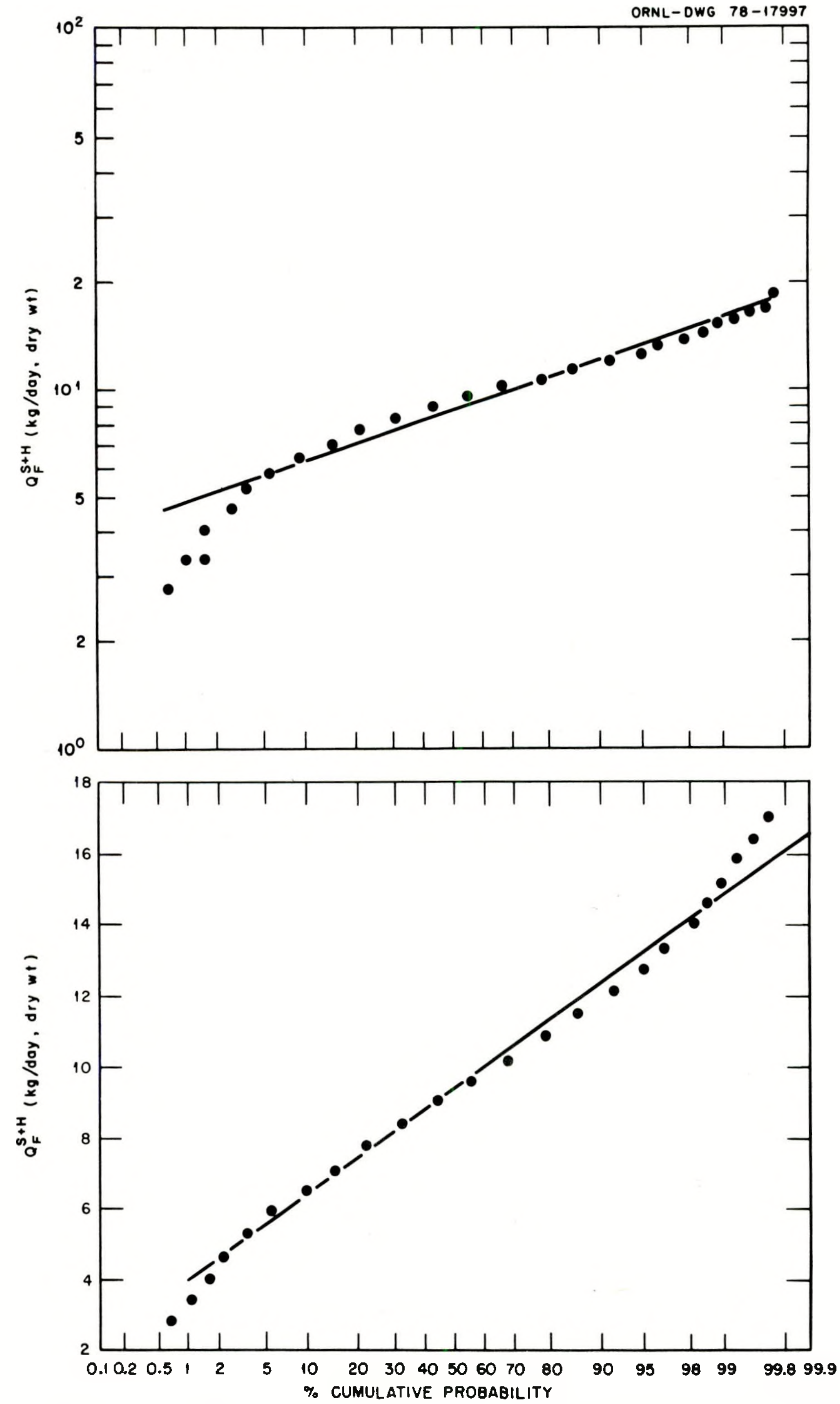

Fig. 3.15. Lognormal and normal probability plots of the average daily intake of succulents and hay Q_F^{S+H} by dairy cows.

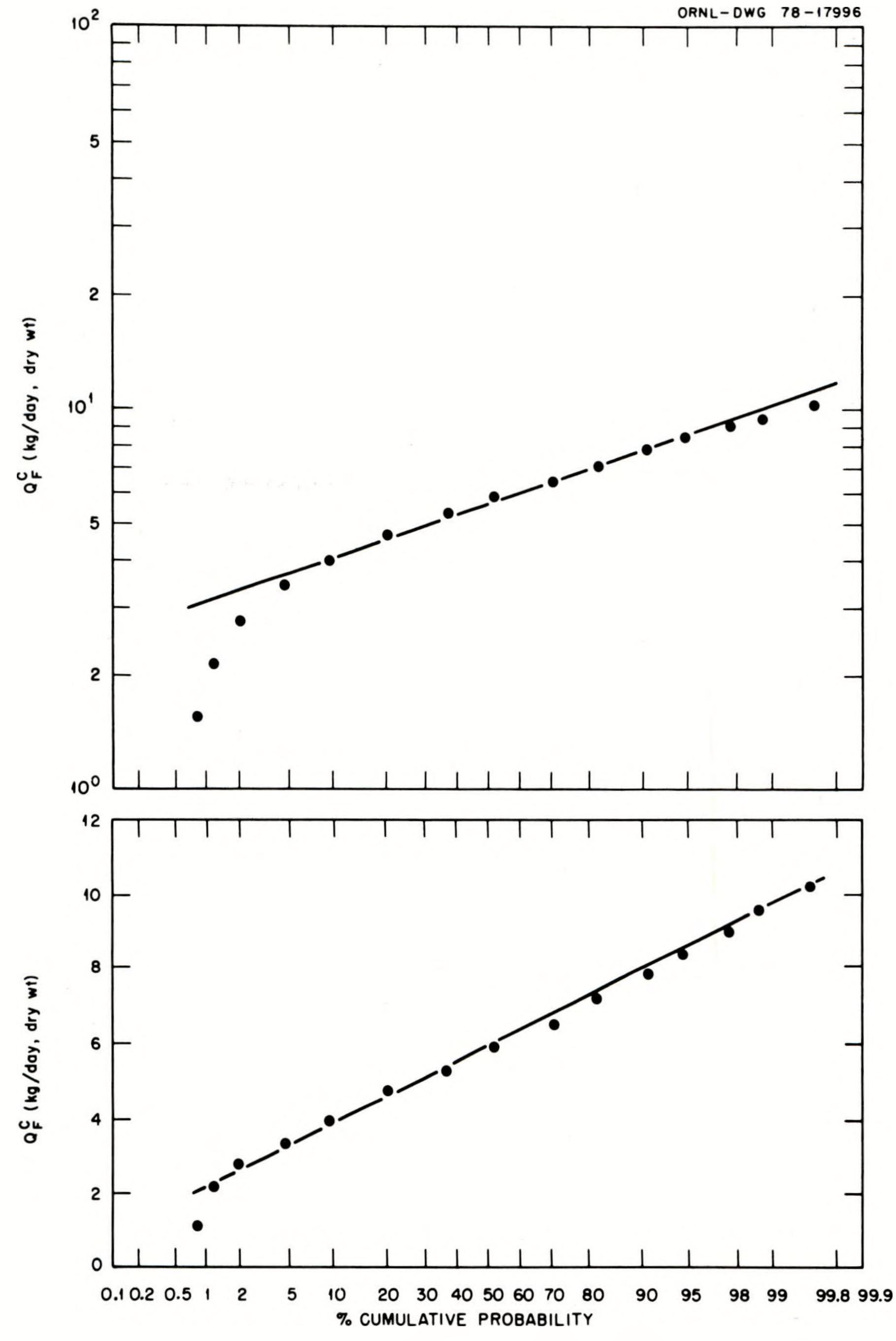

Fig. 3.16. Lognormal and normal probability plots of the average daily intake of concentrates Q_F^C by dairy cows.

3.5 The Fraction of Total Feed Composed of Fresh Forage, f_s, and the Fraction of the Year Fresh Forage is Utilized, f_p.

(Roberta W. Shor and David E. Fields)

3.5.1 Description of the data base and assumptions

All of the data used for an analysis of f_s and f_p were provided by the Dairy Herd Improvement Association (DHIA) through the Animal Physiology and Genetics Institute of the U.S. Department of Agriculture as described in Sect. 3.4. No values were obtained for the fraction of total feed composed of fresh forage. Therefore, the assumption was made that the amount of succulent feed given to dry-lot dairy cows would be similar to the amount of pasture consumed by pastured dairy cows during the grazing season. This assumption is based on data which indicate that during the time of the year when pasture growth is optimum for use, pasture forage will replace stored succulent feed (Parsons 1978). The University of Tennessee dairy herd, for example, is fed about 40% green chop during the summer months (Holmes 1978), which corresponds with the average amount of succulents fed to dry lot dairy cows as estimated from the DHIA data in Sect. 3.4. It is estimated that only 24% of the total dry matter intake is from direct grazing during an average 170 day grazing season in the southern region of the DHIA (Butcher and McCraw 1978), but the additional fraction of the total intake composed of green chop is not included in this estimate. The data used to estimate the fraction of the year when dairy cows are utilizing fresh forage f_p are derived from DHIA information on the number of days per year reported for about 11,500 dairy herds.

3.5.2 Results

Lognormal and normal probability plots for f_s are presented in Fig. 3.17. Again, the data appear more normally than lognormally distributed; however, values occurring above the 20% cumulative probability level are reasonably lognormal. The solid line in the lognormal plot in Fig. 3.17 was drawn to fit visually the data above the 20% cumulative probability level. Lognormal and normal probability plots for f_p are presented in Fig. 3.18. In this figure, the solid line in the lognormal plot visually fits the data above the 30% cumulative probability level. It should be noted that the parameter f_p should be reasonably easy to obtain on a site-specific basis. The results of the analysis of f_s and f_p are presented in Table 3.12 on the basis of normal statistics. As for Q_F^T a lognormal distribution is estimated for f_s and f_p above the 20% and 30% cumulative probability levels, respectively, for analysis of the pasture-cow-milk pathway in Sec. 4.

For all fractional parameters such as f_s and f_p the distributions are truncated. Theoretically, a value of 1.0 for such parameters cannot be exceeded. This should be noted when extrapolating values beyond the 99*th* percentile.

Table 3.12. A statistical analysis of f_p and f_s for herds of dairy cows

Parameter	Mean	Standard deviation	X_{99}	NRC	Range	Number of herds
f_s[a]	0.43 (0.50)[b]	0.13	0.73 (0.99)		0.1-0.8	2927
f_p[c]	0.40 (0.50)	0.22	0.91 (0.99)		0-1.0	11468

[a] f_s is the fraction of the total dry matter intake composed of fresh pasture forage per day per cow.

[b] Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

[c] f_p is the fraction of the year in which fresh forage is utilized by the cow.

Not Above analysis based on normal statistics; NRC default values are not provided because of the site-dependency of these parameters.

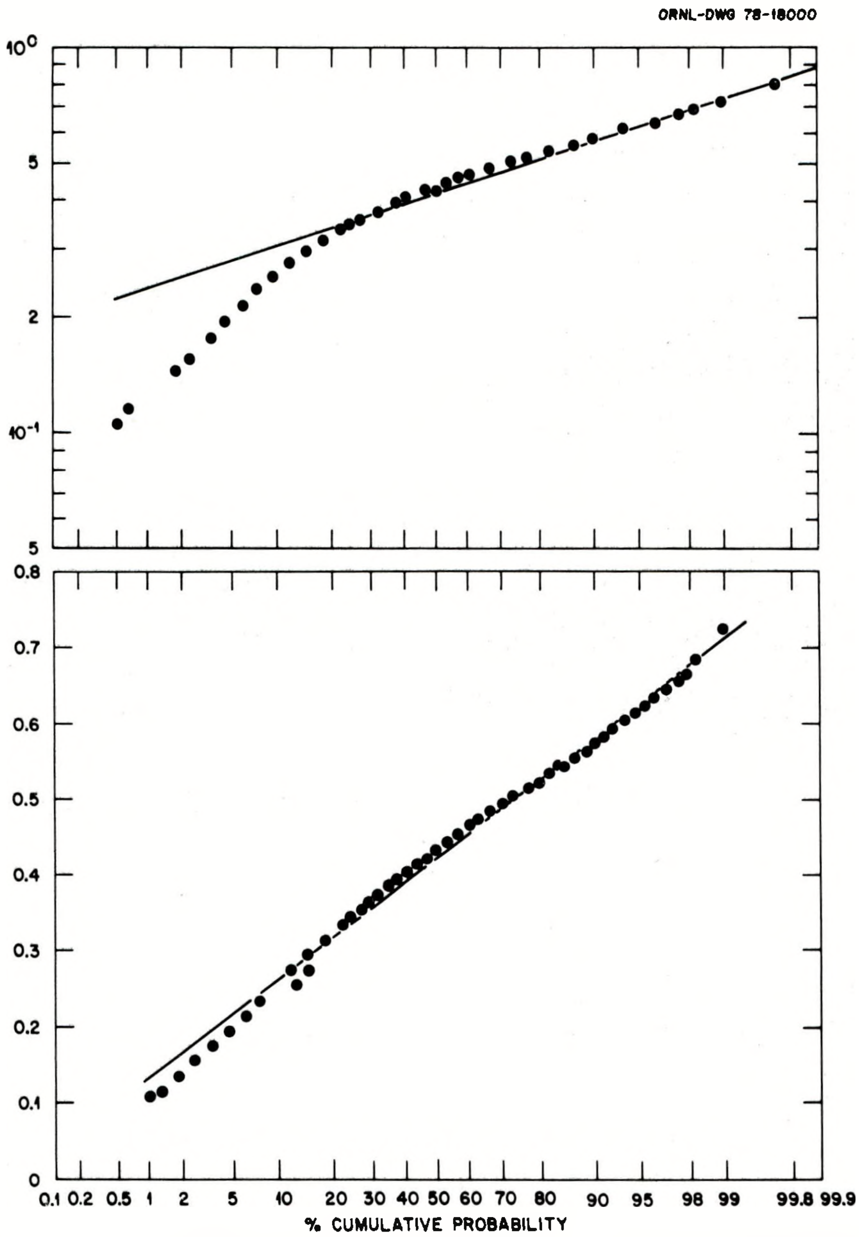

Fig. 3.17. Lognormal and normal probability plots of the fraction of total feed composed of fresh forage f_s for dairy cows.

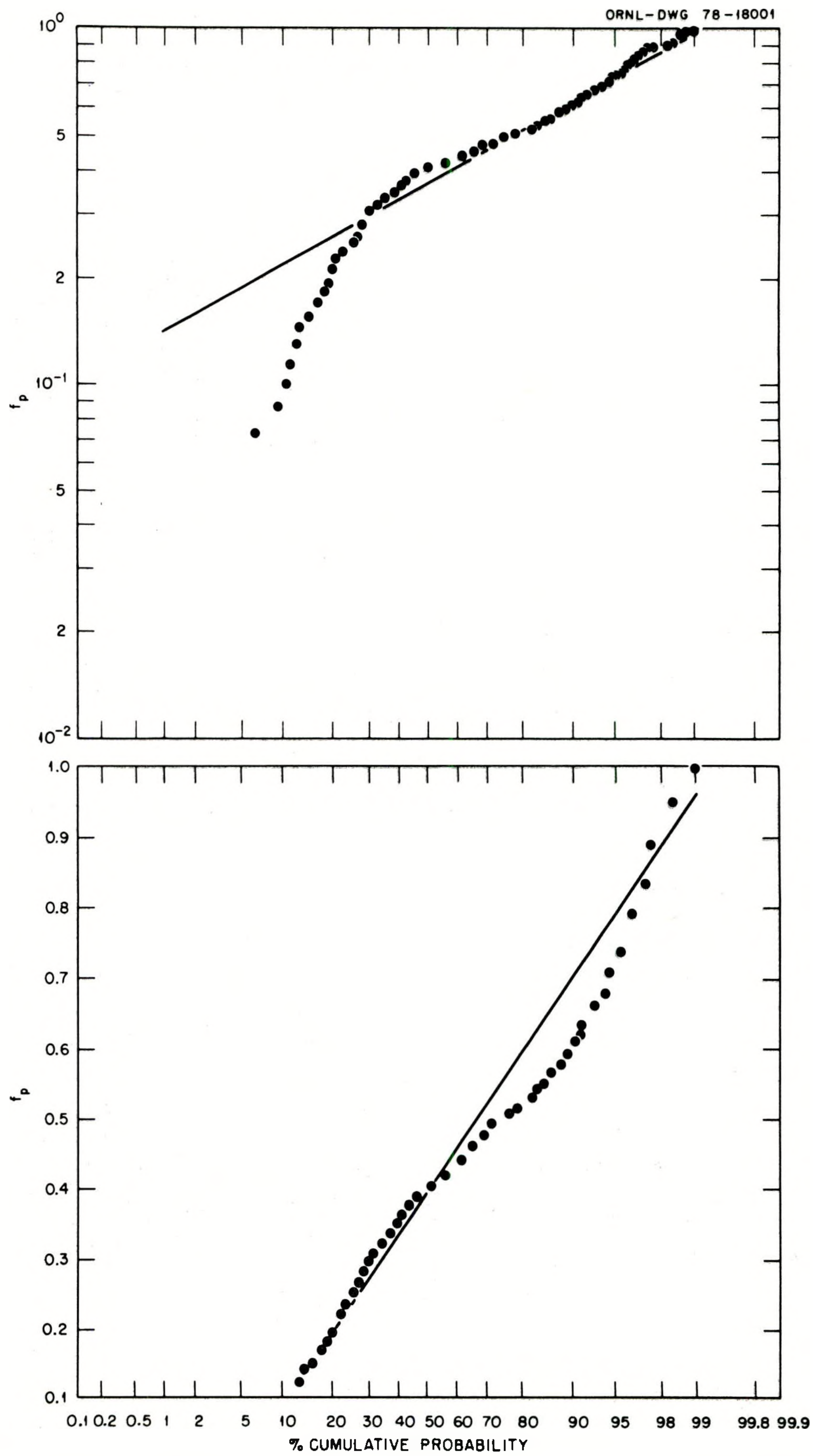

Fig. 3.18. Lognormal and normal probability plots of the fraction of the year when dairy cows are utilizing fresh forage, f_p.

3.6 The Coefficient for the Transfer of Radionuclides from Animal Intake to Milk, F_m.

(F. Owen Hoffman)

3.6.1 Description of the parameter

The ratio at equilibrium between the concentration of a radionuclide in milk and the daily amount ingested by a dairy animal (Ci/liter per Ci/day) is parameterized by the milk transfer coefficient F_m (day/liter). Generic default values given in NRC Regulatory Guide 1.109 (1977a) for F_m are based mainly on the values for stable elements in UCRL-50163, Part IV (Ng et al. 1968). This reference has been updated through a recent review of measured and derived values of F_m for both stable elements and individual radionculides (Ng et al. 1977). The generic default values in Regulatory Guide 1.109 (USNRC 1977a) are 6×10^{-3} day/liter for iodine, 8×10^{-4} day/liter for strontium, and 1.2×10^{-2} day/liter for cesium. These values are specific for the transfer of the stable elements into the milk of dairy cows. The NRC default values for iodine are based on a staff review of the literature rather than on the Ng et al. (1968) value.

In this study, a statistical analysis of F_m is performed for the elements iodine, strontium, and cesium. An analysis is also performed on reported values of F_m for iodine in the milk of dairy goats. The generic default value recommended by the NRC (1977a) for the transfer of iodine into the milk of dairy goats is 6×10^{-2} day/liter.

Values of F_m for radioisotopes are assumed to be equivalent to values of F_m for the stable element, although the radiological decay constant λ_i of the isotope and the time t between transfer of the isotope from ingestion by the dairy animal until its appearance in milk can be taken into account in the following manner:

$$F_m^* = F_m \exp(-\lambda_i t) , \qquad (3.8)$$

where

F_m^* = milk transfer coefficient for the radioisotope (day/liter),
F_m = milk transfer coefficient for the stable element (day/liter).

3.6.2 Description of the data base

Most of the data selected for analysis of F_m have been taken directly from UCRL-51939 (Ng et al. 1977). Because of the emphasis on analysis of uncertainties associated with the pasture-cow-milk pathway for ^{131}I, original references were reviewed for F_m values of iodine in the milk of dairy cows and goats. Although a few values are representative of F_m for stable elements, most values are actually specific for radioisotopes of these elements. The values of F_m selected for a statistical analysis are listed in Tables 3.13, 3.14, and 3.15, respectively, for iodine, strontium, and cesium in cow's milk. Table 3.16 lists the values considered in the analysis of F_m for iodine in goat's milk.

The values selected for an analysis of F_m for strontium and cesium are average values reported in the recent review by Ng et al. (1977). The values selected for analysis for iodine are composed of both arithmetic and geometric means obtained from data reported in the original references. Since annual or seasonal average values of F_m are non-existent, arithmetic or geometric mean values from each reference are used in order to approximate the effect of time-averaging. Arithmetic means are used when provided by the original reference. Geometric means are calculated when only individual observations are available. Values of F_m reported from studies of ^{131}I released from underground weapons tests are not included in this analysis because of evidence in Ng et al. (1977) indicating that the physicochemical form of the ^{131}I produced from these tests may produce significantly lower values of F_m than forms of ^{131}I released to the environment from nuclear facilities.

3.6.3 Results

Lognormal plots of arithmetic means or geometric means of F_m listed in Tables 3.13 through 3.15 are presented in Figs. 3.19 through 3.21, respectively for iodine, strontium, and cesium in cow's milk. A lognormal plot of F_m values listed in Table 3.16 is presented in

Fig. 3.22 for iodine in goat's milk. With the exception of Fig. 3.22, these plots indicate that the assumption of a lognormal distribution for F_m is reasonable. The results of the statistical analyses of these parameters are based on Eqs. (2.3) through (2.13) and are presented in Table 3.17.

3.6.4 Discussion

The results in Table 3.17 lead us to question the suitability of the NRC default values for iodine and strontium because of the associated low cumulative probabilities (P = 0.01 to 0.21). There is little difference between the F_m values reported for stable iodine and those estimated for ^{131}I. Differences in physicochemical forms of iodine, vegetation type, and variation among cows have more significant effects on the F_m value than radioactive decay between time of ingestion of contaminated feed by the dairy animal and the appearance of the radioisotope in milk. Because values of F_m in Tables 3.13 through 3.16 have come mainly from measurements of ^{131}I, ^{89}Sr, ^{90}Sr, ^{134}Cs, and ^{137}Cs, it is suggested that the time between ingestion and milk production in Eq. (3.8) be ignored when attempting to derive for these isotopes a value of F_m^* from a value of F_m for the stable element.

Limitations in the analysis are due primarily to the limited size of the data base and unquantified correlations between the amount of contaminated feed ingested, milk production, feed type and quality, or the breed of the animal and the value of F_m. If validation experiments are attempted, it is suggested that measurements of the forage-to-milk transfer coefficient, C_m/C_v (kg/liter), be made to test for a possible correlation between Q_f and F_m.

The forage-to-milk transfer coefficient is the product of the parameters F_m, Q_F, and f_s:

$$C_m/C_v = Q_F^T \cdot f_s \cdot F_m \, , \tag{3.9}$$

where

Q_F^T = total daily intake of dry matter (kg/day);

f_s = fraction of the total feed that is contaminated pasture forage;

F_m = intake-to-milk transfer factor (day/liter);

C_m = concentration of the radionuclide in milk (Ci/liter);

C_v = concentration of the radionuclide in forage (Ci/kg dry wt).

