CONF-791103--48

Imprecision of Dose Predictions for Radionuclides Released to the Atmosphere: An Application of the Monte Carlo-Simulation-Technique for Iodine Transported via the Pasture-Cow-Milk Pathway

G. Schwarz
F. O. Hoffman

Presented at the
1979 Winter Meeting of the American Nuclear Society
November 11-16, 1979
San Francisco, California

IMPRECISION OF DOSE PREDICTIONS FOR RADIONUCLIDES RELEASED TO THE ATMOSPHERE: AN APPLICATION OF THE MONTE CARLO-SIMULATION-TECHNIQUE FOR IODINE TRANSPORTED VIA THE PASTURE-COW-MILK PATHWAY*

G. Schwarz
F. O. Hoffman
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Introduction

Mathematical models are in common use for determining compliance with regulatory standards promulgated to restrict releases of radioactive substances into the environment. However, because such models represent only an approximation of the real world, their predictions are subject to uncertainties. These uncertainties are inherent in the modeling process, i.e., in conceptualizing the model, in the transition to the computational model, and in the inherent variability of values for parameters used in these models.

A quantification of the uncertainty associated with the application of these models is best determined through model validation studies (i.e., field testing) conducted under the conditions for which the model calculations were intended (Shaeffer, 1979). Unfortunately, such experiments are difficult to perform because the level of time and funding required is often prohibitive and because the measurement of some input parameters (such as the internal dose conversion factor) is impractical. Therefore, alternative methods to determine the potential uncertainty in

---

*Research sponsored by the Division of Reactor Research and Technology, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

environmental radiation assessment models have been developed and applied to dose prediction models (Stocum, 1970, Hoffman et al., 1978, ICRP, 1978, and Shaeffer and Hoffman, 1979). These methods are based solely on an analysis of the variability of input parameters and the impact of their variability on the predicted dose, an approach that we refer to as an "imprecision analysis." A deficiency of the method is that it must assume that the model's structure is correct, and therefore fails to provide an indication about the actual deviation of the predicted dose from reality.

Approaches Available for Imprecision Analysis

In the absence of validation experiments for dose prediction models, uncertainty analyses have focused on investigation of the statistical properties of input parameters and on the subsequent implication of their variability on model output. Two approaches have been considered to investigate the propagation of uncertainties in dose prediction models.

The first method, an analytical approach described by Shaeffer (1979), takes advantage of the fact that multiplicative chain models with lognormally distributed input parameters will have a lognormally distributed output. This method utilizes simple straightforward mathematical procedures that do not require the use of a computer. (Aitchison and Brown 1969) However, several limitations are associated with the application of this analytical methodology to contemporary dose prediction models. These limitations arise from the requirements that all models analyzed using this approach must be either reduced to or approximated by a linear chain of multiplicative parameters and that the

variability of values for each input parameter be approximated by a lognormal distribution. However, most models used to assess the environmental