Table 3.13. Reported values of F_m for iodine secreted into cow's milk

Reported values: Arithmetic or geometric mean	Maximum	Minimum	Comments	References
------day/liter------				
1.7×10^{-2}	5.4×10^{-2}	6.6×10^{-3}	Geometric mean derived from $^{131}I_2$ grass deposition experiments	Sasser and Hawley (1966)
1.0×10^{-2}	1.7×10^{-2}	7.0×10^{-3}	Geometric mean, ^{125}I fed twice daily	Miller et al. (1965)
2.7×10^{-3}	6.8×10^{-3}	1.7×10^{-3}	Geometric mean, from stable iodine analysed in milk, pasture, and concentrates. (12 kg dry matter/ day pasture intake assumed)	Aldermann and Stranks (1967)
9.0×10^{-3}	1.8×10^{-2}	4.8×10^{-3}	Geometric mean from studies with dietary concentrations and milk concentrations of stable iodine	Kirchgessner (1959)
9.9×10^{-3}	3.4×10^{-2}	3.8×10^{-3}	Geometric mean from single dosing experiments using ^{131}I and monitoring milk concentrations for seven days	Lengemann et al. (1957)
1.1×10^{-2}	2.2×10^{-2}	5.0×10^{-3}	Geometric mean from daily dosing with ^{131}I using nine cows	Lengemann and Comar (1964)
4.2×10^{-3}			Arithmetic mean from daily dosing experiments using two cows and ^{131}I	Lengemann (1969)
7.0×10^{-3}			Arithmetic mean from ^{131}I single dose experiments	Garner et al. (1960)
5.6×10^{-3}			Arithmetic mean from ^{131}I daily dosing experiments	Garner et al. (1960)

Table 3.13. (continued)

Reported values: Arithmetic or geometric mean	Maximum	Minimum	Comments	References
------------day/liter------------				
9.3×10^{-3}	1.0×10^{-2}	8.5×10^{-3}	Geometric mean derived from single dose experiments using ^{131}I	Lengemann and Swanson (1957)
1.0×10^{-2}	1.3×10^{-2}	7.4×10^{-3}	Geometric mean from daily dosing with 15 mg of Na ^{131}I	Lengemann and Swanson (1957)
8.6×10^{-3}	1.3×10^{-2}	5.4×10^{-3}	Geometric mean derived from milk and diet stable iodine analysis	Hanford et al. (1934)
1.9×10^{-2} 1.8×10^{-2}			Arithmetic mean from equilibrium values for ^{131}I calculated from Chinese fallout monitoring data obtained near Dresden and Monticello Nuclear Power Plants	Shaeffer (1978b) from Weiss et al. (1975)
3.5×10^{-2} 8.1×10^{-3}			Arithmetic means from values obtained from averaging ^{131}I data taken from 2 sites near Quad Cities Nuclear Power Station	Weiss and Keller (1977)
8.1×10^{-3}			Calculated equilibrium value for ^{131}I based on biological half-life in milk	Ng et al. (1977)
9.9×10^{-3}			Equilibrium value for stable iodine based on data for biological half-life in milk	Ng et al. (1977)
1.0×10^{-2} 1.1×10^{-2}	2.7×10^{-2} 1.8×10^{-2}	5×10^{-3} 6.3×10^{-3}	Geometric means derived from using both ^{131}I and stable iodine	Comar (1963)

Table 3.14. Values of F_m for strontium

Arithmetic mean	Maximum	Minimum	Notes
---------------- day/liter ----------------			
6.5×10^{-4}	6.9×10^{-4}	6.2×10^{-4}	Oral administration of ^{85}Sr chloride
1.0×10^{-3}	1.8×10^{-3}	4.6×10^{-4}	^{89}Sr in mixed fission products
1.2×10^{-3}			Carrier free ^{89}Sr
6.6×10^{-4}			^{89}Sr, values derived from a single intake experiment
8.0×10^{-4}	8.0×10^{-4}	7.9×10^{-4}	^{89}Sr, values derived from single intake experiments
1.2×10^{-3}	1.7×10^{-3}	6.5×10^{-4}	^{89}Sr, values derived from single intake experiments
1.0×10^{-3}			^{89}Sr in a high strontium diet
1.6×10^{-3}			Chronic feeding with ^{90}Sr
2.0×10^{-3}	2.6×10^{-3}	1.6×10^{-3}	^{90}Sr
3.8×10^{-3}			^{90}Sr, chronic feeding with hay
1.6×10^{-3}			^{90}Sr, world-wide fallout
1.7×10^{-3}	2.6×10^{-3}	4.5×10^{-4}	^{90}Sr world-wide fallout
6.4×10^{-4}			^{90}Sr
1.2×10^{-3}			^{90}Sr, incorporated in fodder
1.1×10^{-3}			^{90}Sr, incorporated in fodder
1.1×10^{-3}			^{90}Sr, applied to soil surface of pasture
1.0×10^{-3}			Based on stable strontium

Table 3.14. (continued)

Arithmetic mean	Maximum	Minimum	Notes
----------	day/liter	----------	
1.4×10^{-3}			Estimated on the basis of biological half-time in milk of stable Sr.
4.5×10^{-3}			Based on stable strontium

Reference: Ng et al. (1977).

Table 3.15. Values of F_m for cesium

Average	Maximum	Minimum	Notes
------------------ day/liter --------------------			
1.3×10^{-2}			Carrier free ^{134}Cs
1.5×10^{-2}	2.2×10^{-2}	8.4×10^{-3}	Oral administration of ^{134}Cs chloride
1.5×10^{-2}			^{134}Cs
1.6×10^{-2}			Chronic feeding with ^{134}Cs
9.2×10^{-3}			^{134}Cs chloride tracer with high hay ration
1.4×10^{-2}			^{134}Cs chloride with high grain ration
9.6×10^{-3}			Carrier free ^{137}Cs
9.8×10^{-3}			^{137}Cs chloride
8.9×10^{-3}	1.1×10^{-2}	7.3×10^{-3}	^{137}Cs chloride fed daily
4.1×10^{-3}	5.1×10^{-3}	3.6×10^{-3}	^{137}Cs, world-wide fallout, winter feed
2.5×10^{-3}	4.5×10^{-3}	1.8×10^{-3}	^{137}Cs, world-wide fallout, summer feed
7.5×10^{-3}			^{137}Cs
3.6×10^{-3}			Stable cesium
8.7×10^{-3}			^{137}Cs, fallout
3.5×10^{-3}	4.1×10^{-3}	1.8×10^{-3}	^{137}Cs, fallout
4.1×10^{-3}	5.1×10^{-3}	3.6×10^{-3}	^{137}Cs, fallout
2.5×10^{-3}	3.6×10^{-3}	2.0×10^{-3}	^{137}Cs, fallout
4.6×10^{-3}	7.0×10^{-3}	2.9×10^{-3}	^{137}Cs, fallout
4.8×10^{-3}	6.4×10^{-3}	3.6×10^{-3}	^{137}Cs, fallout, high K diet
1.2×10^{-2}	1.5×10^{-2}	8.8×10^{-3}	^{137}Cs, fallout, low K diet
9.9×10^{-3}			^{137}Cs, fallout
4.8×10^{-3}			^{137}Cs, fallout

Table 3.15. (continued)

Average	Maximum	Minimum	Notes
------------------ day/liter ------------------			
6.4×10^{-3}			^{137}Cs, fallout
4.9×10^{-3}	6.4×10^{-3}	3.6×10^{-3}	^{137}Cs, fallout
4.5×10^{-3}			^{137}Cs, fallout
1.5×10^{-2}			^{137}Cs applied to soil surface of pasture
7.1×10^{-3}			Estimated for stable cesium on basis of half-life in milk

Reference: Ng et al. (1977).

Table 3.16. Average value of F_m for the transfer of iodine into the milk of goats

F_m (day/liter)	Comments	Reference
0.5	Average for nine goats at the end of 25 days of daily oral administration of ^{131}I.	Lengemann (1970)
0.48	Average for six goats receiving ^{131}I daily.	Lengemann (1970)
0.62	Average for six goats receiving ^{131}I daily plus an additional 4 mg stable iodine.	Lengemann (1970)
0.37	Average for 16 goats sampled from the 15th to the 21st day of ^{131}I dosing; *(steady state conditions not achieved)*.	Lengemann (1970)
0.47	Average for two mixed breed milk goats orally dosed twice daily with ^{131}I.	Lengemann (1969)
0.65	Average value for ^{131}I steady state; taken from unpublished data.	Comar (1963)
0.28	Average of data plotted for 14 goats given ^{131}I twice daily for periods ranging from 12.5 to 24.5 days.	Lengemann and Wentworth (1966)
0.48	Average derived from stable element data for diet intake and milk concentrations for goats.	Comar (1966)
0.17	Average value for a single goat given ^{131}I twice daily *(steady state value not reported)*.	Binnerts et al. (1962)
0.06	Average value for a single goat given ^{125}I twice daily *(steady state value not reported)*.	Binnerts et al. (1962)

Table 3.17. Statistical analysis of F_m for iodine, strontium, and cesium

Element	μ	σ	n	X_p	X_m	$\bar{X}$	X_{99}	NRC	Range
Dairy cows				----------	----------	day/liter	----------	----------	----------
Iodine	-4.6	0.55	20	7.4E-3 (0.29)[a]	1.0E-2 (0.50)	1.2E-2 (0.61)	3.6E-2 (0.99)	6.0E-3 (0.17)	2.7E-3 — 3.5E-2
Strontium	-6.7	0.53	19	9.3E-4 (0.30)	1.2E-3 (0.50)	1.4E-3 (0.60)	4.2E-3 (0.99)	8.0E-4 (0.21)	6.4E-4 — 4.5E-3
Cesium	-5.0	0.57	27	4.8E-3 (0.28)	6.7E-3 (0.50)	8.0E-3 (0.61)	2.6E-2 (0.99)	1.2E-2 (0.84)	2.5E-3 — 1.6E-2
Dairy goats[b]									
Iodine	-1.1	0.73	10	0.20 (0.23)	0.33 (0.50)	0.43 (0.64)	1.8[c] (0.99)	0.06 (0.01)	6.0E-2 — 6.5E-1

[a]Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

[b]Data do not appear to be lognormal, but results based on lognormal statistics.

[c]Such high values can occur only when milk production is less than 1 liter per day.

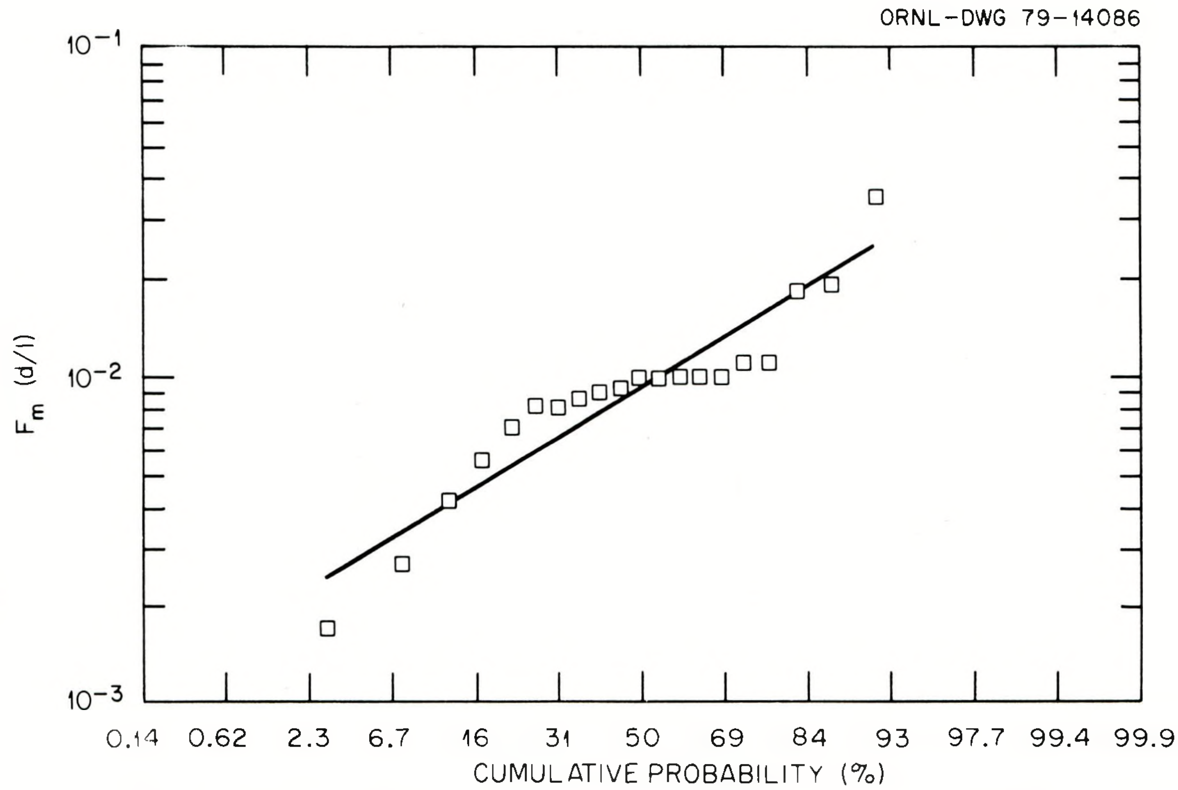

Fig. 3.19. Lognormal probability plot of the milk transfer coefficient F_m for iodine in dairy cows.

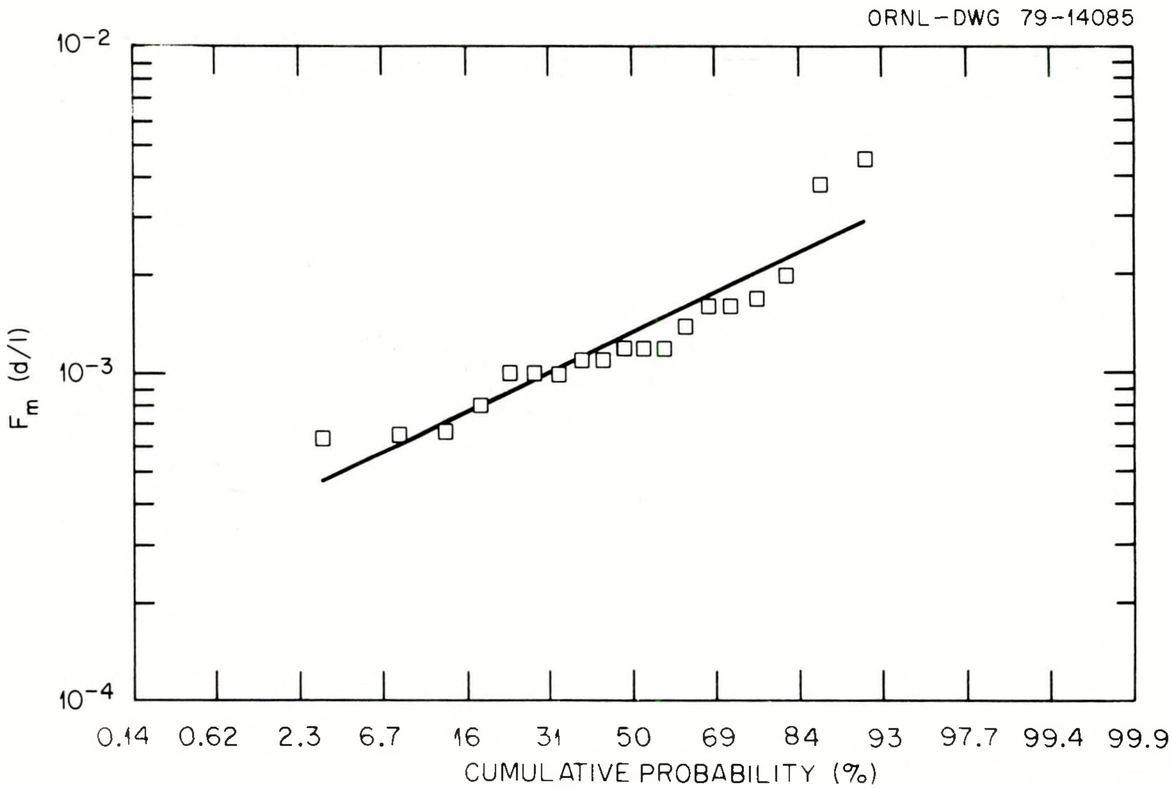

Fig. 3.20. Lognormal probability plot of the milk transfer coefficient F_m for strontium in dairy cows.

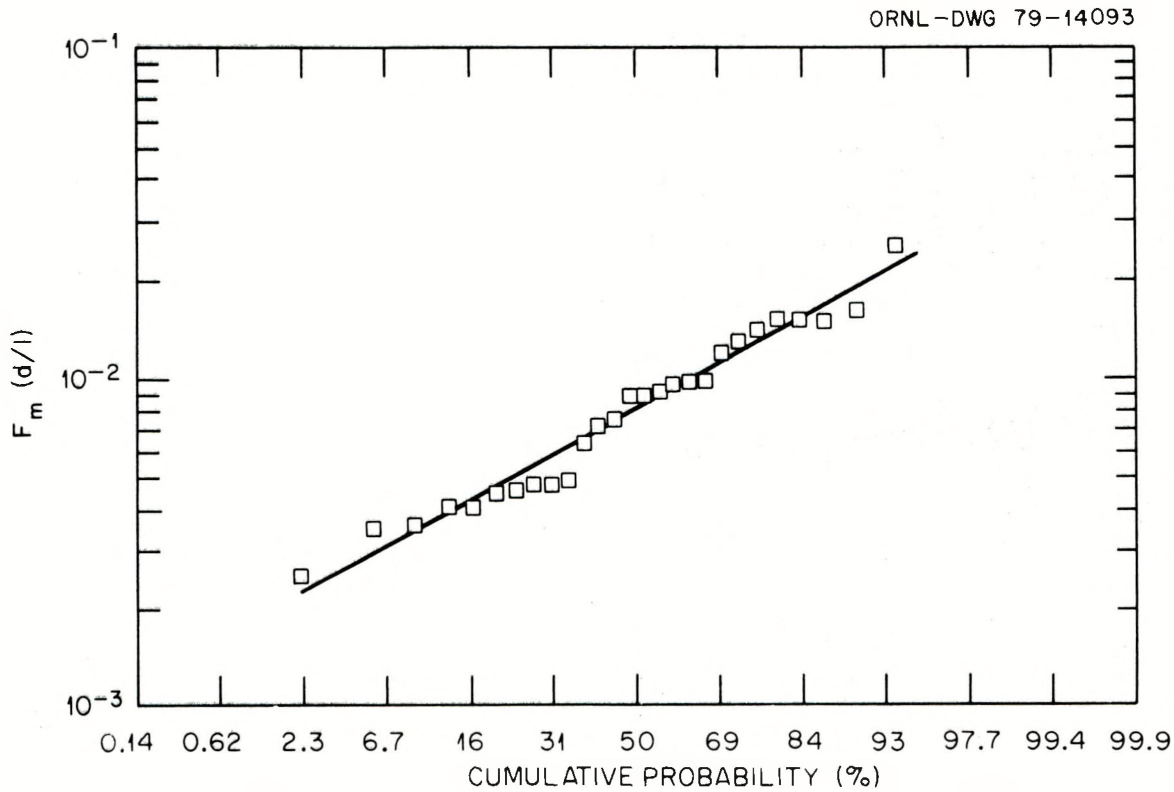

Fig. 3.21. Lognormal probability plot of the milk transfer coefficient F_m for cesium in dairy cows.

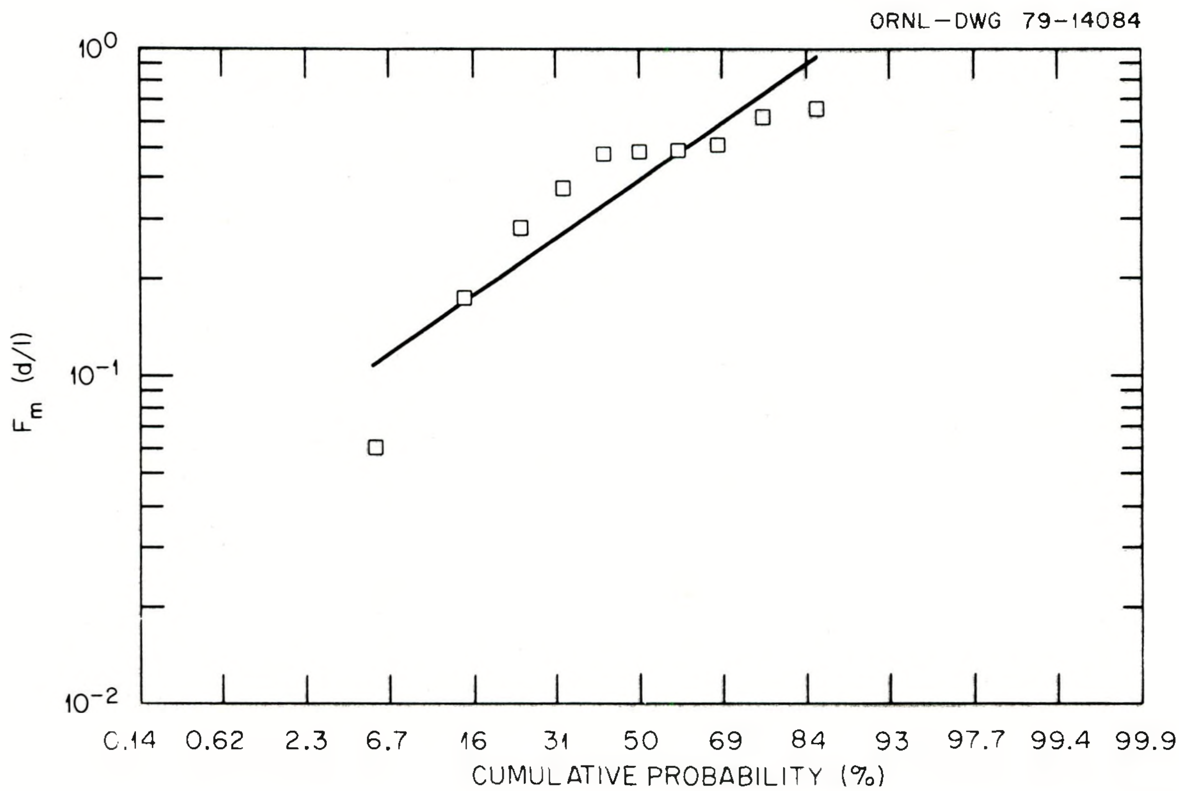

Fig. 3.22. Lognormal probability plot of the milk transfer coefficient F_m for iodine in dairy goats.

3.7 The Coefficient for the Transfer of Radionuclides from Animal Intake to Meat, F_f

(Craig A. Little)

3.7.1 Description of the parameter

The forage-to-meat transfer parameter F_f (day/kg) relates the concentration of a radionuclide or stable element in the muscle of an animal (per kg fresh weight) to its daily intake of that radionuclide or stable element at equilibrium. Values for the parameter are derived from UCRL-50163 (Ng et al., 1968) by the NRC (1977a) in the following manner: The concentration in meat (C_{meat} in Table 10B; Ng et al., 1968) is divided by the concentration in plants (C_p in Table 10A; Ng et al., 1968). The result is then divided by the assumed beef cattle feed intake rate of 50 kg, wet wt/day.

3.7.2 Description of data base

The data base used by the NRC to calculate F_f for bovines is, with the exception of neptunium, the data base of Ng et al. (1968). However, the information on concentration in vegetation acquired by Ng et al., while extensive, is specific for vegetation eaten by humans not bovines. Therefore, no correlation should be expected between the plant and meat concentrations given in the Ng et al. document. Another limitation of the NRC calculations of F_f is that the data in most of the references cited by Ng et al. have little or no statistical information accompanying the stated elemental concentrations. For example, in the book by Bowen (1966; Table 5.7) concentrations of 61 separate elements are listed without standard error or range for eight different mammalian tissues. Unfortunately, the original literature from which both Bowen and Ng et al. compiled their data also omit this information. Only a few of the papers surveyed in this report list more than a single value, an average, or a range for each element measured. The lack of statistics is probably a reflection of both the difficulty in sampling and the expense of analysis and, therefore, suggests that replicate sampling was not possible.

Therefore, the generation of values of F_f utilizing data based on concentrations in unassociated meat and vegetation is suspect, because there is no evidence that the reported meat concentrations resulted from the reported plant concentrations. In addition, the uncertainties involved with this approach are difficult to quantify. Because of these problems, we have restricted our analysis to either measured values of F_f (Ward and Johnson 1965, Huber et al. 1971) or measured values of concentrations of nuclides in meat and forage directly associated with each other (Book et al. 1972).

3.7.3 Results

Very few studies have been performed which allow the calculation of a distribution of measured values of the meat transfer coefficient, F_f. One study by Ward and Johnson (1965), however, does provide for an analysis of the transfer of ^{137}Cs in beef and dairy cattle. The distribution of the meat transfer coefficient appears lognormal (Fig. 3.23). A comparison of the distribution of Ward and Johnson's published meat transfer factors to the NRC value for Cs is given in Table 3.18. The NRC value is approximately equal to the 10*th* percentile of the distribution calculated from Ward and Johnson (1965) and nearly 20 times less than the 99% probability value.

Similar data were published by Book et al. (1972) for ^{137}Cs in deer of Northern California (Table 3.18). Assuming a daily intake for deer of 1 kg/day, dry wt, these data yield even higher meat transfer coefficients than those derived from the Ward and Johnson data. A paper by Huber, et al. (1971) presented experimental data for Mo, Cu, and Fe in tissues of dairy cattle and their daily intake. Using these data, estimates of F_f were calculated by Eqs. (2.3) through (2.13) for the meat transfer coefficient (Table 3.18). For all three elements, the NRC values are comparable to the calculated 99% probability value. At present, we are aware of no other published data on experimentally derived values of F_f or measured elemental concentrations in associated meat and forage which contain the necessary statistical information to allow calculation of the distribution of meat transfer coefficients.

3.7.4 Limitations and criticisms of F_f

The primary criticism of the values of F_f recommended in NRC Regulatory Guide 1.109 is that most of the original data on elemental concentrations in meat are not directly related to the existent data for elemental concentrations in plants. Before easily defensible meat transfer factors can be generated, the above criticism should be rectified. The best method of establishing values for F_f and the associated uncertainty would derive F_f from controlled feeding experiments designed to relate the concentration in the experimental bovine to the elemental intake in forage. Another method of estimating forage-to-meat transfer and its variance is to take replicate samples of both forage crops (in approximately the same proportions as beef cattle diet) and freshly butchered meat at several national locations. Although criticism of cause-and-effect is not eliminated by such experimentation, it can be minimized by careful planning. Such a sampling study can be performed at much lower cost than the previously mentioned feeding study, and such a study incorporates time-dependent and geographical variability.

Table 3.18. Statistical distribution of the meat transfer coefficient F_f derived from experiments or concentrations of elements in associated meat and forage[a]

Element	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Range	Notes
				d/kg						
Fe	-4.8	0.89	3	3.7E-3 (0.19)	8.2E-3 (0.50)	1.2E-2 (0.67)	6.5E-2 (0.99)	4.0E-2 (0.96)	4.2E-3 to 2.3E-2	2
Cu	-7.4	0.96	3	2.4E-4 (0.17)	6.1E-4 (0.50)	9.7E-4 (0.68)	5.7E-3 (0.99)	8.0E-3 (1.0)	2.8E-4 to 1.8E-3	2
Mo	-7.4	1.1	3	1.8E-4 (0.14)	6.1E-4 (0.50)	1.1E-3 (0.71)	7.9E-3 (0.99)	8.0E-3 (0.99)	7.6E-4 to 2.8E-3	2
Cs	-4.5	0.81	24	5.8E-3 (0.21)	1.1E-2 (0.50)	1.5E-2 (0.66)	7.3E-2 (0.99)	4.0E-3 (0.10)	4.7E-3 to 9.7E-2	3
Cs	-2.8	0.41	15	5.1E-2 (0.34)	6.2E-2 (0.50)	6.6E-2 (0.58)	1.6E-1 (0.99)		4.6E-2 to 1.8E-1	1

[a]Values in parentheses indicate the cumulative probability, $P(X \leq X_u)$.

Notes: 1. Derived from Book et al. (1972); Northern California deer.
2. Derived from Huber et al. (1971); dairy cattle.
3. From Ward and Johnson (1965); beef cattle and dairy cows at least 6 months of age.

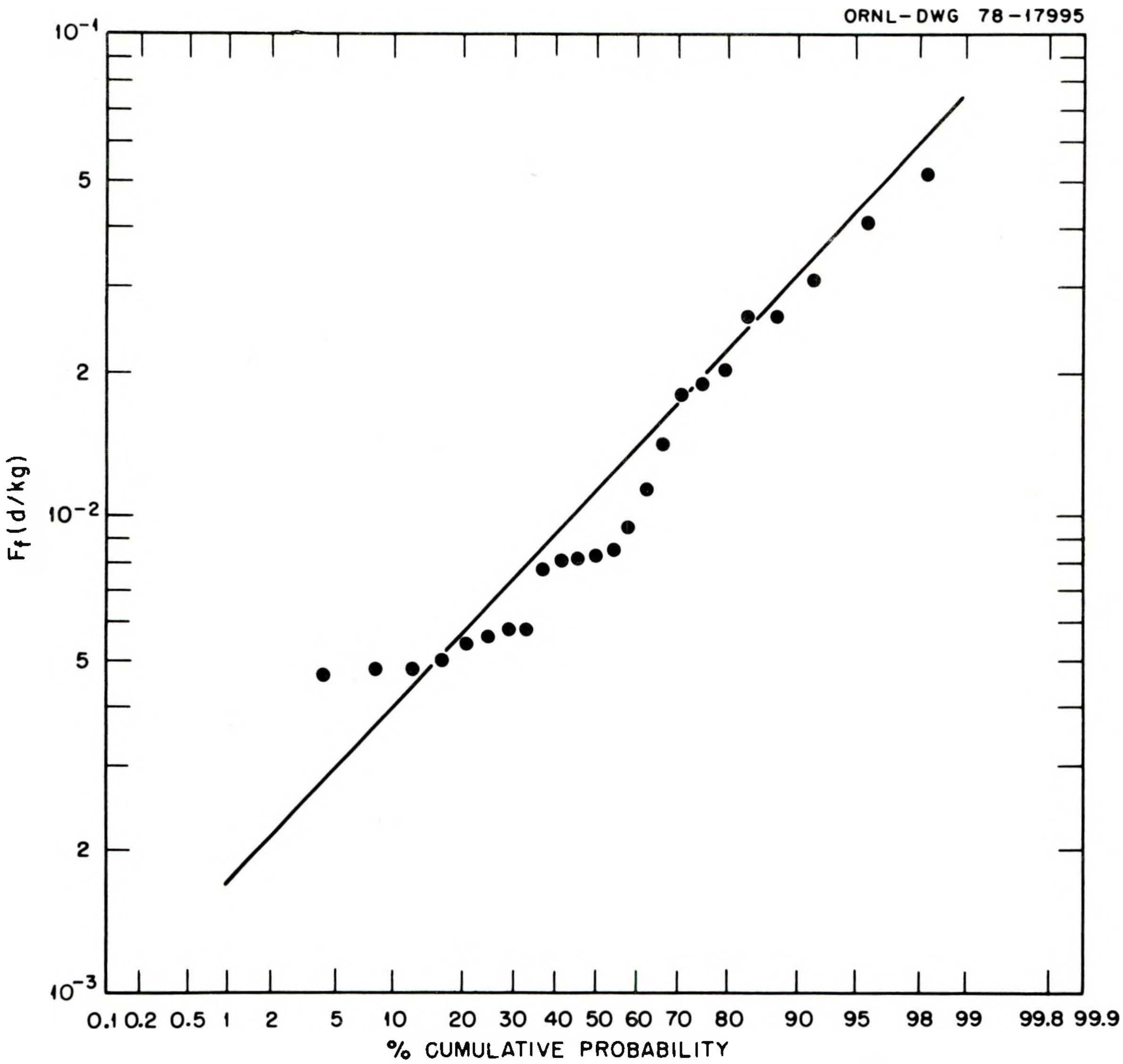

Fig. 3.23. Lognormal probability plot of the meat transfer coefficient F_f for ^{137}Cs in beef cattle and dairy cows at least 6 months of age.

3.8 The Soil Loss Constant $\lambda_{s\ell}$ Due to Leaching from Soils

(Charles F. Baes III)

3.8.1 Description of the parameter

In NRC Regulatory Guide 1.109 (1977a), it is assumed that the only loss of nuclides from the root zone of the soil is via natural radioactive decay (λ_i). However, a radionuclide may be leached from the soil by percolating water, and thus be moved through the soil-root zone and effectively become unavailable for plant uptake.

The NRC model can account for this loss by an alteration from its present form to the following form:

$$\frac{B_{iv}\,[1 - (\exp - (\lambda_i + \lambda_{s\ell})t_b)]}{P(\lambda_i + \lambda_{s\ell})} , \qquad (3.10)$$

where

B_{iv} = concentration factor for uptake of radionculide i from the soil (unitless);

P = effective surface density of the top 15 cm of soil (kg/m^2);

t_b = time for which soil has been exposed to contaminated air or water (year^{-1});

λ_i = radioactive decay constant for nuclide i (year^{-1}); and

$\lambda_{s\ell}$ = leaching decay constant of radionuclide (year^{-1}).

One approximation of $\lambda_{s\ell}$ is determined by the following equation:

$$\lambda_{s\ell}(\text{year}^{-1}) = \frac{V_w}{d_s[1 + (\frac{\rho}{\theta}\,k_d)]} , \qquad (3.11)$$

where

V_w = velocity of vertical water percolation (cm/year);

d_s = depth of the soil-root zone (cm);

ρ = soil bulk density (g/cm^3);

θ = soil water content (ml/cm^3);

K_d = equilibrium distribution coefficient of the nuclides species between soil and water (ml/g).

This model states that the radionuclide being leached may travel through the soil at the same rate as the percolating water if the nuclide has no adsorption on soil (K_d = 0). If the radionuclide is completely bound to the soil ($K_d = \infty$), then there is no downward movement of the radionuclide. In this report estimates of $\lambda_{s\ell}$ are made for Pu, Sr, Cs, I, and Tc.

3.8.2 Description of the data base

The parameters ρ and θ have been extensively measured and are well documented in the literature (UTAES 1963, Holtan et al. 1968, Jakubick 1976, Wheeler 1976). Analytical determinations of K_d for various elements are often "buried" as supplemental information in references addressing a variety of soil/water interaction problems. Time and availability of references precluded an extensive review of the parameter K_d in this report, and thus, the following analysis is based on the readily available references on valves of K_d for plutonium (Rhodes 1957 a,b; Jukubick 1976), technetium and iodine (Wildung et al. 1975), strontium (Klechkovsky 1957; Rhodes 1957a; Juo and Barber 1970; Wheeler 1976), and cesium (Klechkovsky 1957; Dahlman 1973; Rogowski and Tamura 1965; Rhodes 1957b). As for the parameter K_d, references for analytical determinations of V_w in the field are not readily available, and thus the analysis of V_w is based on very limited data (LaRue et al. 1968; Lyon et al. 1956; Ogil'vi and Fedorovich 1966).

3.8.3 Results

Soil bulk density ρ appears to be lognormally distributed (Fig. 3.24), and estimates of X_p, X_m, $\overline{X}$, and X_{99} were determined from Eqs. (2.3) through (2.13). However, the distribution of θ is more nearly normal than lognormally distributed (Fig. 3.25).

The reported values of K_d for a given element may range by a factor of approximately 10^3. This high degree of variability reflects the dependence of K_d on the physicochemical form of the element, the composition of the soil, soil pH, organic content of the soil, and competing anion or cation species. Measurement technique may also influence the value of K_d. Typical values of V_w may also range by approximately a factor of 10^3 between agricultural situations, because V_w is influenced by percent and type of crop cover, annual rainfall, soil composition, irrigation and soil management practices, and other environmental variables. The p.d.f. for V_w and K_d for the various nuclides were not determined, but lognormality was assumed and parameter estimates determined accordingly. When only a range could be obtained from the literature only X_m was estimated. The results are presented in Table 3.19.

A plow layer or root zone depth of d_s = 15 cm was assumed, and $\lambda_{s\ell}$ was determined for a theoretical range, a range based on observed data, and a median value of $\lambda_{s\ell}$ [based on Eq. (3.14)]. The results of these determinations are given in Table 3.20. The theoretical range of $\lambda_{s\ell}$ may include 4-7 orders of magnitude. This range may vary from a high $\lambda_{s\ell}$ in soils characterized by low density, high water content, high water percolation rate, and low affinity for the nuclide to a low $\lambda_{s\ell}$ in soils characterized by high density, low water content, low water percolation rate, and high affinity for the nuclide. The theoretical range of $\lambda_{s\ell}$ based on observed data includes 3-5 orders of magnitude.

3.8.4 Limitations

The model for $\lambda_{s\ell}$ given by Eq. (3.11) should be considered a first order approximation of the actual physical movement of a surface-deposited nuclide through the soil. If $K_d \to 0$ and, thus, all of the nuclide is solubilized, then the migration velocity of the nuclide is equal to that of water, V_w (the term $(\frac{\rho}{\theta}K_d) \to 0$). As $K_d \to \infty$ and all the nuclide is bound to the soil, there is no migration [Eq. (3.11)] becomes $V = \frac{V_w}{\infty}$ and $V \to 0$. However, between these extreme circumstances

Eq. (3.11) is likely to be only an approximation of the actual $\lambda_{s\ell}$ because the solubilization rate of the nuclide into the percolating water and the dispersive characteristics of the soil are not represented in Eq. (3.11). It is assumed that these two processes will give lower values of $\lambda_{s\ell}$ than that given by Eq. (3.11). Therefore, in situations between the extremes described above Eq. (3.11) probably overestimates $\lambda_{s\ell}$, and thus overestimates the removal of the nuclide from the soil.

Because of the wide range of variation associated with the theoretical values of $\lambda_{s\ell}$ given by Eq. (3.11), *in situ* measurements of $\lambda_{s\ell}$, or the determination of site-specific values for the parameters of Eq. (3.11) should be made. If such measurements are impractical or impossible then the p.d.f. of V_w and K_d should be determined via field or laboratory studies, because these two parameters are the greatest sources of uncertainty in the estimation of $\lambda_{s\ell}$.

Field studies are also needed to determine the relative importance of $\lambda_{s\ell}$ in transport of radionuclides out of the soil-root zone as compared to other methods of removal. This section considers only losses from the root zone via leaching. However, soil leaching of tightly bound nuclide species such as Cs^+ may prove insignificant in the removal process as compared to losses via soil erosion. Furthermore, movement of radionuclides may be enhanced by burrowing animals, earthworms, and foraging animal species. The harvesting of vegetation exhibiting large values of B_{iv} may also remove significant quantities of radionuclides from the soil. If these pathways prove to be important, then specific loss constants for each of these processes can be quantified and incorporated into Eq. (3.10).

Table 3.19. A statistical analysis of parameters determining $\lambda_{s\ell}$

Parameter	μ	σ	n	X_{01}[a]	X_p	X_m	$\bar{X}$	X_{99}	Observed range
V_w(cm/year)[b]	4.3	0.87	8	9.7	35	74	110	560	36.5-376
ρ(g/cm^3)[b]	0.34	0.11	299	1.1	1.4	1.4	1.4	1.8	0.93-1.84
K_d(ml/g)[b]									
Pu^{4+}						1000			200-5000
$(TcO_4)^-$						0.14			0.007-2.8
I^-						6.5			0.08-525
Cs^+	5.9	1.7	10	7.0	20	370	1500	19000	36.5-30000
Sr^{2+}	4.4	1.7	10	1.6	4.5	81	350	4200	2-1000
Parameter	$\bar{X}$	S.D.[c]	n		X_{01}[d]			X_{99}[e]	
θ(ml/cm^3)[f]	0.22	0.070	299		0.057[d]			0.38[e]	0.03-0.40

[a] $X_{01} = \exp(\mu - 2.326\,\sigma)$

[b] Parameter value estimates based on lognormal statistics.

[c] S.D. = Standard Deviation.

[d] X_{01} based on $\bar{X} - 2.326$ S.D.

[e] X_{99} based on $\bar{X} + 2.326$ S.D.

[f] Parameter value estimates based on normal statistics.

Table 3.20. Estimates of $\lambda_{s\ell}$: theoretical range, range based on observed data, and median estimates

Nuclide	Theoretical high[a]	Observed high[b]	Median[c]	Observed low[d]	Theoretical low[e]
	----------------------------	----------------------------	year^{-1}	----------------------------	----------------------------
Pu^{4+}	6.44×10^{-2}	5.38×10^{-2}	7.75×10^{-4}	7.93×10^{-6}	3.88×10^{-6}
$(TcO_4)^-$	3.66×10^{1}	2.47×10^{1}	2.61×10^{0}	1.41×10^{-2}	6.86×10^{-3}
I^-	3.03×10^{1}	2.11×10^{1}	1.16×10^{-1}	7.56×10^{-5}	3.70×10^{-5}
Cs^+	1.76×10^{0}	2.92×10^{-1}	2.09×10^{-3}	1.32×10^{-6}	6.47×10^{-7}
Sr^{2+}	6.63×10^{0}	4.44×10^{0}	9.55×10^{-3}	3.97×10^{-5}	1.94×10^{-5}

[a]Theoretical high estimates based on X_{99} values for V_w and θ and X_{01} values for ρ and K_d.

[b]Observed high estimates based on observed maximum values of V_w and θ and observed minimum values of ρ and K_d.

[c]Median estimates based on median (X_m) values for all parameters.

[d]Observed low estimates based on observed maximum values of ρ and K_d and observed minimum values of V_w and θ.

[e]Theoretical low estimates based on X_{99} values for ρ and K_d and X_{01} values for V_w and θ.

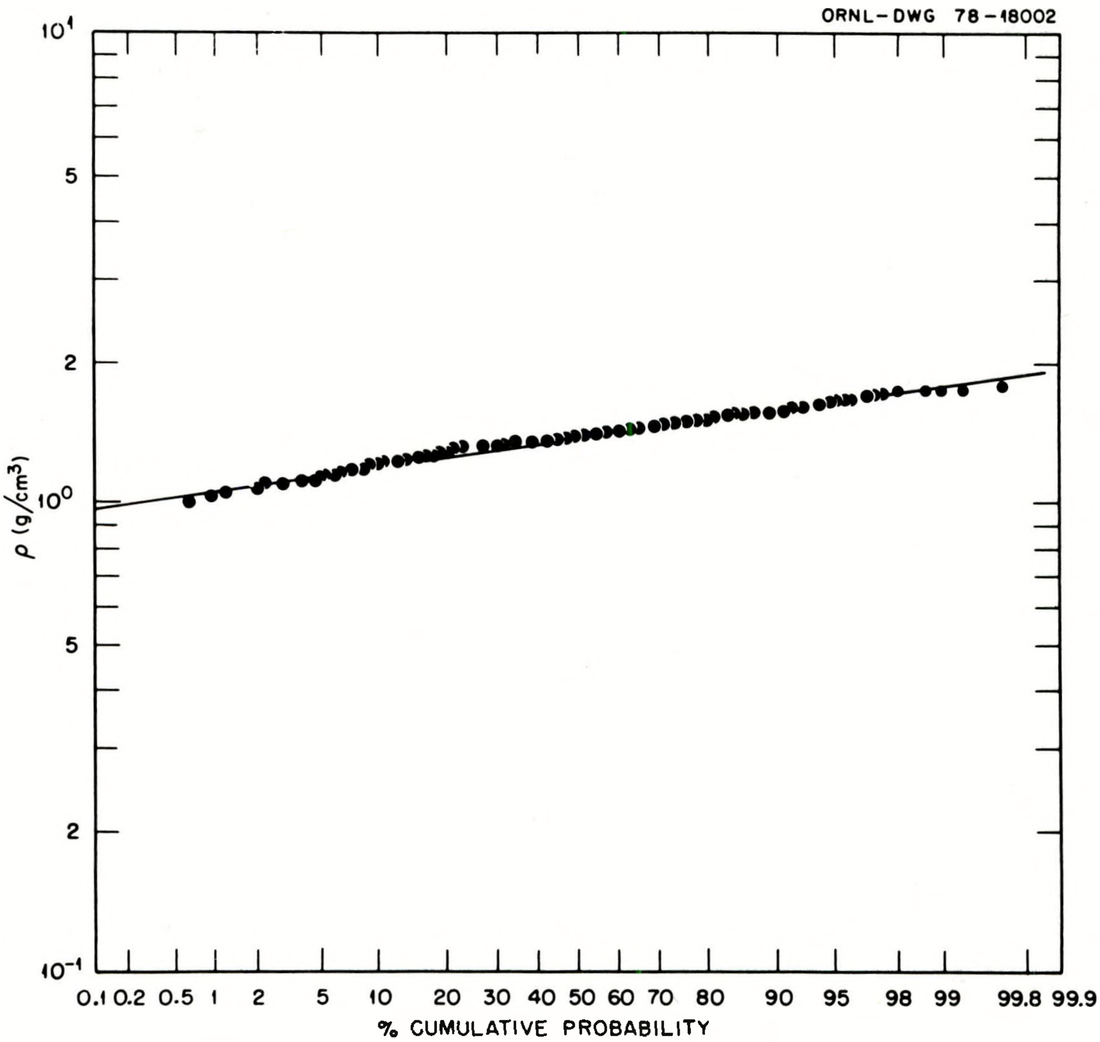

Fig. 3.24. Lognormal probability plot of soil bulk density ρ for agricultural soils in the United States.

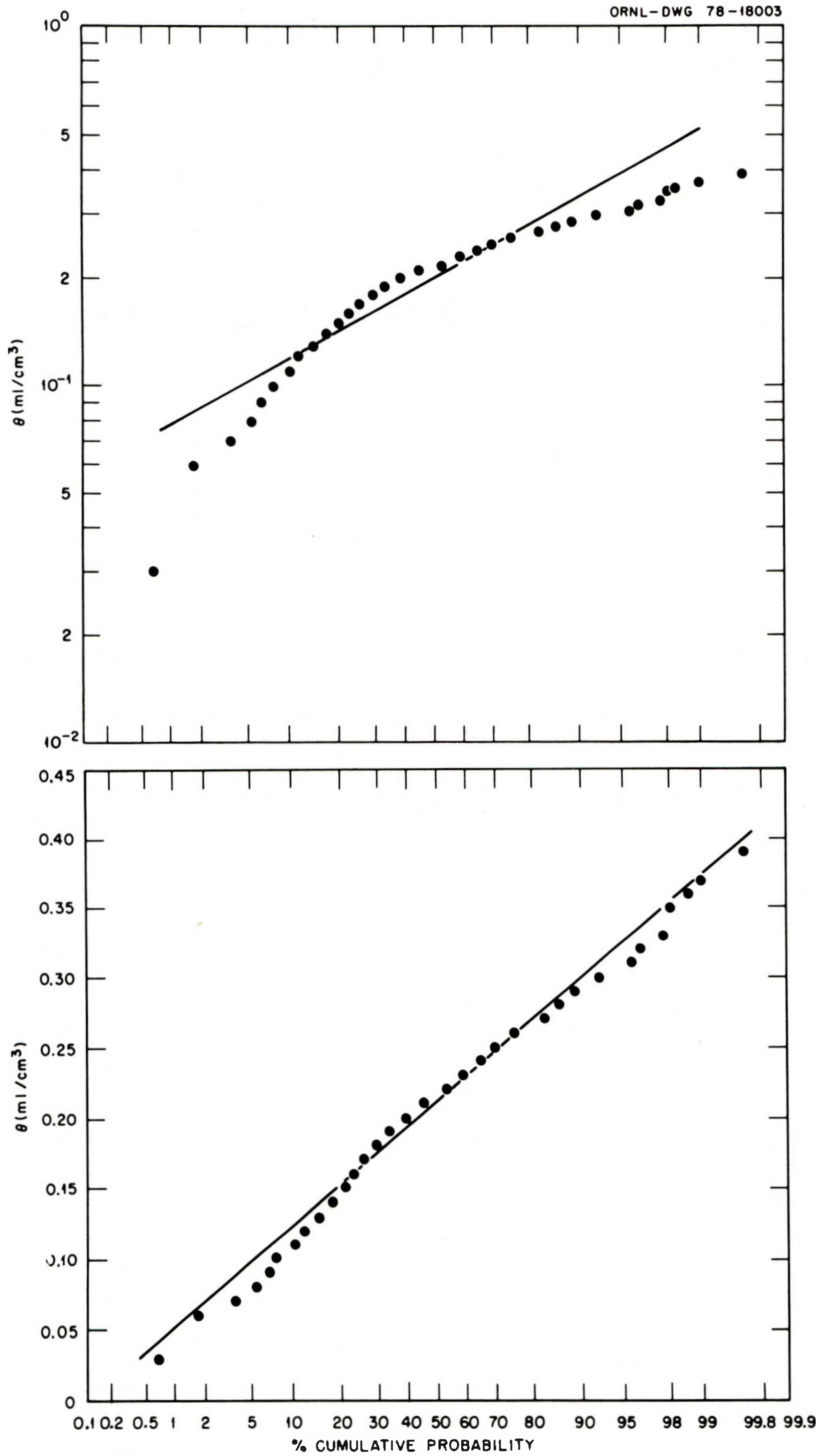

Fig. 3.25. Lognormal and normal probability plots of soil volumetric water content θ for agricultural soils in the United States.

3.9 Concentration Ratio of Radionuclides in Vegetation and Soils, B_{iv}

(F. Owen Hoffman)

3.9.1 Description of the parameter

The transfer of radionuclides from soil to vegetation is parameterized in NRC Regulatory Guide 1.109 by a ratio, B_{iv} (Ci/kg fresh weight vegetation per Ci/kg dry weight soil). Time and funding limitations precluded a detailed statistical analysis of this parameter for specific radionuclides. However, because of the tendency for $(^{99}TcO_4)^-$ to exhibit large B_{iv} values in vegetation (Till et al. 1978), an attempt is made to estimate an absolute maximum value of B_{iv}.

3.9.2 An estimation of theoretical maximum values for B_{iv}

The value of B_{iv} for the assessment of radionuclide uptake into vegetation considered in this analysis is the ratio of the concentration of radionuclide per kg of vegetation to the concentration in soil (per kg) prior to vegetation uptake. This special consideration is important because large observed values of B_{iv} can be associated with a significant removal of radionuclide from the soil system, but this process is not considered in the NRC Regulatory Guide 1.109 model. It is emphasized that measured values of B_{iv} do not usually reflect the concentration in soils prior to uptake by the plant and the subsequent incorporation into edible tissues. Therefore, for the purposes of calculations performed with the NRC Regulatory Guide 1.109 model a simple relationship is proposed for determining a theoretical absolute maximum value of B_{iv}. This relationship is:

$$B_{iv\ max} = \frac{P}{Y_v} , \qquad (3.12)$$

where

Y_v = biomass of the edible portion of vegetation in kg/m² (wet or dry weight as specified),

P = soil density in the root zone in kg/m² (dry weight).

This relationship assumes that all of a radionuclide deposited in the root zone of the soil is taken up by the edible portion of the vegetation. Under such situations determination of this parameter from field measurements would be difficult because the actual observed soil concentration would be zero, thus producing an infinitely large value of B_{iv}. Assuming a root zone soil density P of 240 kg/m^2 (USNRC 1977a) and a median value for leafy vegetables of 2 kg/m^2 (fresh weight) as reported in Sect. 3.1, an estimate of $B_{iv\ max}$ would be 120. This value represents the complete uptake from soil by leafy vegetables. If one assumes that the radionuclide taken up from soil is distributed uniformly throughout the entire plant, consideration of the fraction of the whole plant which is edible can be used to reduce the above estimate of $B_{iv\ max}$. This fraction can be considered as the ratio of Y_v of the edible portions of the plant to Y_v for the entire plant inclusive of the roots. This is equivalent to substituting a value for Y_v in Eq. (3.12) that is specific for the entire plant biomass.

Harvesting of vegetation exhibiting value of B_{iv} approaching $B_{iv\ max}$ will constitute the removal of a significant amount of radioactivity from the agricultural system. A simplified method for calculating this effect would be to quantify a harvesting loss constant λ_{sh} (year^{-1}) and incorporate this loss constant into Eq. (3.10). The loss constant λ_{sh} can be calculated by using Eq. (3.13):

$$\lambda_{sh} = \left(\frac{B_{iv} \cdot Y_v}{P} \right) H , \qquad (3.13)$$

where

Y_v = is the harvested biomass of vegetation (kg/m^2),

H = is the number of harvest per year (assuming harvesting to be a continuous process occurring at uniform intervals).

If the primary source of removal of radioactivity from the agricultural system is due to harvesting, the equilibrium concentration in vegetation (C_v) resulting from a continuous deposition rate into soil would be

$$C_v = d_i' \cdot B_{iv}/\lambda_{sh} \; . \tag{3.14}$$

Since Eq. (3.12) describes $B_{iv\ max}$, substituting Eqs. (3.12) and (3.13) into Eq. (3.14) produces

$$C_v = d_i' \cdot B_{iv\ max}/H \; , \tag{3.15}$$

where

d_i' is the rate of deposition into soil (Ci/kg • year), and
$B_{iv\ max}$ is specific for the harvested portion of the available vegetation biomass.

Failure to consider the removal effects of harvesting when large values of B_{iv} are used in the models of NRC Regulatory Guide 1.109 can result in calculating an accumulation of more radioactivity in vegetation than originally deposited. When the primary contribution to the dose is via the soil-plant pathway and subsequent consumption vegetation by man, the consideration of the removal effects of harvesting for vegetation exhibiting large values of B_{iv} will be most important for long-lived isotopes and long-term release periods.

3.10 Bioaccumulation Factors for Freshwater Fish, B_{ip}

(F. Owen Hoffman)

3.10.1 Description of the parameter

The relationship at equilibrium between the concentration of an element or radionuclide in an aquatic organism and water is parameterized as the bioaccumulation factor B_{ip}. This parameter is estimated by

$$B_{ip} = C_f/C_w \, , \tag{3.16}$$

where

C_f = concentration in the organism (per kg wet weight),
C_w = concentration in water (per liter).

The specific nuclides selected for analysis in this study are isotopes of the elements strontium, iodine, and cesium. Values of B_{ip} are specific for the edible tissues of freshwater finfish. Generic default values provided by the NRC in Regulatory Guide 1.109 (1977a) are 30 (liters/kg) for strontium, 2000 for cesium, and 15 for iodine. The basis for these default values is the reference UCRL-50564, Revision 1, by Thompson et al. (1972).

3.10.2 Description of the data base

The source of data used for the statistical analysis performed herein is the extensive compendium of bioaccumulation factors comprising ORNL-5002 (Vanderploeg et al. 1975). Although values of B_{ip} are dependent on a variety of environmental factors such as trophic level of the organism, concentrations of related elements in water, water quality, etc., the statistical analysis is performed primarily upon the values listed in Tables 3.21 through 3.23 in this section. Because values of B_{ip} are usually based on single measurements and are not averaged over appropriate time periods (three months to one year, depending on the season of maximum catch), an approximation of the effect of time averaging is attempted by averaging single values of B_{ip}, reported in ORNL-5002, for specific locations. The values in Tables 3.21 and 3.23 for strontium and cesium, respectively, are derived from unfiltered water samples. With the exception of only two entries in Table 3.22, the values of B_{ip} for iodine were generated by Vanderploeg et al. (1975) by assuming an iodine concentration in water of 1 μg/liter.

The ORNL-5002 report (Vanderploeg et al. 1975) includes mathematical expressions relating values of B_{ip} for Sr and Cs to concentrations in water of Ca and K, respectively. Concentrations of Ca and K for the major freshwater systems in the United States were obtained from a U.S. Department of Interior document on the geochemistry of rivers and lakes (Livingstone 1963). A range of B_{ip} values for Sr and Cs based on the mathematical expressions in Vanderploeg et al. (1975) and the data from Livingstone (1963) is included in Sect. 3.10.3 for comparison with statistical analysis of B_{ip} in Tables 3.21 through 3.23.

3.10.3 Results

Lognormal probability plots of B_{ip} values for Sr, I, and Cs are presented in Figs. 3.26 through 3.28, respectively. Since B_{ip} values for Sr appear to be correlated with the Ca content of water, an additional analysis was performed for values of Sr obtained from ORNL-5002 (p. 74, Vanderploeg et al. 1975) for water bodies having a Ca content ranging from 20 to 60 ppm. A plot of these data is included in Fig. 3.26. The data are insufficient to specify whether a normal or lognormal distribution is most descriptive. However, for the purposes of a statistical analysis lognormality is assumed. Therefore, the results of the analysis in Table 3.24 are based on lognormal statistics using Eqs. (2.3) through (2.13). The cumulative probabilities $P(X \leq X_u)$ are included in parentheses within the table.

The distribution of B_{ip} for strontium spans almost four orders of magnitude if no consideration is given to the concentration of Ca in water. For a Ca concentration of 20-60 ppm in water, the median value of B_{ip} for Sr is one order of magnitude less than the 99*th* percentile. This 99*th* percentile is comparable to the default value recommended by the NRC in Regulatory Guide 1.109 (1977a). The median value of B_{ip} for cesium is almost one order of magnitude less than the 99*th* percentile, while the median value for iodine is only about a factor of 4 less than the 99*th* percentile. The NRC default value for Cs is approximately equal to the estimated mean, but for I the default value is approximately a factor of 2 less than the estimated median value of B_{ip}.

The results for iodine are probably biased. Most of the values of B_{ip} for I listed in Vanderploeg et al. (1975), and subsequently included for analysis in this report, are based on measured iodine concentrations in fish muscle and a conservatively assumed iodine concentration in water of 1 μg/liter. Quantification of the error introduced by this assumption will be dependent upon increasing the relevant B_{ip} data base for iodine.

In ORNL-5002 (Vanderploeg et al. 1975), methods are given for estimating B_{ip} values for Sr and Cs based on the concentrations of [Ca] and [K] respectively in water (in ppm). The equation for estimating the Cs B_{ip} for piscivorous fish is as follows:

$$B_{ip}\ Cs = 1.5 \times 10^4/[K]_w \ , \qquad (3.17)$$

where

$[K]_w$ = concentration of K in water with suspended solids <50 ppm.

For non-piscivorous fish the values of B_{ip} are reduced by a factor of 3. For turbid waters (suspended sediments >50 ppm), the values of B_{ip} in Eq. (3.17) are reduced by a factor of 5.

Concentrations of potassium [K] for major water bodies in the United States (Livingstone 1963) are given in Table 3.25. These concentrations indicate a range of B_{ip} for Cs of 30 to 50,000 (liters/kg) with average values of 260 to 3,800. The calculational procedure for estimating B_{ip} for Sr is (Vanderploeg et al. 1975):

$$B_{ip}\ Sr = \exp[\text{intercept} + (\text{slope} \times \ln\ [Ca]_w)] \ , \qquad (3.18)$$

where

$$\text{intercept} = 5.18 \pm 1.11 \text{ [standard error of the mean (s.e.)]}$$
$$\text{slope} = -1.21 \pm 0.37 \text{ (s.e.)}$$
$$[Ca]_w = \text{concentration of Ca in water (ppm)} .$$

The concentrations of calcium in water $[Ca]_w$ in ppm for the major water bodies of the United States are given in Table 3.26. The data in this table indicate a B_{ip} Sr range of 2.4×10^{-3} to 214 with an average value of 1.1. The calculated ranges for Sr and Cs obviously encompass the range of measured values of B_{ip} for both Sr and Cs.

Table 3.21. Values of B_{ip} for strontium in freshwater finfish[a]

Value	Location	Original reference
0.82	Average of five values for Clinch River, Tennessee	Nelson (1967)
2.0	Average of two values for Lake Glisstjarn, Sweden	Agnedal (1967)
5.0	Average of two values for Lake Erken, Sweden	Agnedal (1967)
6.0	Average of two values for Lake Storacksen, Sweden	Agnedal (1967)
8.0	Average of two values for Lake Magelungen, Sweden	Agnedal (1967)
9.8	Value reported for Windermere, United Kingdom	Tempelton and Brown (1964)
32	Value reported for River Prysor, United Kingdom	Tempelton and Brown (1964)
138	Average of three values for Lake Langsjou, Sweden	Agnedal (1967)
198	Value reported from Loch Glutt, United Kingdom	Tempelton and Brown (1964)

[a]Derived from ORNL-5002 (Vanderploeg et al. 1975).

Table 3.22. Values of B_{ip} for iodine in freshwater finfish[a]

Value	Location	Original reference
28	Average of two values from Switzerland	Fellenberg (1923)
48	Single value from Germany	Bleyer (1926)
37	Average of two values from New Zealand	Hercus and Roberts (1927)
10	Single value from Lake Erie	Tressler and Wells (1924)
35	Average of two values from Lake Erie	Mazzocco (1930)
25	Average of two values from Mississippi River	Tressler and Wells (1924)
35	Average of two values from Potomac River	Tressler and Wells (1924)
40	Single value (no location specified)	Monier-Williams (1950)
30	Average of four values (no location specified)	Causeret (1962)
15[b]	Single value from Block River, Michigan	Robertson and Chaney (1953)
40	Single value from Pacific Coast Stream	Jarvis et al. (1953)
132[b]	Average of five values from Lake Michigan	Copeland et al. (1973)

[a]Derived from ORNL-5002 (Vanderploeg et al. 1975).

[b]With the exception of these values, all other values are based on an assumed iodine concentration in water of 1 μg/liter.

Table 3.23. Values of B_{ip} for cesium in freshwater finfish[a]

Value	Location	Original reference
4,850	Average of two values for Lake Trawsfynyd, England	Preston et al. (1967)
1,100	Average of six values for English River	Preston et al. (1967)
281	Average of six values for White Oak Lake, Tennessee	Kolehmainen (1972)
1,513	Average of three values for Lake Maggiore, Italy	Bortoli et al. (1966) Bortoli et al. (1967)
800	Average of three values for Lake Varese, Italy	Bortoli et al. (1966) Bortoli et al. (1967)
1,363	Average of three values for Lake Comabbio, Italy	Bortoli et al. (1966) Bortoli et al. (1967)
3,100	Average of three values for Lake Monate, Italy	Bortoli et al. (1966) Bortoli et al. (1967)
1,100	Average of three values for Par Pond, South Carolina	Harvey (1970)

[a]Derived from ORNL-5002 (Vanderploeg et al. 1975); values are specific to measurements of the isotope ^{137}Cs.

Table 3.24. A statistical analysis of B_{ip} for Sr, I, and Cs in freshwater finfish

Element	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Range
				kg/liter					
Sr[a]	2.4	1.8	9	0.43 (0.04)[b]	11 (0.50)	56 (0.82)	730 (0.99)	30 (0.71)	0.82-198
Sr[c]	0.86	1.0	11	0.87 (0.16)	2.4 (0.50)	3.9 (0.69)	24 (0.99)	30 (0.99)	0.74-10
I[a]	3.5	0.61	13	23 (0.27)	33 (0.50)	40 (0.62)	140 (0.99)	15 (0.10)	10-132
Cs[a]	7.2	0.86	8	640 (0.19)	1300 (0.50)	1900 (0.67)	9400 (0.99)	2000 (0.68)	281-4850

[a]Based on averaged data in Tables 3.21 through 3.23.

[b]Values in parentheses give the cumulative probability, $P(X \leq X_u)$.

[c]Based on observations when Ca in water ranges from 20-60 ppm.

Table 3.25. Concentrations of potassium in water $[K]_w$ for the major water bodies of the United States[a]

Water body	Concentrations of $[K]_w$ Minimum	Average	Maximum
	ppm		
Great Lakes	1.4	4.3	8.2
Atlantic Coast drainage (Northern U.S.A.)	0.8	1.7	3.3
Atlantic Coast drainage (Southern U.S.A.)	0.7	1.6	2.8
Eastern tributaries of the Gulf of Mexico	0.3	1.2	2.2
Mississippi drainage	1.0	4.1	11
Rio Grande and tributaries	3.1	8.7	24
Colorado and Sacramento Rivers	0.9	3.5	6.1
Columbia River system	1.1	6.9	34
Grand mean of averages		4.0	
Minimum and maximum values	0.3		34

Reference: Livingstone (1963).

Table 3.26. Concentrations of calcium in water $[Ca]_w$ for the major water bodies of the United States[a]

Water body	Concentrations of $[Ca]_w$		
	Minimum	Average	Maximum
	ppm		
Great Lakes	14.1	29	39
Atlantic Coast drainage	4.0	24	72
Eastern tributaries of the Gulf of Mexico	3.8	16	44
Mississippi drainage	5.9	63	201
Rio Grand and tributaries	39	250	601
Colorado and Sacramento River systems	9.6	65	148
Columbia River system	3.0	19	30
Grand mean of averages		67	
Minimum and maximum values	3.0		601

Reference: Livingstone (1963).

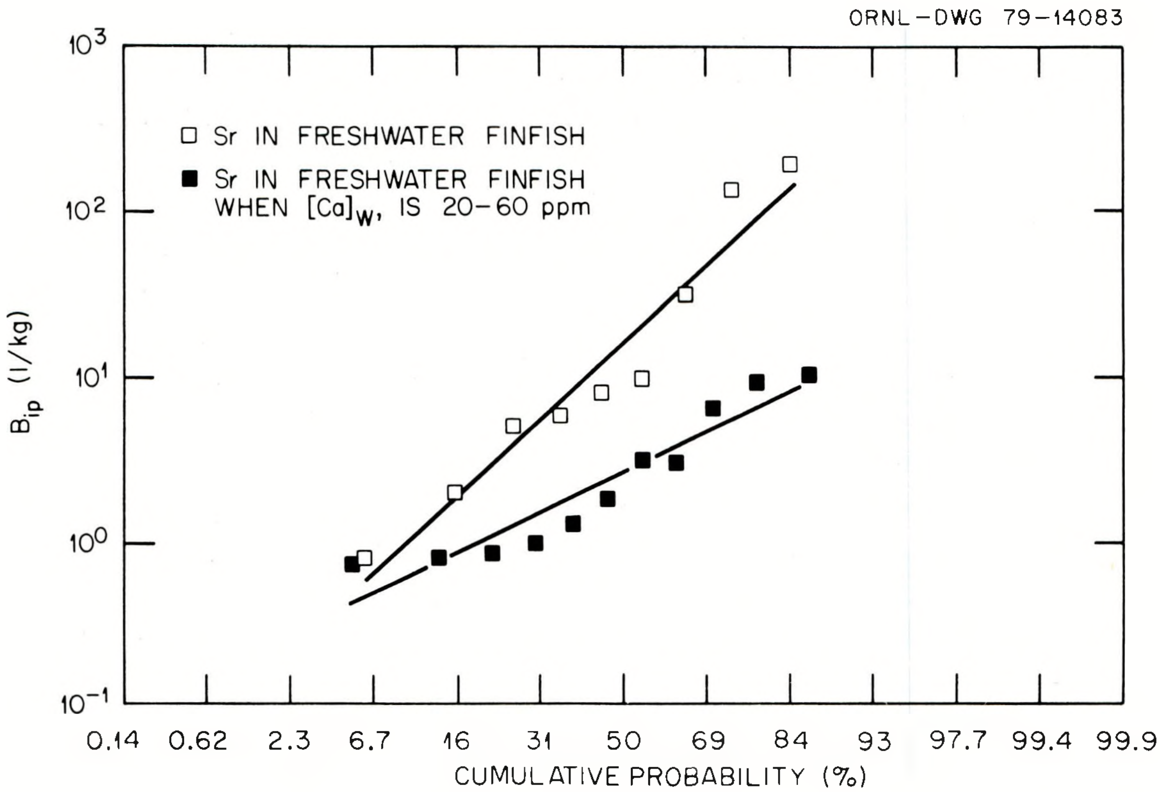

Fig. 3.26. Lognormal probability plots of the bioaccumulation factor B_{ip} for strontium in freshwater fish and for strontium in freshwater fish when the concentration of the calcium in water $[Ca]_w$ is 20-60 ppm.

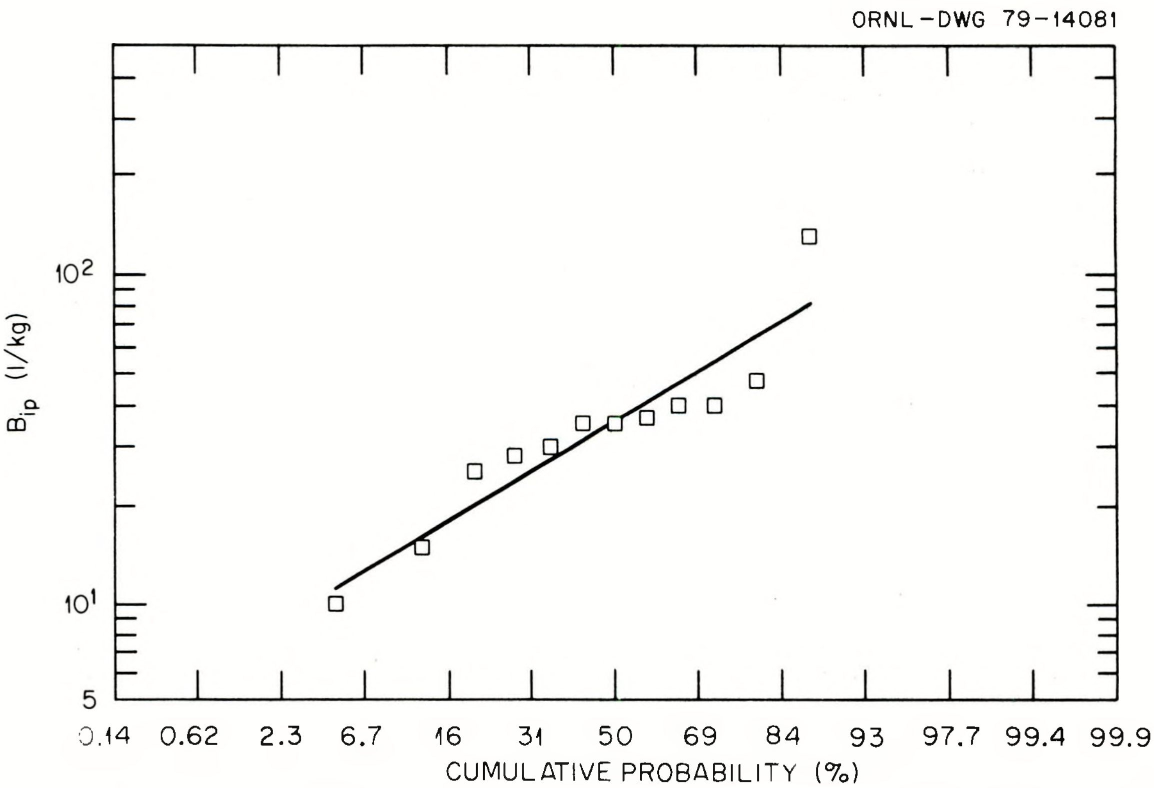

Fig. 3.27. Lognormal probability plot of the bioaccumulation factor B_{ip} for iodine in freshwater fish.

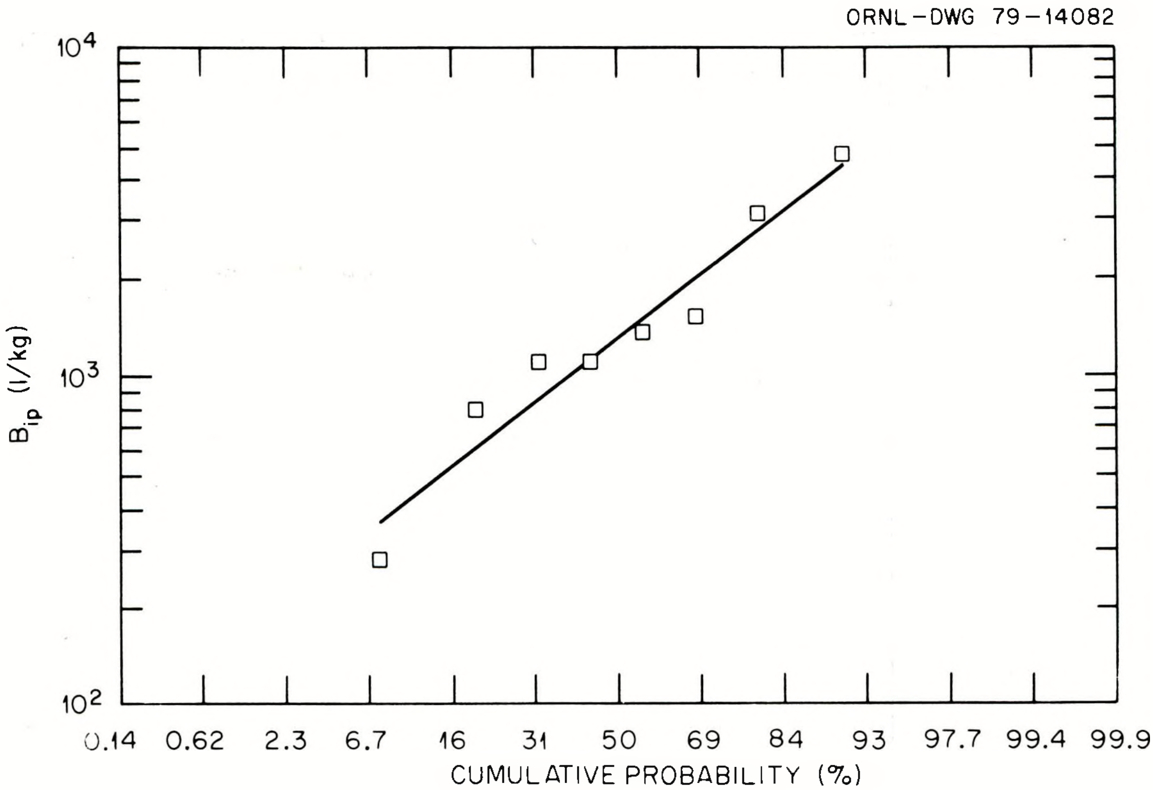

Fig. 3.28. Lognormal probability plot of the bioaccumulation factor B_{ip} for cesium in freshwater fish.

3.11 Annual Dietary Intake and Respiration Rates, U_{ap}

(Elizabeth M. Rupp)

3.11.1 Description of the parameter

Determination of the amount of contaminated materials incorporated into the human body is dependent on dietary habits and inhalation rates. Although the variability in consumption and inhalation rates can be attributed to numerous factors, the primary factor considered in this analysis is age dependency. The age-dependent parameters selected for analysis in this study are:

1. the consumption of milk and milk products U_{ap}^{M}(liter/year);
2. the consumption of water U_{ap}^{W}(liter/year);
3. the consumption of fruits, vegetables, grains, meat, poultry, and fish U_{ap}^{F}(kg/year); and
4. the average annual volumetric inhalation rate U_{ap}^{A}(m^3/year).

Attempts are made, where sufficient data permit, to distinguish between the variability of annual average values among single individuals and the variability among the average of population groups. Generic default values for the various age categories of U_{ap} currently recommended by the NRC (1977a) for maximum individuals and population averages are listed in Table 3.27.

3.11.2 Description of the data base and assumptions

Data acquisition for the analysis of U_{ap} involved an extensive review of documented surveys, interviews, metabolic and nutrient balance studies, and personal communications. An emphasis was placed on obtaining data for milk consumption by infants and small children because this information is relevant to the assessment of the radiological impact from the transport of ^{131}I over the pasture-cow-milk pathway. The analysis of uncertainties of model predictions of the dose to an infants' thyroid from ingestion of ^{131}I transported through this pathway is performed in Sect. 4 of this report.

The references reviewed for U_{ap} are listed in Tables 3.28 through 3.30. Despite the extensive appearance of this data base, none of the data obtained were direct measurements of U_{ap} as defined in NRC Regulatory Guide 1.109. The parameter U_{ap} as defined is time-averaged over a period of one year; however, the data obtained do not reflect this extent of time averaging. At best, the data reflect observations of single individuals of different age categories over a time period of several months. At worst, the data have been derived from time averaging over only a few hours or days. The most current and complete data obtained on milk consumption by individual infants are limited to metabolic balance studies of upper-middle-class infants in Cincinnati, Ohio, and in Iowa City, Iowa. The variability of U_{ap} reflected in these limited studies does not necessarily reflect the variability of milk consumption by infants throughout the entire United States.

Statistical information on U_{ap} values for average individuals was derived using several techniques. An estimate of the variability for average individuals was obtained from observations of single individuals by using the standard error of the mean (s.e.) of the logarithms for lognormally distributed data. This value was substituted for σ in Eqs. (2.3) through (2.13) to produce the results listed in Table 3.31. If data reported were not given for single individuals but averaged for groups of individuals, an average value was obtained for each reference source. These average values were then subjected to statistical analysis (Table 3.32). Data obtained for age groups other than infants are reported either as frequency distributions or average values and range.

3.11.3 Results

Lognormal probability plots were made for data obtained from observations of individual infant milk consumption (Figs. 3.29 through 3.31). The assumption of lognormality appears reasonable. The results of the analysis of these data, based on lognormal statistics using Eqs. (2.3) through (2.13) are given in Table 3.31. Table 3.32 summarizes the results of averaged data from various references for milk consumption of groups of individuals aged 0 to 2 years, again assuming lognormality. Table 3.33 shows the frequency distribution of milk consumption of individual children, teenagers, and adults as derived from the investigations of Pao and Burk (1975). These data are from a one day recall survey, and extrapolation to annual average milk consumption rates for these age groups may lead to invalid conclusions. The relative frequency of consumption by infants of human milk, whole cow milk, evaporated milk, and powdered formula is presented in Table 3.34. Averages and ranges for the annual intake of water by various age groups U^W_{ap} are presented in Table 3.35. Average values for the consumption of solid foods U^F_{ap} for various age groups are presented in Table 3.36, and selected maximum values are presented in Table 3.37. Normal and lognormal probability plots of U^F_{ap} for infants are given in Fig. 3.32. Infant consumption of solid foods appears to be more normally than lognormally distributed. Average values for volumetric inhalation rates U^A_{ap} of various age groups are presented in Table 3.38. Inhalation rate (resting) appears to be lognormally distributed for infants (Fig. 3.33).

A percentage frequency distribution of age-groups for the entire United States is presented in Table 3.39. This table indicates that the majority of the U.S. population (67%) is over the age of 19 with 56% between the ages of 19 and 65. Therefore, in the calculation of doses to large populations, only small differences should be expected in the results when the calculations are based on reference adult values than when age-dependent calculations are performed. It appears as if age dependency need only be considered when doses to critical groups of the population are in question (Etnier and Till 1979).

The time period between harvest and human consumption of foods is an important factor to consider for the calculation of doses received via ingestion pathways for short-lived radionuclides. If the concentration of radionuclides in harvested food stuffs (C_h) is known, then the concentration at the time of human consumption (C_i) can be calculated as:

$$C_i = C_h \exp\left(-\lambda_i t_h\right) \quad , \qquad (3.19)$$

where

λ_i = the radiological decay constant of the radionuclide,

t_h = the time period between harvest and consumption.

Table 3.40 lists values of t_h for water, milk, meat, fish, and produce.

These values are the averages of the range of time delays reported to Dr. Blanchard in private communications with D. C. Fuener, U.S. Department of Agriculture, Midwest Regional office, Chicago, Illinois, for beef, pork, and poultry; R. Rubin, National Marine Fisheries Service, Division of Marketing Service, Chicago, Illinois, for finfish, shellfish, lobster, and crab; and P. L. Breakiron, U.S. Department of Agriculture, Agriculture Resources Service, Beltsville, Maryland, for vegetables and fruits.

3.11.4 Discussion

The variability of dietary habits among individuals does not appear to be as large as the variability among some of the transfer coefficients (F_m, F_f, and B_{ip}). Generally, less than a factor of 2 separates the median values from the 99*th* percentile values. Nevertheless, there is some uncertainty in extrapolating from available data sets to obtain information that is supposedly representative of the entire U.S. population. It is also likely that certain regions or locations within the United States may exhibit dietary habits markedly different from the results reported in this section. Therefore, caution must be applied when data obtained from isolated surveys or metabolic balance studies are used to describe the dietary habits of the maximum and average exposed individuals in a select population group.

Correlations between values of U_{ap} and other parameters investigated in this study can be easily postulated. Perhaps the strongest relationship can be expected between values of U_{ap} and the various metabolic and anatomical parameters which comprise the internal dose conversion factor, such as organ mass, fractional uptake, and retention. However, with the exception of the correlation of all of these parameters with age for determining a ^{131}I thyroid dose conversion factor for infants, no additional consideration of covariance between U_{ap} and other parameters is included in this report because of the absence of data allowing quantification of suspected relationships.

Table 3.27. Recommended default values of U_{ap} (in lieu of site-specific information)

Pathway	Average individual			Maximum exposed individual			
	Child	Teen	Adult	Infant	Child	Teen	Adult
	kg/year						
Fruits, vegetables, and grain	200	240	190		520	630	520
Leafy vegetables					26	42	64
Meat and poultry	37	59	95		41	65	110
Fish	2.2	5.2	6.9		6.9	16	21
Shellfish	0.33	0.75	1.0		1.7	3.8	5
	liter/year						
Milk	170	200	110	330	330	400	310
Drinking water	260	260	370	330	510	510	730
	m^3/year						
Inhalation	3700	8000	8000	1400	3700	8000	8000

Reference: USNRC (1977a).

Table 3.28. References reviewed for U_{ap} for infants consuming milk and solid foods

References	Study type	Milk type[a]	Solid food included	Number of infants	Location
Nelson (1931)	Balance	WCM	No	9	Iowa City, Iowa
Kahn et al. (1969)	Balance	EV	Yes	30	Cincinnati, Ohio
Durbin et al. (1970)	Balance	EV, formula	Yes	10	Berkeley, California
Fomon et al. (1963)	Balance	Formula	No	12	Iowa City, Iowa
Fomon and May (1958)	Balance	HM	No	9	Iowa City, Iowa
Fomon et al. (1971)	Balance	Formula	Yes	55[b]	Iowa City, Iowa
Fomon et al. (1977)	Balance	Formula	Yes	45	Iowa City, Iowa
Fomon (1978, unpublished)	Balance	Formula	Yes	20[b]	Iowa City, Iowa
Fomon (1978, unpublished)	Balance	Formula	Yes	25[b]	Iowa City, Iowa
Fomon (1978, unpublished)	Balance	Formula	Yes	426[b]	Iowa City, Iowa
Fomon (1978, unpublished)	Balance	Formula	Yes	36	Iowa City, Iowa
Beal (1954)	Survey	WCM, EV	Yes	58	Denver, Colorado
Filer and Martinez (1963)	Survey	Various	Yes	4310	U.S.A.
Guthrie (1963)	Survey	WCM, EV	Yes	40	University Park, Pennsylvania
Eagles and Steele (1971)	Survey	WCM	Yes	226	U.S.A.
USDA (1965)	Survey	WCM	Yes	428	U.S.A.

[a]HM = human milk, WCM = whole cow milk, EV = evaporated milk.

[b]Note: 100 infants were randomly selected from Foman's 1971 report and his unpublished data for analysis of milk intake performed in Sect. 3.11.3.

Table 3.29. References reviewed for U_{ap} for infants for solid foods, water, and respiration rate

Reference	Parameter	Study type	Number of infants	Location
Kahn et al. (1969)	Solid foods	Balance	30	Cincinnati, Ohio
Durbin et al. (1970)	Solid foods	Balance	10	Berkeley, California
USDA (1965)	Solid foods	Survey	1055	Total U.S.A.
Walker et al. (1963)	Water	Survey	797	Florida; Georgia; New Mexico; and Michigan
Kahn et al. (1964)	Respiration	Balance (radiocesium)	8	Cincinnati, Ohio
ICRP-23 (1975)	Respiration	Review	---	---

Table 3.30. References reviewed for U_{ap} for age groups other than infants

Reference	Parameter	Type study	Number of individuals	Comments, location
Pao and Busk (1975)	Milk	Survey	5193	Child, teen, adult; Northeastern region
Walker et al. (1963)	Water	Survey	797	Child; Florida; Georgia; New Mexico; and Michigan
Rupp et al. (1979)	Fish, shellfish	Survey	1500	Per capita; Total U.S.A.
Honstead et al. (1971)	Freshwater fish	Survey	10	Adult (maximum); Richland, Washington
ICRP-23 (1975)	Respiration rate	Review		Child, teen, adult (Review)
USDA (1965)	Solid foods	Survey		Child, teen, adult; Total U.S.A.
Essig and Corley (1969)	Water, solid foods	Review		Child, teen, adult; Richland, Washington
Cook et al. (1975)	Water, other beverages	Survey	8500	New York state

Table 3.31. Individual and average milk consumption of infants, U_{ap}^{M} [a]

Age group (months)	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Range
				liters/year[b]					
<u>0-4</u> Individual	5.6	0.13	100	226 (0.45)[c]	270 (0.50)	273 (0.53)	366 (0.99)	330 (0.94)	199-388
Average (s.e. = 0.013)[d]				270 (0.50)	270 (0.50)	270 (0.50)	280 (0.99)		
<u>4-6</u> Individual	5.7	0.20	45	287 (0.42)	299 (0.50)	305 (0.54)	476 (0.99)	330 (0.69)	175-431
Average (s.e. = 0.030)[d]				299 (0.50)	299 (0.50)	299 (0.50)	320 (0.99)		

[a] Three significant figures shown for clarity, although results accurate only to two places.

[b] These data values were actually calculated in terms of ml/day. They are expressed as liters/year for purposes of comparison with the NRC default values which are time averaged over 1 year in liters/year.

[c] Values in parentheses indicate cumulative probabilities, $P(X \leq X_u)$.

[d] Average values based on standard error; s.e. = $(\sigma/\sqrt{n})$.

Reference: Fomon et al. (1971, 1977) and Foman (1978, unpublished).

Table 3.32. Average annual milk consumption of various age groups from 0-2 years[a]

Age groups (months)	μ	σ	n[b]	X_p	X_m	$\bar{X}$	X_{99}	Range of report averages
				liters/year				
0-4	5.6	0.10	12	268 (0.47)[c]	270 (0.50)	272 (0.52)	341 (0.99)	236-325
4-6	5.7	0.12	7	295 (0.45)	299 (0.50)	301 (0.52)	395 (0.99)	256-362
1-6	5.7	0.13	7	294 (0.45)	299 (0.50)	301 (0.52)	404 (0.99)	248-334
6-12	5.6	0.21	4	259 (0.42)	270 (0.50)	276 (0.54)	441 (0.99)	243-375
0-12	5.6	0.13	7	266 (0.45)	270 (0.50)	273 (0.53)	366 (0.99)	240-344
12-18	5.4	0.12	3	218 (0.45)	221 (0.50)	223 (0.52)	293 (0.99)	190-247
12-24	5.4	0.09	3	220 (0.47)	221 (0.50)	222 (0.51)	273 (0.99)	197-234

[a]Three significant figures given for clarity although values accurate to only two places.

[b]The n refers to number of reports from which report averages were derived.

[c]Values in parenthesis indicate cumulative probabilities, $P(X \leq X_u)$.

References: Nelson (1931); Kahn et al. (1969); Durbin et al. (1970); Filer and Martinez (1963); Beal (1954); Fomon and May (1958); Fomon et al. (1963, 1971, 1977); Fomon (1978, unpublished); Guthrie (1963); Eagles and Steele (1971); USDA (1965).

Table 3.33. Daily milk consumption U_{ap}^{M} of individuals aged 3-5, 9-11, 15-17, and 20-34 years[a]

Range (ml/day)	1-120	121-240	241-360	361-480	481-730	731-970	971-1380	1331-3472
Average (ml/day)[b]	60	180	300	420	606	850	1150	2402
Age group								
3-5 years								
% frequency	2.8	9.6	16.0	14.4	30.0	18.2	7.8	1.0
% probability[c]	2.8	12.4	28.4	42.8	72.8	91.0	98.8	99.8
				(1249 observations)				
9-11 years								
% frequency	1.3	6.1	17.5	11.7	27.0	23.9	10.5	1.7
% probability[c]	1.3	7.4	24.9	36.6	63.6	87.5	98.0	99.7
				(1103 observations)				
15-17 years								
% frequency	5.6	4.7	21.0	7.4	25.9	19.4	12.2	3.6
% probability[c]	5.6	10.3	31.3	38.7	64.6	84.0	96.2	99.8
				(860 observations)				
20-34 years								
% frequency	22.4	13.9	24.8	8.1	18.3	5.9	4.6	1.9
% probability[c]	22.4	36.3	61.1	69.2	87.5	93.4	98.0	99.9
				(1980 observations)				

[a]One day recall.

[b]Arithmetic mean of range.

[c]% probability indicates the cumulative probability, $P(X \leq X_u)$.

Reference: Pao and Burk (1975).

Table 3.34. Relative frequency of infants drinking various kinds of milk

Feeding	Age (months)							
	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 9	9 to 12
	Relative frequency (%)							
Breast-fed	20	15	12	10	8	5	2	<1
Milk-based formulas[a]	64	65	59	49	41	29	3	1
Milk-free formulas[a]	10	10	10	10	8	6	2	1
Evaporated milk formulas	4	4	3					
Evaporated milk and water			2	2	2	2	1	1
Fresh cow's milk	2	6	14	29	41	58	92	96

[a]Commercially prepared.

Reference: Fomon (1975). These estimates were based on market research data and modified slightly by Fomon on the basis of his findings from 15 reports in the open literature.

Table 3.35. Average annual intake of tap water and beverages other than milk U_{ap}^{W} for various age groups

Age group	Tap water		Water-based drinks		NRC (drinking water)	
	Average	Range	Average	Range	Average	Maximum
	liters/year					
Infant	85	58-124				300
Child	120	76-180			260	510
Teen	102	79-121	265	200-335	260	510
Adult	93	70-150	400	266-524	370	730

References: 1. Walker et al. (1963) for infant and child (includes water used to dilute formula and fruit juices).
2. Cook et al. (1975) for teens and adults.

Table 3.36. Age-related average ingestion values U^F_{ap} for various foods[a]

Food	Infant (<1 year)	Child (1-11 years)	Teen (>11-18 years)	Adult (>18 years)
	kg/year			
Fruits, vegetables, and grains	88(1-3)	150(3)	185(3)	176(3)
Leafy vegetables	0.7(3)	7(4)	11(4)	18(4)
Meat and poultry	18(1-3)	50(3)	82(3)	94(3)
Freshwater finfish	0.14(5)	0.18(5)	0.31(5)	0.54(5)
Saltwater finfish	0.84(5)	1.6(5)	2.6(5)	3.9(5)
Shellfish	0.12(5)	0.34(5)	0.53(5)	1.4(5)

[a]Numbers in parentheses refer to references below.

References:
1. Kahn et al. (1969).
2. Durbin et al. (1970).
3. USDA (1965, No. 11).
4. Blanchard (1978, unpublished).
5. Rupp et al. (1979).

Table 3.37. Age-related maximum ingestion values U_{ap}^{F} for selected foods

	Infant (<1 year)	Child (1-11 years)	Teen (11-18 years)	Adult (>18 years)
	kg/year			
Leafy vegetables		26(1)[a]	36(1)	55(1)
Freshwater finfish[b]	0.94-5.1(2)	3.2-14.8(2)	5.6-11.5(2)	8.4-57.7(2)
Saltwater finfish[b]	2.3-6.2(2)	7.9-33.1(2)	13.7-36.6(2)	21.1-65.4(2)
Shellfish[b]	0.6-2.3(2)	3.9-12.9(2)	5.6-14.1(2)	11.5-44.1(2)
Columbia River sport fish[c]		23(3)	24(3)	20(3)

[a] Values in parentheses refer to references listed below.

[b] The 95*th* percentile and maximum value are given for infants. The 99*th* percentile and maximum value are given for all other age groups.

[c] Average values of the top ten reporting individuals.

References:
1. Blanchard (1978, unpublished).
2. Rupp et al. (1979).
3. Honstead et al. (1971).

Table 3.38. Average inhalation rate U^A_{ap} of various age groups

Age group	Average value[a]	NRC
	----------m^3/year----------	
Infant (<1 year)	1387	1400
Child (10 years)	4672	3700[b]
Teen (11-18 years)		8000
Adult (>18 years)	8030	8000

[a]Whenever possible averages include male and female members of the given age group; data obtained from ICRP-23 (1975).

[b]NRC value is specific to a child 4 years of age.

Table 3.39. Resident population of the United States by age group[a]

Age group (years)	Number of residents	Percent of total
<1	3.16 E6	1.5
1-11	3.64 E7	16.8
12-19	3.31 E7	15.3
>20	1.43 E7	66.5
Total	2.16 E8	100

[a]USDC (1978); median age 29.4 years.

Table 3.40. Average time period t_h between harvesting and consumption of foods[a]

Foodstuffs	Delay time: Private or local	Delay time: Commercial
	hr	hr
Drinking water	12	24
Milk	24	72
Beef and pork	300	300
Poultry	24	240
Fish, shellfish	24	200
Fresh fruits and vegetables:		
perishable	24	84
other	24	168

[a]Times do not include retail display time which may be as long as 14 days for beef, pork, and poultry and five days for finfish and shellfish.

Reference: Blanchard (1978, unpublished).

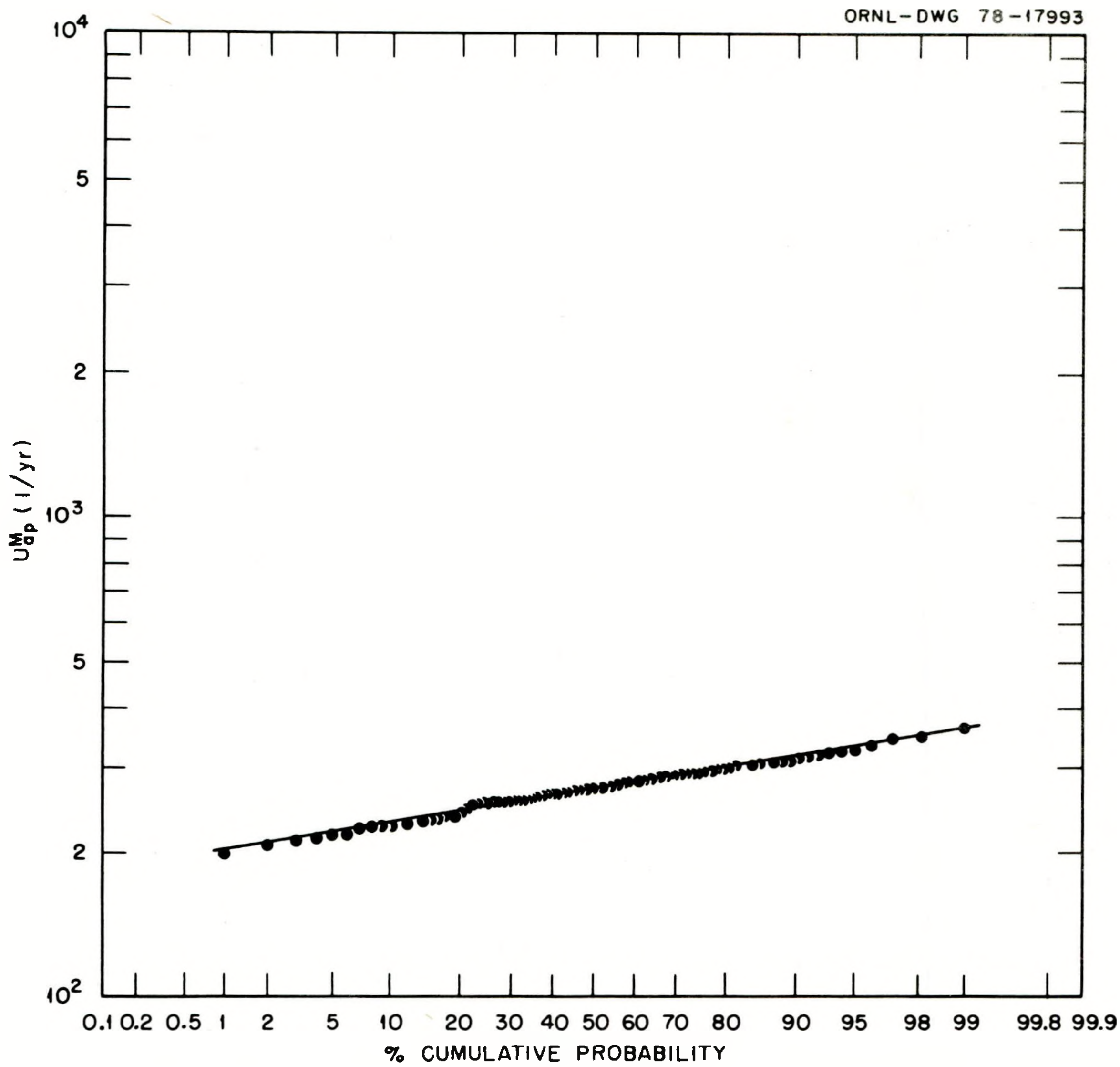

Fig. 3.29. Lognormal probability plot of individual milk consumption U_{ap}^M for infants ages 0-4 months.

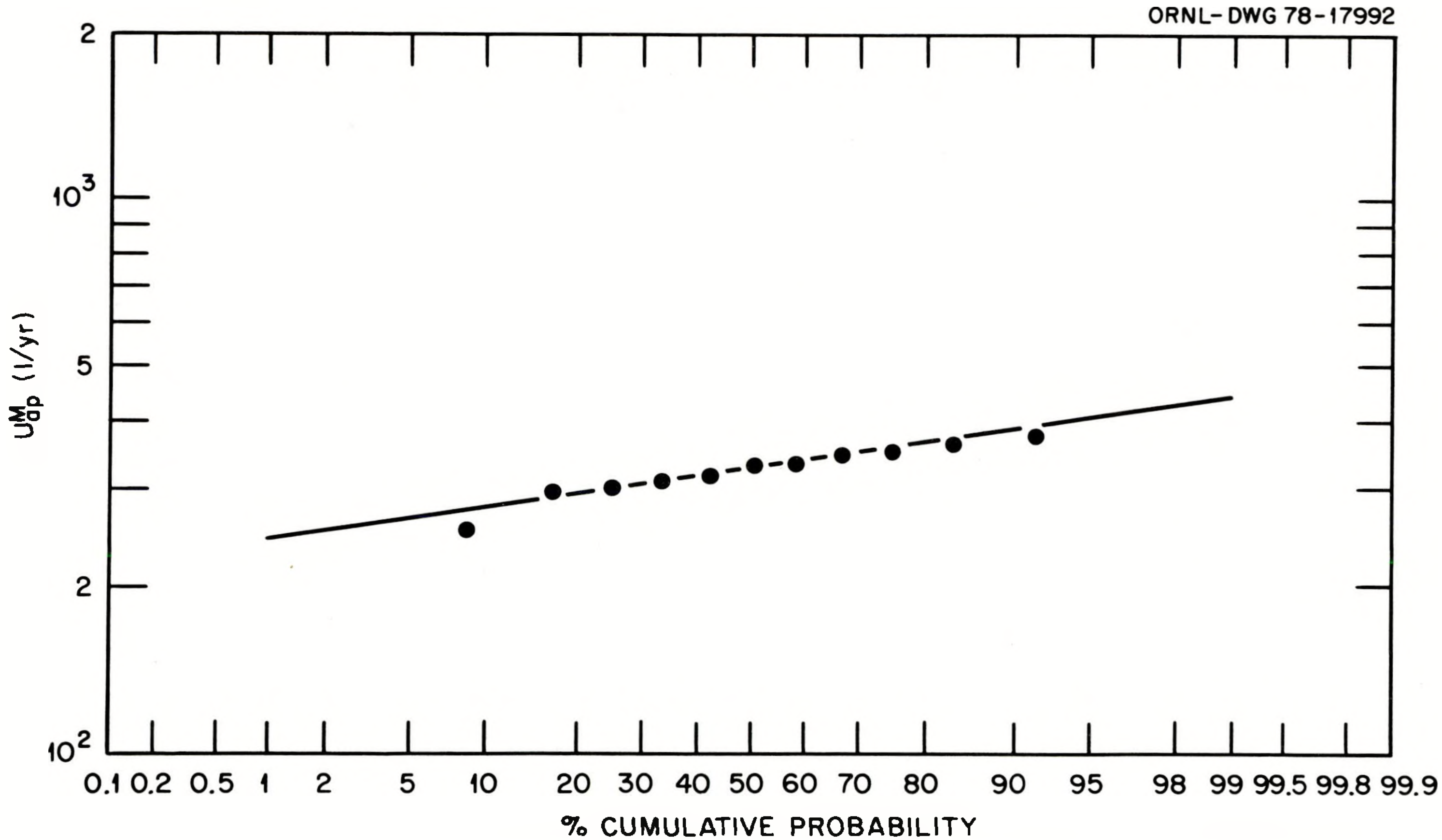

Fig. 3.30. Lognormal probability plot of individual milk consumption U_{ap}^{M} for infants aged 0-6 months.

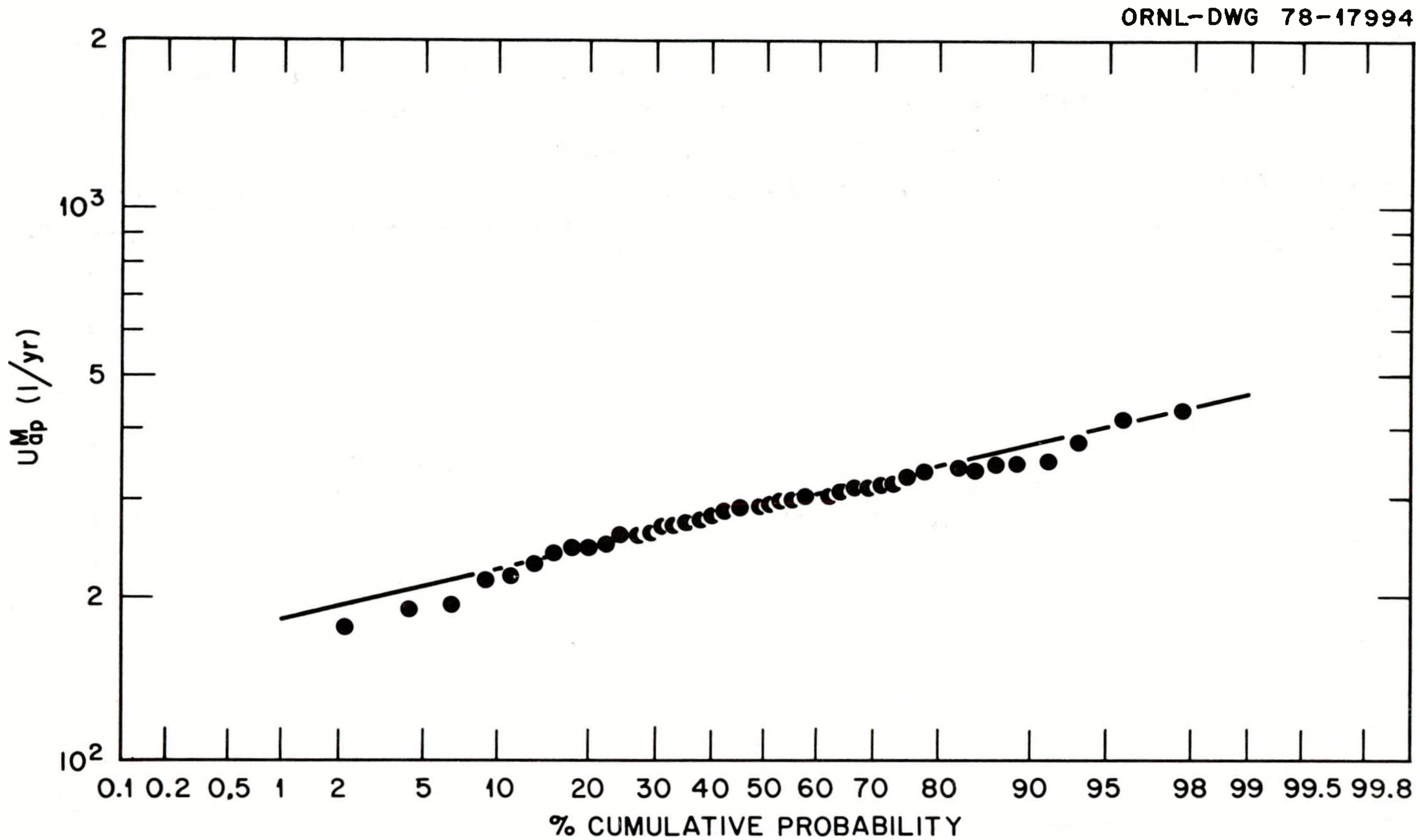

Fig. 3.31. Lognormal probability plot of individual milk consumption U^M_{ap} for infants aged 4-6 months.

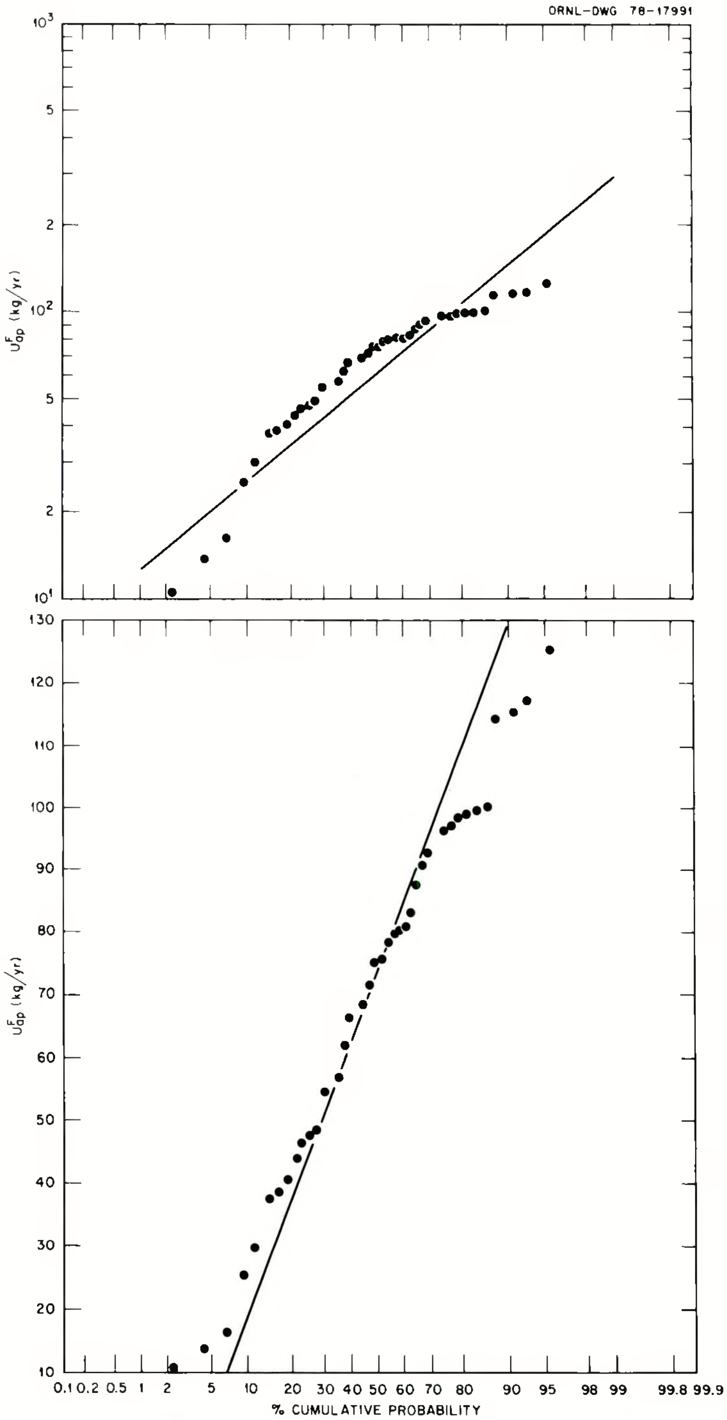

Fig. 3.32. Lognormal and normal probability plots of individual consumption of solid funs U_{ap}^F for infants aged 4-6 months.

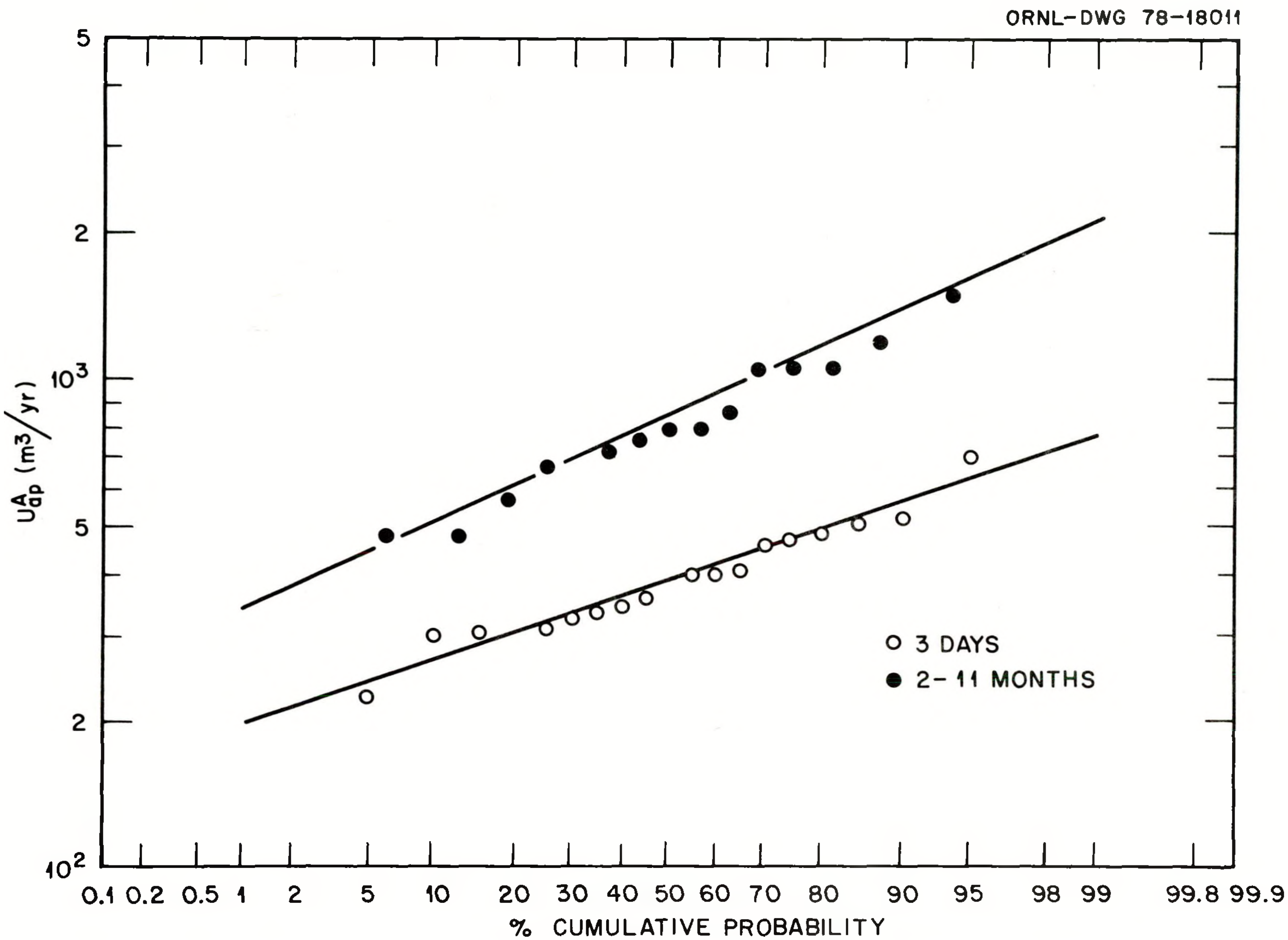

Fig. 3.33. Lognormal probability plots of individual resting respiration rate U^A_{ap} for infants aged 3 days and 2-11 months.

3.12 ^{131}I Ingestion Thyroid Dose Conversion Factor for Infants, D

(Donald E. Dunning, Jr.)

3.12.1 Description of the parameter

In order to determine the impact on man from environmental releases of radioiodine, it is necessary to relate the concentration of the nuclide in inhaled air or ingested foodstuffs to the dose ultimately delivered to the human thyroid. This relationship is expressed by the dose conversion factor D. In the present applications, the term "dose conversion factor" is defined as the dose commitment (rem) delivered to the infant thyroid by 1 μCi of ingested ^{131}I.

In assessments of dose to man from ^{131}I in the environment, young children comprise the critical segment of the population because of anatomical and metabolic characteristics, milk consumption rate, and greater radiosensitivity (Federal Radiation Council 1966). The calculation of age-specific estimates of dose from ^{131}I to the infant thyroid is affected by several biological and physical parameters. An attempt has been made here to assess the uncertainty in the estimation of three principal biological parameters: the fraction of ingested ^{131}I taken up by the thyroid, the effective half-time of residence, and the mass of the thyroid.

Because the thyroid dose from ingested iodine is delivered predominantly by the radioiodine deposited in the thyroid, contribution to dose from cross irradiation by radioiodine in surrounding organs and tissues is considered to be negligible. Therefore, the dose equivalent delivered to the thyroid D may be expressed by the equation

$$D = S(\text{thyroid}) \cdot \tilde{A} \ (\text{rem}) \ , \qquad (3.20)$$

where

S(thyroid) = the average dose equivalent rate (rem/μCi-day) to the thyroid due to 1 μCi of the radionuclide uniformly distributed in that organ (Snyder et al. 1974),

$\tilde{A}$ = the time-integrated activity (μCi-day) of radioiodine in the thyroid.

In the present study several simplifying assumptions have been adopted. In calculating S(thyroid), the ratio of the dose equivalent rate contributions of beta emissions to photons is assumed to be the same for the child as for the adult; that is, the photon contribution to S(thyroid) is assumed to be 6.5% that of the beta contribution for both children and adults. The value of S(thyroid) may then be approximated as:

$$S(\text{thyroid}) = \frac{10.38}{m} \; (\text{rem}/\mu\text{Ci-day}) \; , \tag{3.21}$$

where

10.38 is derived from energies and intensities (Kocher 1977) and the assumption described above,

m is the mass of the thyroid (grams).

The dose commitment to the thyroid due to the ingestion of 1 μCi of ^{131}I can be approximated as

$$D = \left[\frac{10.38}{m}\right] \left[f \, \frac{\left\{1 - \exp\left[-\frac{(\ln 2)t}{T_{eff}}\right]\right\}}{\frac{\ln 2}{T_{eff}}} \right] \tag{3.22}$$

where

f = the fraction of ^{131}I absorbed by the thyroid,

T_{eff} = the effective half-time of residence in the gland,

t = the time of integration.

When t is large, the equation can be further simplified as

$$D = f \left(\frac{10.38}{m}\right) \left(\frac{T_{eff}}{\ln 2}\right) \; (\text{rem}/\mu\text{Ci}) \; . \tag{3.23}$$

The equation thus reduces to a simple multiplicative chain model.

Complete absorption of all ingested iodine into the blood is assumed. This assumption may be of questionable validity for newborn infants as noted by Morrison et al. (1963). However, the above equation produces an identical result to that calculated with an earlier methodology (ICRP 1959), using an effective energy of 0.2 as suggested by the ICRP (1968) and values for all other parameters as discussed below.

An important simplifying assumption in this calculation has been that the biological parameters remain constant throughout the intake period and shortly afterward. This is reasonable for a single pulse intake, because essentially the entire dose commitment from ^{131}I is delivered within several weeks after intake. For chronic intake, however, this assumption would not be entirely correct. Thus, an additional error component is introduced into the calculation of the dose conversion factor, as a result of changes in the individual metabolism and growth during the intake and integration period. This simplification is necessitated by the coarse nature of the available data. The resulting estimates of dose may be of a somewhat conservative nature. A more sophisticated calculation might be carried out by allowing the parameters to vary continually as a function of age; this calculation, however, would require sufficiently detailed data to develop a regression equation for each of the parameters as a function of age.

The dose conversion factor for ^{131}I in the infant thyroid currently listed by NRC in lieu of site-specific information is 13.9 rem/μCi (USNRC 1977a). The value specified for the mass of the infant thyroid is 2 grams, fractional uptake to the thyroid is 0.3, and the biological half-time in the thyroid is 20 days (Hoenes and Soldat 1977).

3.12.2 Description of the data base

Thyroid mass. The values of thyroid mass for various ages used in this study are shown in Table 3.41. Mochizuki et al. (1963) studied the weights of normal thyroid glands coming to autopsy in New York City. Kay et al. (1966) compiled the weights of the thyroids of normal children and adolescents through the age of 19 years from autopsy data in six hospitals in the United States and observed a significant difference in the mean weights from different geographic regions. Gaffney and Moore (1964) also list values of thyroid mass for a number of infants in different areas of the United States. The geographic sources of the data compiled by Spector (1956) are specific only to those regions in which the occurrence of goiters is not abnormally high. However, these values tend to be slightly higher than those found by the other authors, and they may be suspect.

One problem in data analysis is that results from several of the studies are expressed only in terms of mean values of numerous individual observations within a given age bracket, and others are reported as individual observations. This inconsistency may introduce another source of error into the analysis.

Thyroid uptake. Data used for the estimation of 24-hour thyroidal uptake in infants of various ages is shown in Table 3.42. Ogborn et al. (1960), Van Middlesworth (1954), and Fisher et al. (1962) have reported 24-hour uptake data for ^{131}I in the thyroids of newborn children in the United States. The range of values reported in these studies is very great, from a low of 6.3% of the iodine input to a high of 97%. Oliner et al. (1957) report thyroidal uptake data for children ranging in age from 2.5 months to 18 years. The range of uptake values over the entire 18-year span is much less than that of the newborn infants described above. Although not directly applicable to this study, the ^{131}I uptake observed by Anoussakis et al. (1973) in Greek children and by Karhausen et al. (1970) in Belgian children occur within the high end of the range for American newborn children.

Karhausen et al. (1970) note elevated 24-hour uptakes and levels of both inorganic and protein-bound iodine in children less than six months of age. Anoussakis et al. (1973) also observe high rates of ^{131}I uptake in newborn children which decrease progressively with age into early adulthood. Oliner et al. (1957) describe a state of thyroidal hyperactivity which exists through the age of four years and possibly longer. This state is characterized by elevated levels of protein-bound radioiodine even when 24-hour uptake is not significantly higher than the normal adult. Fisher et al. (1962), however, report that the initially elevated uptake in neonatal infants reaches a peak at about two days and returns to normally low levels by five days of age. This pattern is attributed to an increased thyroid-stimulating hormone effect initiated by stress and/or neonatal temperature fluctuations.

One inconsistency among these studies is the mode of iodine intake. Ogborn et al. (1960), Van Middlesworth (1954), and Fisher et al. (1962) injected iodine directly into their patients, whereas Oliner et al. (1957) relied on oral administration. This inconsistency should make little difference if the assumption of essentially complete absorption of iodine from the gastrointestinal system is accepted. Morrison et al. (1963), however, observed a higher level of uptake for intramuscular administration than for oral administration in newborn infants.

Half-time of ^{131}I in the thyroid. Little information is available describing the biological half-time T_b of iodine in the thyroids of children. Rosenberg (1958) reports a range of 21 to 200 days in adults. A similar wide range of values might be expected for other age groups. Rosenburg notes a direct relationship between the biological half-time and the age of the individual and an inverse relationship between uptake and age in subjects from 22 to 50 years of age. If this trend is valid, we might expect children to exhibit shorter values of T_b and greater uptakes. This is indeed observed. Quimby et al. (1958) and Bryant (1969) respectively estimate a 23-day biological half-time for newborn and six-month old infants. Morrison et al. (1963) suggest that a T_b of 15-25 days may be appropriate for the newborn. In a study of nine neonatal infants Fisher et al. (1962) found a mean value of approximately 11 days from a range of 4 to 40 days. Cook and Snyder (1965) calculate a somewhat shorter half-time of about six days for ^{131}I in the thyroids of one-year-old children.

Sufficient data were unavailable to confirm a lognormal distribution of the data, but it was assumed that the distribution of data for the child is of a similar nature to that of the adults reported by Rosenberg (1958) shown in Fig. 3.34. Radiological decay of ^{131}I may be taken into account in order to calculate an effective half-life of residence in the thyroid T_{eff} according to the equation:

$$T_{eff} = \frac{T_r \cdot T_b}{T_r + T_b} , \qquad (3.24)$$

where

T_r is the half-life for radiological decay, 8.04 days (Kocher 1977),
T_b is the biological half-time.

3.12.3 Results

Lognormal probability plots are shown for the fractional uptake, T_b and thyroid mass in Figs. 3.34 through 3.36, respectively. Estimates of each individual parameter and of the dose commitment obtained from the ingestion of one microcurie of ^{131}I are presented in Tables 3.43 and 3.44 for each of the age categories considered. At least two distinct age categories seem to be appropriate. Newborn infants exhibit a great variability in thyroidal uptake of ^{131}I, whereas slightly older infants appear to exhibit lower and less varied uptake. Also, the mass of the thyroid increases rapidly after birth. Any differences in the effective half-lives for the two groups might be considered artifacts attributable to the paucity of data upon which the calculations were based.

Data used in this study have been restricted to that appropriate for U.S. populations, which is of primary concern to the NRC. Dolphin (1971) indicates that both uptake and thyroid mass are functions of dietary iodine intake. Dietary iodine levels, general dietary habits, and nutritional status show a great deal of geographic variation. In areas of chronic iodine deficiency, adaptations may occur which permit very high levels of iodine accumulation in the thyroid relative to the extracellular fluids (Cuddihy 1964). This accumulation is accompanied by enlargement and other alterations of the gland. Therefore, it would be very important to obtain values of each parameter which are appropriate for a given assessment area if greater accuracy and precision in the dose conversion factor D were to be desired.

Kay et al. (1966) found that the average mass of the thyroid for a given age group was greater in midwestern subjects than in subjects from the eastern United States. Oddie et al. (1968) and Cassidy and VanderLaan (1958) note greater radioiodine uptake in subjects from northeastern United States than in those from western or southern states. Furthermore, there may be significant variation with respect to changes in dietary habits with time. Pittman et al. (1969) note a significant decrease in ^{131}I thyroidal uptake in patients at a U.S. hospital during the period from 1959 to 1968, which they attribute to increased levels of iodine in the diet, especially in processed bread. Oddie et al. (1970) attribute this trend primarily to the use of iodized salt. Bernard et al. (1972) describe a similar shift in the normal range of ^{131}I uptake over a period of 15 to 20 years in patients of all ages.

It is apparent that these parameters are extremely sensitive to both spatial and temporal variation. This concern was expressed within some of the individual studies reviewed. Data used in this study have been reported by various investigators in different areas of the United States over a time span of many years, and thus should reflect both spatial and temporal variation. Site-specific data would be preferable to the general data considered here, but special studies would have to be initiated to make such information available.

3.12.4 Limitations

All statistics in this analysis are based on the assumption of lognormal distributions of the data. In some cases (e.g., thyroid mass and biological half-time), there are not sufficient data to verify this assumption. Additional data are needed for all parameters involved in the dose calculation, but especially for the biological half-time of ^{131}I in the infant thyroid and thyroid mass of children between the ages of 6 months and 1.5 years. With one exception, the data used for thyroid mass analysis were available only as mean values of a number of individuals computed over a rather large age span (e.g., one- to two-years olds). More reliable estimates of the variability of the thyroid mass should be obtained from data with a finer resolution with respect to the individuals studied and their age. Such data were not available at the time of this study. However, the biological half-time T_b of ^{131}I in the infant thyroid appears to be the most poorly documented parameter. Further studies of the influence of dietary iodine levels upon uptake, retention, and thyroid mass would certainly be of value. Such studies could help to pinpoint any additional intervariate correlations which may be present.

Table 3.41. Mass of thyroid, m

Mass (g)	Age	Reference
0.5	11 hr	1
0.6	11 months	1
0.6	45 hr	1
0.7	4.5 hr	1
0.8	11 hr	1
1.0	46 hr	1
1.0	13.8 hr	1
1.0 ± 0.1	0-1 month	3
1.5 ± 0.7	0-1 month	2
1.6 ± 0.5	7-12 months	3
1.9 ± 0.5	1-2 years	3
2.0 ± 0.9	7-12 months	2
2.04	6-12 months	4
2.53	1-2 years	4
2.6 ± 1.4	1-2 years	2

References:
1. Gaffney and Moore (1964) reported single values.
2. Kay et al. (1963) reported mean values.
3. Mochizuki et al. (1963) reported mean values.
4. Spector (1956) reported mean values.

Table 3.42. Fractional uptake of ^{131}I by thyroid, f_m

Uptake	Age[a]	Reference	Uptake	Age	Reference
0.063	n	1	0.364	n	1
0.089	n	1	0.38	2.5 months	2
0.093	n	1	0.39	n	3
0.111	n	1	0.40	21 months	2
0.111	n	1	0.42	n	3
0.113	n	1	0.44	2 years	2
0.126	n	1	0.46	n	4
0.137	n	1	0.46	n	3
0.143	n	1	0.49	n	3
0.165	n	1	0.52	n	3
0.172	n	1	0.56	n	3
0.180	n	1	0.58	n	3
0.18	1.5 years	2	0.58	n	3
0.19	2 years	2	0.61	n	3
0.194	n	1	0.61	n	4
0.195	n	1	0.61	n	4
0.200	n	1	0.62	n	4
0.222	n	1	0.62	n	3
0.239	n	1	0.62	n	3
0.26	22 months	2	0.64	n	3
0.261	n	1	0.65	n	3
0.264	n	1	0.65	n	3
0.27	8 months	2	0.67	n	3
0.282	n	1	0.67	n	4
0.290	n	1	0.69	n	3
0.29	2 years	2	0.72	n	3
0.297	n	1	0.73	n	3
0.30	2 years	2	0.74	n	3
0.302	n	1	0.75	n	3
0.309	n	1	0.76	n	3
0.32	2 years	2	0.76	n	3
0.35	15 months	2	0.76	n	3
0.35	n	3	0.88	n	3
0.35	n	3	0.94	n	4
0.354	n	1	0.97	n	4

[a]n = newborn.

References:
1. Ogborn et al. (1960)
2. Oliner et al. (1957)
3. Fisher et al. (1962)
4. Van Middlesworth (1954)

Table 3.43. Estimates of parameters determining for iodine and estimates of D for newborn children

Parameter	μ	σ	n	X_p	X_m	$\bar{X}$	X_{99}	NRC	Observed range
				g^{-1}					
Reciprocal of thyroid mass	0.17	0.35	8	1.1 (0.36)[a]	1.2 (0.50)	1.3 (.57)	2.7 (0.99)	0.5 (0.01)	0.67-2.0
				(-)					
Fractional uptake	-1.0	0.70	59	0.23 (0.24)	0.37 (0.50)	0.47 (0.64)	1.0[b] (0.99)	0.3 (0.39)	0.063-0.97
				days					
T_{eff}[c] [Based on values given by Quimby et al. (1958), Morrison et al. (1963), and Fisher et al. (1962)]	1.7	0.13	3	5.38 (0.45)	5.47 (0.50)	5.52 (0.53)	7.41 (0.99)	5.73 (0.64)	4.7-6.0
				rem/μCi					
D	3.6	0.80		19 (0.21)	37 (0.50)	50 (0.66)	240 (0.99)	13.9 (0.11)	

[a]Values in parenthesis indicate cumulative probability, $P(X \leq X_u)$.

[b]A value of 1.9 was calculated for X_{99}, but actual values cannot exceed 1.0.

[c]Three significant figures shown for purposes of clarity.

Table 3.44. Estimates of parameters determining D for iodine and estimates of D for 6-24 month old infants

Parameter	μ	σ	n	X_p	X_m	$\overline{X}$	X_{99}	NRC	Observed range
				g^{-1}					
Reciprocal of thyroid mass	-0.56	0.50	7	0.44 (0.31)[a]	0.57 (0.50)	0.65 (0.60)	1.8 (0.99)	0.5 (0.40)	0.39-1.7
				(-)					
Fractional uptake	-1.2	0.29	10	0.28 (0.39)	0.30 (0.50)	0.31 (0.56)	0.59 (0.99)	0.3 (0.49)	0.18-0.44
				days					
T_{eff} [Based on values given by Bryant (1969) and Cook and Snyder (1965)]	1.5	0.39	2	3.9 (0.35)	4.5 (0.50)	4.8 (0.58)	8.0[b] (0.99)	5.73 (0.74)	3.4-6.0
				rem/μCi					
D	2.4	0.70		6.8 (0.24)	11 (0.50)	14 (0.64)	56 (0.99)	13.9 (0.63)	

[a]Values in parenthesis indicate cumulative probability, $P(X \leq X_u)$.

[b]Calculated X_{99} for T_{eff} is 11.0 days, but actual values cannot exceed the radiological half-life T_r of ^{131}I of 8.04 days.

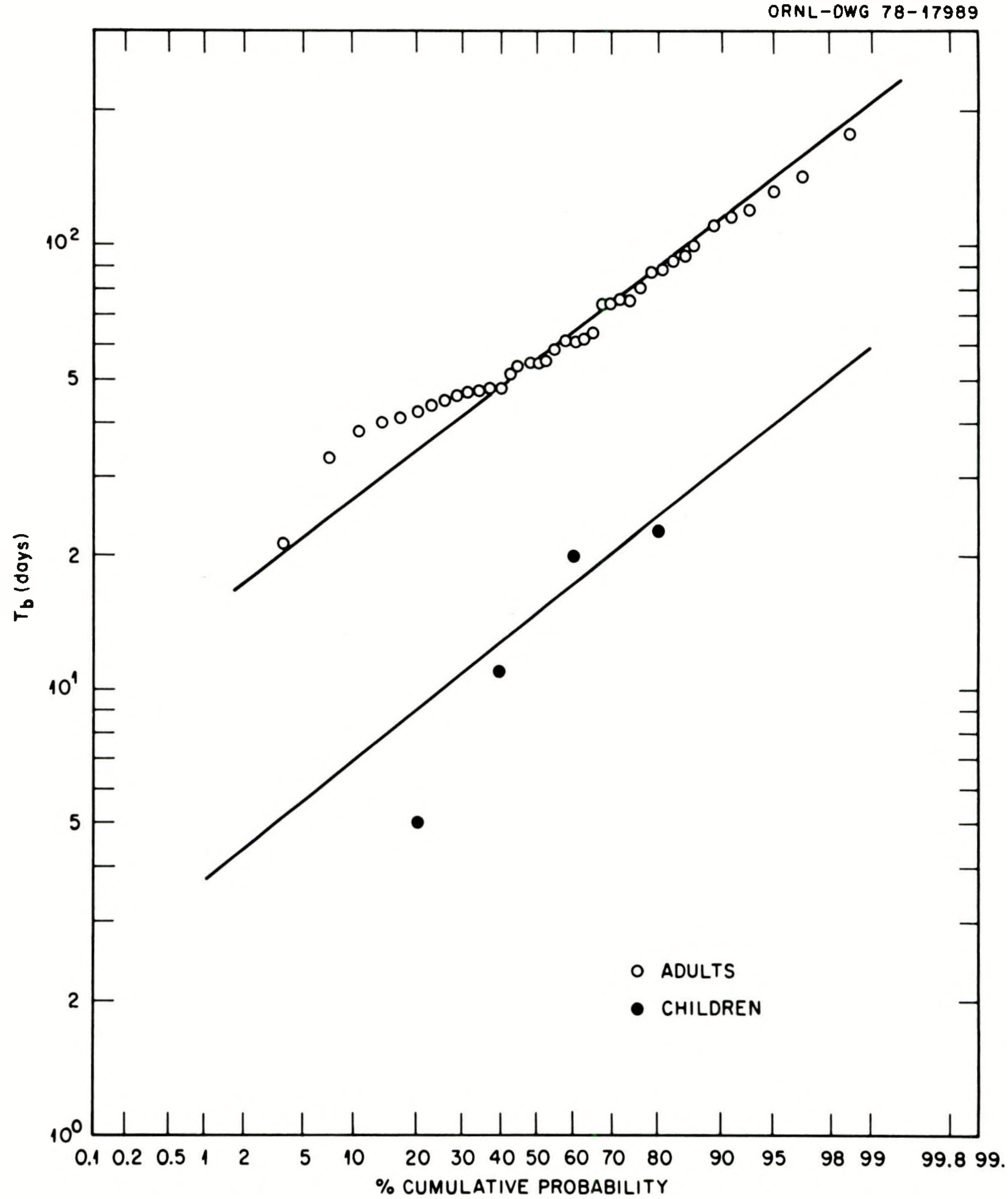

Fig. 3.34. Lognormal probability plots of the biological half-time T_b for ^{131}I in the thyroids of adults and children aged 1 year.

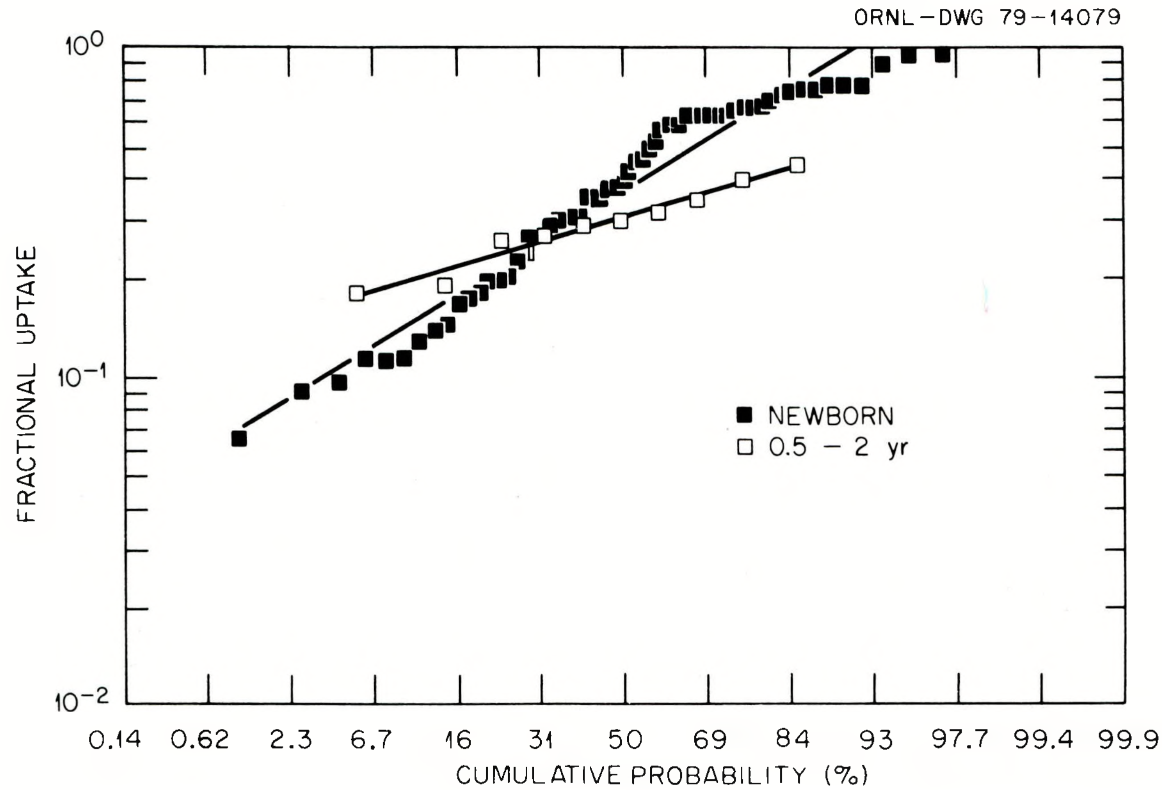

Fig. 3.35. Lognormal probability plots of fractional thyroidal uptake of ^{131}I for individuals newborn and aged 0.5-2 years.

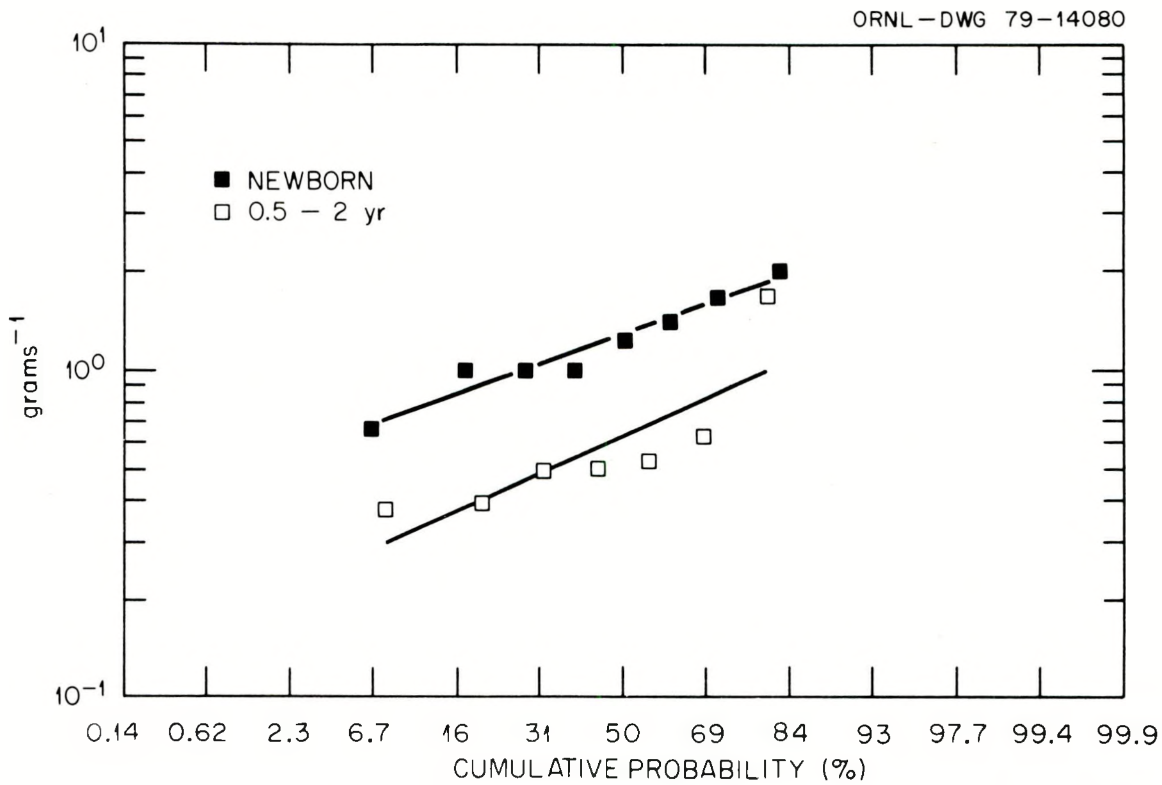

Fig. 3.36. Lognormal probability plots of the reciprocal of thyroid mass for individuals newborn and aged 0.5-2 years.

4. PREDICTION OF THE TRANSPORT OF ^{131}I THROUGH THE PASTURE-COW-MILK PATHWAY AND THE SUBSEQUENT DOSE TO AN INFANT'S THYROID

(F. Owen Hoffman)

4.1 Parameters Included in the Analysis

The transport of ^{131}I over the pasture-cow-milk pathway and the subsequent dose to an infant's thyroid can be estimated via a simple multiplicative chain model:

$$R = \chi \cdot k \cdot V_D \cdot 1/\lambda_{eff} \cdot Q_F^T \cdot f_s \cdot F_m \cdot f_p \cdot U^M \cdot D \;, \qquad (4.1)$$

where

χ = equilibrium air concentration (pCi/m^3);

k = a unit conversion factor (86400 sec/day);

V_D = an air concentration pasture grass transfer factor (m^3/kg, dry wt · sec);

$1/\lambda_{eff}$ = $T_{eff}/\ln 2$ = effective mean-time on pasture vegetation (days);

Q_F^T = total daily dry matter intake of a dairy cow (kg/day);

f_s = fraction of the total dry matter intake composed of fresh forage;

f_p = fraction of a year that dairy cows receive fresh forage;

F_m = intake-to-milk transfer factor (day/liter);

U^M = annual milk consumption rate for infants, ages 0.5 to 1.5 years (liters/year);

D = thyroid dose conversion factor for infants, ages 0.5 to 1.5 years (mrem/pCi ingested);

R = Annual dose (mrem/year) to the thyroid.

Reduction of the more detailed equations in NRC Regulatory Guide 1.109 (1977a) to Eq. (4.1) is possible because of the dominant importance of the milk pathway to the contribution of dose and the relatively short half-life of ^{131}I which negates a significant accumulation in the root-zone of soils. Additional parameters which could be considered are the fraction of milk consumed that is obtained from contaminated pastures (f_d) and the reduction of milk concentration produced by radioactive decay during the time (t) between milk production and milk consumption ($\exp - \lambda_i t$). These parameters are best determined on a site-specific basis and are not included in the following analysis.

Most of the parameters in Eq. (4.1) appear to be lognormally distributed. The parameters Q_F^T, f_s, and f_p appear to be more normally than lognormally distributed (see Sect. 3.4 and 3.5). Combinations of normal and lognormal distributions in a multiplicative chain model require numerical solutions; however, if all of the parameters are lognormal, analytic solutions are possible because the average (μ) and variance (σ^2) of logarithms for each parameter are additive and thus the product of the model exhibits lognormality (Sect. 2). A lognormal distribution is therefore approximated for Q_F^T, f_s, and f_p. An examination of Figs. 3.13, 3.17, and 3.18 indicates that this approximation is valid for values above the 20% to 30% cumulative probability levels. The assumption of lognormality for these parameters results in an underestimation of probabilities associated with parameter values which are less than the 20% to 30% cumulative probability levels. The error in the lower percentiles is not important when the objective of a model is to produce values which give a $\geq$50% probability of not being exceeded. Values of μ and σ for Q_F^T, f_s, and f_p are determined graphically from Figs. 3.13, 3.17 and 3.18 in the following manner:

$$\mu = \ln 50\% \text{ cumulative probability value and}$$

$$\sigma = \ln \left(\frac{84\% \text{ value}}{50\% \text{ value}}\right) \text{ cumulative probability.}$$

For the approximated lognormal distributions of Q_F^T, f_s, and f_p, the respective values of μ are 2.7, -0.87, and -1.0. The respective values of σ are 0.12, 0.24, and 0.41.

The removal of χ from Eq. (4.1) produces an estimate of the ratio of dose (R) to air concentration (mrem • m^3/pCi • year); additionally, the substitution of r/Y_v (the ratio of the vegetation interception fraction to pasture biomass) for V_D will give an estimate of the ratio of dose commitment (R) to deposition rate ($\dot{d}$) (mrem • m^2 • sec/pCi • year); and the additional elimination of the parameters $1/\lambda_{eff}$ and k produces an estimate of the ratio of dose commitment (R) to total deposition at equilibrium (mrem • m^2/pCi • year).

The statistics for V_D, which apply to only the molecular form $^{131}I_2$, are taken directly from an analysis performed in a previous investigation (Shaeffer and Hoffman, in press) in which average values derived from numerous short-term experiments at Jülich, Germany, and Idaho Falls, Idaho, were found to be quite similar. The value of V_D (3.9×10^{-2} m^3/kg • sec) for the NRC was derived by using typical meteorological conditions for Oak Ridge, Tennessee, to estimate a deposition velocity V_d of 0.68×10^{-2} m/sec from Regulatory Guide 1.111 (1977b) and dividing by the dry weight equivalent of the Regulatory Guide 1.109 default value for the standing crop biomass Y_v of pasture grass (0.175 kg/m^2). The estimation of values of deposition velocity V_d from Regulatory Guide 1.111 is discussed further by Miller and Hoffman (1979).

Statistical values for the parameters used to estimate the thyroid dose from infant consumption of milk containing ^{131}I transported via the pasture-cow-milk pathway are given in Table 4.1. These values are subject to the limitations discussed in Sect. 3 for each of the parameters considered herein.

Table 4.1. Parameter values of importance to the analysis of the variability of thyroid dose from the transport of ^{131}I over the pasture-cow-milk pathway

Parameter	μ	σ^2	X_{median}	$NRC_{default}$	Notes
			-------- $m^3/kg \cdot sec$ ----		
V_D	-2.1	2.3E-3	0.12	0.039	*a,b*
			-------- m^2/kg --------		
r/Y_v	0.61	0.19	1.8	5.7	*c*
			-------- m^2/kg --------		
$1/Y_v$	1.1	0.35	3.0	5.7	*c*
			-------- days ---------		
$1/\lambda_{eff}$	1.84	0.020	6.3	7.4	
			-------- kg/day -------		
Q_F^T	2.7	0.014	15	12.5	*d*
			-------- (-) --------		
f_s	-0.87	0.058	0.42	1.0	*e*
			--------- (-) ---------		
f_p	-1.0	0.17	0.37	1.0	*e*
			------ day/liter ------		
F_m	-4.6	0.30	9.7E-3	6.0E-3	
			----- liters/year -----		
U^M	5.7	0.04	300	330	*f*
			------- mrem/pCi ------		
D	-4.5	0.49	1.1E-2	1.39×10^{-2}	*g*

[a] NRC value calculated from a weighted deposition velocity of 0.68×10^{-2} m/sec derived from Regulatory Guide 1.111 (USNRC 1977b).

[b] Divided by a dry matter standing crop biomass (Y_v) of 0.175 kg/m^2. Reference: Miller and Hoffman (1979).

[c] NRC value is calculated as 1.0 divided by 0.175 kg/m^2.

[d] NRC value is converted to dry matter equivalent assuming fresh forage to be 0.25 dry matter.

[e] The value 1.0 is assumed in lieu of site-specific information.

[f]U^M is assumed to be representative of infants and small children 0.5 to 1.5 years of age.

[g]D is assumed to be representative of infants 0.5 to 1.5 years of age.

4.2 Analysis of Pathway Ratios

The values of μ and σ^2 for each parameter in Table 4.1 can be used to calculate the variability of the following equilibrium ratios, which are products of multiplicative chain models.

(1) The milk-to-pasture forage ratio C_m/C_v (kg dry wt/liter) is defined as

$$C_m/C_v = Q_F^T \cdot f_s \cdot F_m \, , \tag{3.9}$$

where

C_m = the concentration of ^{131}I in milk at equilibrium (pCi/liter),

C_v = the concentration of ^{131}I in pasture forage at equilibrium (pCi/kg, dry wt).

(2) The milk-to-pasture ratio C_m/C_p (m^2/liter) is defined as

$$C_m/C_p = 1/Y_v \cdot Q_F^T \cdot f_s \cdot F_m \, , \tag{4.2}$$

where

C_p = the equilibrium concentration of ^{131}I in pasture forage per unit ground area (pCi/m^2).

(3) The milk-to-deposition ratio C_m/C_d (m^2/liter) is defined as

$$C_m/C_d = r/Y_v \cdot Q_F^T \cdot f_s \cdot F_m \, , \tag{4.3}$$

where

C_d = the total deposit of ^{131}I at equilibrium on an area of pasture (pCi/m^2).

(4) The milk-to-air ratio for $^{131}I_2$, C_m/χ (m^3/liter), is defined as

$$C_m/\chi = k \cdot V_D \cdot 1/\lambda_{eff} \cdot Q_F^T \cdot f_s \cdot F_m \quad . \tag{4.4}$$

(5) The dose-to-air ratio for $^{131}I_2$, R/χ (mrem · m^3/pCi · year), is defined as

$$R/\chi = C_m/\chi \cdot f_p \cdot U^M \cdot D \quad . \tag{4.5}$$

(6) The dose-to-deposition rate, R/d, (mrem · m^2 · day/pCi · year), is defined as

$$R/\dot{d} = C_m/C_d \cdot 1/\lambda_{eff} \cdot f_p \cdot U^M \cdot D \quad , \tag{4.6}$$

where

$\dot{d}$ = deposition rate (pCi/m^2 · day) .

According to Eq. (2.15) the mean of the logarithms of the output of a multiplicative chain model is equal to the sum of the means of logarithms of each multiplicative parameter in the model. According to Eq. (2.16) the variance of the logarithms of the model output is equal to the sum of the variances of logarithms of each input parameter. The values of μ and σ^2 in Table 4.1 are therefore used to calculate μ and σ^2 for each of the above ratios. Values of μ and σ for these ratios are then used in Eqs. (2.3) through (2.13) to produce the results presented in Table 4.2. The contribution of the individual input parameters to the overall uncertainty in each ratio presented in Table 4.2 can be calculated by dividing σ^2 for the input parameter by σ^2 for the ratio.

Table 4.2. Statistical analysis of pathway ratios calculated with parameters used to estimate the pasture-cow-milk transfer and thyroid dosimetry of ^{131}I

Ratios	μ	σ	X_p	X_m	$\overline{X}$	X_{99}	NRC	Notes
Milk-to-pasture (per mass vegetation)			kg/liter					
C_m/C_v	-2.8	0.61	4.2E-2 (0.27)	6.1E-2 (0.50)	7.3E-2 (0.62)	0.25 (0.99)	7.5E-2 (0.63)	*a* *d*
Milk-to-pasture (per unit ground area)			m^2/liter					
C_m/C_p	-1.7	0.85	8.9E-2 (0.20)	0.18 (0.50)	0.26 (0.66)	1.3 (0.99)	0.43 (0.84)	*a,b*
Milk-to-areal deposition			m^2/liter					
C_m/C_d	-2.1	0.75	7.0E-2 (0.23)	0.12 (0.50)	0.16 (0.65)	0.70 (0.99)	0.43 (0.96)	*a,b*
Milk-to-air concentration			m^3/liter					
C_m/χ	8.3	0.62	2700 (0.27)	4000 (0.50)	4900 (0.62)	1.7E4 (0.99)	1900 (0.11)	*a,e*
Dose-to-air concentration			mrem • m^3/pCi • year					
R/χ	8.5	1.0	1800 (0.16)	4900 (0.50)	8100 (0.69)	5.0E4 (0.99)	8600 (0.71)	*a,c,e*
Dose-to-deposition rate			mrem • m^2 • day/pCi • year					
$R/\dot{d}$	-0.12	1.1	0.26 (0.14)	0.89 (0.50)	1.6 (0.71)	12 (0.99)	15.0 (>0.99)	*a,b,c*

Table 4.2. (continued)

Notes

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[a]NRC value calculated assuming $f_s = 1.0$.

[b]NRC value calculated assuming $v = 1.0$ for iodine.

[c]NRC value calculated assuming $f_p = 1.0$.

[d]Values in parentheses indicate cumulative probability, $P(X \leq X_u)$.

[e]Values specific for the fraction of ^{131}I in air present as I_2.

4.3 Discussion

The results in Table 4.2 are based on the assumption that the estimated values of μ and σ (formerly referred to as $\hat{\mu}$ and $\hat{\sigma}$ in Sect. 2 of this report) are equal to the true values for these statistical parameters. The relevance of this assumption is difficult to ascertain because of the questionable validity of the primary assumptions made in this report, namely that:

1. the data obtained for the various parameters analysed in Sect. 3 of this report are representative of the true populations of parameter values.
2. the parameters of a multiplicative chain model are statistically independent.
3. the model is an appropriate simulation of reality; therefore correct input will result in correct output.

Because of the limitations of these assumptions, testing of the models used to calculate the ratios in Table 4.2 will ultimately be required in order to improve the reliability of the results. Such testing should be in the form of validation experiments performed under the specific conditions for which the models are applicable.

For some parameters such as $1/Y_v$, Q_F^T, f_s, and f_p, site-specific data may be readily available. The use of such data should reduce the values of σ associated with the model output. However, Table 4.1 indicates that the parameters having the largest values of σ^2 (and thus contributing most to the value of σ for the model output) are the parameters r/Y_v, $1/Y_v$, F_m, and D. The parameter $1/Y_v$ may be relatively easy to obtain on a site-specific basis, but values of F_m and r/Y_v must be derived from experimental procedures. Site-specific values for the parameters used to calculate the dose conversion factor D will probably be the most difficult to obtain. Therefore, the parameters r/Y_v, F_m, and D can be considered fundamentally important for those models in which they are employed as multiplicative factors. Unfortunately, the results calculated for these parameters are directly dependent on a data base that is of insufficient quality for a statistical analysis. It is conceivable that the availability of additional data for these parameters or the application of different criteria for the selection of data could have a noticeable influence on the results of the calculations performed herein.

The values of V_D considered in this analysis are applicable only to the molecular form of iodine (I_2). The small variability indicated for this parameter is based on two time-averaged values derived from numerous short-term measurements conducted at two different locations (Shaeffer and Hoffman, in press). For other physicochemical forms of iodine, V_D may vary by as much as three orders of magnitude. On the average, values of V_D for small aerosols are 10 to 20 times lower, and values for organic iodides are 100 to 1000 times lower than V_D values for I_2 (Hoffman 1977). Therefore, for iodine releases composed of a mixture of chemical and physical forms of iodine, V_D may be another parameter contributing significantly to the variability of the iodine pathway model, although the median value predicted by the model would be significantly lower than the median value predicted for a pure air concentration of I_2.

There are published values for the milk-to-air ratio C_m/χ for iodine (Table 4.3), but because of the difficulty in determining the physicochemical form of the iodine monitored in air and the degree to which measured concentrations represent equilibrium conditions, the applicability of these values to validation of the calculated C_m/χ values in Table 4.2 are limited. Using lognormal statistics to analyze the distribution of the data for this ratio in Table 4.3 results in a value of μ of 6.20 and a value of σ of 0.75, producing a most probable estimate (X_p) of 280 m^3/liter, a median (X_m) of 492, a mean ($\overline{X}$) of 650, and a 99% cumulative probability (X_{99}) of 2800. The value of X_{99} calculated from this set of data is equivalent to about the 28*th* percentile of the distribution calculated for C_m/χ using the values of μ and σ in Table 4.2, which are specific for an air concentration of $^{131}I_2$ in the molecular form. The cumulative probability for the NRC value of 1900 m^3/liter for C_m/χ (listed in Table 4.2) is 11%, and the associated cumulative probability for this value with respect to the distribution of data in Table 4.3 is 96%. This result indicates that the NRC default value of 1900 m^3/liter for C_m/χ may overestimate milk concentrations of ^{131}I resulting from weapons fallout or accidental releases containing a mixture of physicochemical forms of ^{131}I and may underestimate milk concentrations resulting from an air concentration of $^{131}I_2$ only.

The NRC values for the ratios listed in Table 4.2 are generally larger than the 60*th* percentile. The lower percentile (11%) associated with the NRC value for C_m/χ is due primarily to the coupling of Regulatory Guide 1.111 (USNRC 1977b) and Regulatory Guide 1.109 (USNRC 1977a). The coupling of these two documents does not include consideration for the statistical correlation between the deposition rate $\dot{d}$ and the standing crop biomass of pasture forage Y_v. However, the percentile associated with the NRC value for C_m/χ can also be affected by the specific meteorological data chosen for estimating a deposition velocity from Regulatory Guide 1.111.

Table 4.2 indicates that the estimated annual mean dose for a given deposition rate of ^{131}I ($R/\dot{d}$) is approximately a factor of six greater than the estimated most probable dose. The thyroid dose calculated with NRC default values exceeds the 99*th* percentile and is a factor of approximately nine greater than the mean. The effect of including site-specific information in the NRC calculations of dose can be roughly approximated by setting values of σ to zero for those parameters in Table 4.1 assumed to be known on a site-specific basis and substituting their median values in this table for the NRC generic default values. For example, assuming Q_F^T, f_s, and f_p are known on a site-specific basis, the NRC dose estimate ($R/\dot{d}$) would approximate the 87th percentile if no change is made in the default values used for other parameters in the model. The assumption of site-specific information for Q_F^T, f_s, and f_f would reduce the percentile associated with the NRC dose estimate for a given air concentration of $^{131}I_2$ (R/χ) from the 71*st* to the 11*th*. This example demonstrates a potential reduction in conservatism when site-specific information is used for only the agricultural parameters in the NRC calculations. The assumption of providing site-specific data for agricultural parameters but using generic default values for other parameters in the model is not unreasonable considering the relative ease in which agricultural information can be obtained. The NRC generic default values contributing to the reduced conservatism noted in the above example are those listed in Table 4.1 for V_D and F_m.

Table 4.3. Measured milk-to-air ratios C_m/χ for radioiodine and stable iodine

C_m/χ (m^3/ℓ)	Type of measurement	Reference
700	Fallout measurements of ^{131}I	Van As and Vleggar (1971)
541, 816	Fallout measurements of ^{131}I	Basson et al. (1973)
220	Fallout measurements of ^{131}I from Chinese weapons test of 1974	Goldstein et al. (1976)
410	Savannah River Plant release of ^{131}I	Marter (1963)
520	Fallout measurements of ^{131}I	Peirson and Keane (1962)
800	Analysis of stable iodine	Breuer and DeBortoli (1973)
3068, 256, 277	Respective averages of ^{131}I fallout measurements for April-October of 1961, 1962 and 1963	Soldat (1963)
210	Fallout measurements of ^{131}I from Chinese weapons test of 1977	Riedel et al. (1977a)
380	Fallout measurements of ^{131}I from Chinese weapons test of 1976	Riedel et al. (1977b)

5. FINAL DISCUSSION

This report attempts to specify the uncertainties associated with selected parameters which are used as input to the models incorporated in NRC Regulatory Guide 1.109 (1977a) through a statistical analysis of the distributions associated with these parameters. An estimation also is made of the uncertainties associated with the combination of multiplicative parameters used to calculate the transport of ^{131}I over the pasture-cow-milk pathway and the subsequent dose to an infant's thyroid. Uncertainties in release rates from nuclear facilities and in dispersion models are not considered.

The results of the analyses are dependent on three key assumptions:

(1) The available data are representative of the true population of parameter values.

(2) The parameters are statistically independent.

(3) The model is an appropriate simulation of reality; therefore correct input will produce correct output.

All three of these assumptions are questionable. Considerable judgment was exercised in the selection of data because few measurements are available which correspond exactly to the parameters as defined in NRC Regulatory Guide 1.109. Thus, a certain amount of bias is unavoidably inherent in the analyses. Also, in many instances a distribution is assumed for a parameter on the basis of only a few data points. Extrapolation of results based on few data points to the true distribution of parameter values may lead to unsound conclusions. Additional data or the use of different judgmental criteria for the selection of parameter values from the literature could have a marked effect on the results.

Statistical independence is assumed whenever data were not available to quantify suspected relationships. However, covariance is present between the interception fraction for pasture vegetation r and the reciprocal of the standing crop biomass of pasture vegetation $1/Y_v$, and thus these two parameters are replaced by the ratio r/Y_v. Although covariance between other parameters probably exists, quantification of these relationships with the available information is not possible.

Another factor affecting the analyses is time-averaging. Data used in this report for many parameters are usually obtained from experiments ranging over only a few hours or days and have not been sufficiently time-averaged. The parameters used in the models of NRC Regulatory Guide 1.109, on the contrary, are defined as annual average values. Therefore, attempts were made in this report to simulate time-averaging by comparing values averaged over an entire experiment or averaged for a given report or location.

The results outlined in the summary tables (Tables A and B) can be used to identify potentially critical parameters. The criteria for determination of a critical parameter are that the parameter is included in a pathway which potentially may contribute significantly to the total dose and that the parameter has a relatively large value of σ. Some of the parameters with large values of σ can be refined with site-specific information. Site-specific data should be readily available for such parameters as vegetation standing crop or yield Y_v, the fraction of the total feed intake composed of fresh pasture f_s, and the fraction of the year that dairy cows are receiving fresh forage, f_p. Estimates of animal feed consumption rates Q_F can be also obtained from local agricultural stations or county agents. However, values of the milk and beef transfer coefficients F_m and F_f, the plant to soil concentration ratio B_{iv}, and the aquatic bioaccumulation factor B_{ip} are extremely difficult to obtain on a site-specific basis without performing extensive or expensive measurements. Site-specific values of the metabolic and anatomical parameters used to calculate the dose conversion factor D_{aipj} are even less likely to be available because of the difficulty in obtaining such data for human subjects. The isotope or element dependent parameters involved in estimating foodchain transport and the parameters for human uptake and retention of radionuclides will, therefore, probably be responsible for most of the error associated with the NRC Regulatory Guide 1.109 models. The importance of these parameters in contributing to model uncertainty will be especially evident when site-specific information has been obtained for all other input parameters. In fact, the elimination of conservative assumptions from model calculations could result in a high probability of underestimating actual doses if site-specific data are used for some parameters and most probable or median default values are used for other less easily obtained site-specific data.

The problem of uncertainties in model input leading to uncertainties in model output is reflected in the selection of generic default values from a distribution of parameter values. What probability level should determine the selection of a default value to be used in lieu of site-specific information? Should this value coincide with the 50*th*, 70*th*, 99*th*, or 99.9*th* percentile? In a multiplicative chain model composed of lognormally distributed statistically independent parameters, the selection of default values should depend on the percentile desired for model output and the degree to which a given parameter contributes to the output uncertainty. The relationships between the A*th* percentile of the model output o and the corresponding percentile to be selected from an input parameter i can be described as

$$Z_o \sigma_o = \sum_i Z_i \sigma_i \ , \qquad (5.1)$$

Where Z is the number of standard deviations from the mean of a standard normal distribution corresponding to the A*th* percentile of that distribution. Values of Z for specific cumulative probabilities are found in tables contained in most statistical text books (i.e., Neter et al. 1978). Typical values of Z are 0 for the 50*th* percentile, 1.0 for the 84*th* percentile, 1.645 for the 95*th* percentile, and 2.326 for the 99*th* percentile.

The symbol σ_i is the standard deviation of the logtransformed data for each input parameter i, and σ_o is the standard deviation of the logtransformed distribution of the model output o. As discussed in Sect. 2.2 of this report [Eq. (2.16)], the variance of the model output σ_o^2 is equal to the sum of the variances of each input parameter $\sum_i \sigma_i^2$ when the model is a multiplicative chain composed of lognormally distributed, statistically independent parameters.

Equation (5.1) can be used to demonstrate that the selection of a specific percentile (other than the 50*th*) for each parameter in a multiplicative chain model would *not* result in the same percentile for the output. For example, assuming that ten parameters contributed equally to the output uncertainty, then

$$Z_o \sigma_o = 10\ Z_i \sigma_i \ . \qquad (5.2)$$

Since

$$\sigma_o = \sqrt{\Sigma \sigma_i^2} = \sqrt{10} \quad \sigma_i \ ,$$

then

$$Z_o = Z_i \sqrt{10} \ . \qquad (5.3)$$

Therefore, the result of selecting the 84*th* percentile ($Z_i = 1.0$) for each input parameter would produce a value for the output ($Z_o = 3.16$), which is greater than the 99.9*th* percentile. Selection of the 63*rd* percentile ($Z_i = 0.32$) for each input parameter in this special situation would be required to produce the 84*th* ($Z_o = 1.0$) percentile for the model output. This example illustrates the sensitivity of model output to conservatism employed in the selection of values for model input parameters. For this reason, the reader is reminded that the 99*th* percentile and values of the most probable, median and mean are provided only for purposes of describing the distribution estimated for individual parameters. The reader is therefore cautioned that tabulation of the 99*th* percentile in this report does not constitute a recommendation for its use. Selecting the 99*th* percentile for every parameter in a multiplicative chain model could easily result in an extremely conservative prediction. The selection of a percentile associated with a given input parameter should be determined by the percentile desired for model output. The percentile that is most appropriate for regulatory purposes remains to be specified by the regulatory agencies responsible for radiation protection.

It must be emphasized, however, that the distributions of the parameters and model predictions in this report are only estimates of the true uncertainty. The best method for quantifying the uncertainty in parameters and model predictions would be to subject the environmental transport and dosimetric models to experimental testing (i.e., model validation). Such an uncertainty analysis would require experiments to be conducted over the extent of spatial and temporal conditions usually considered for determining compliance with current radiological protection standards. Nevertheless, we realize that such extensive testing may be financially or physically prohibitive. Therefore, in lieu of validation experiments, an analysis of uncertainties in the data available in the literature for input parameters, as has been performed herein, is the only viable alternative for estimating the uncertainty in model predictions. Recognizing the limitations with this approach, environmental monitoring should always be implemented to ensure that the actual uncertainty in model predictions is not unacceptably large.

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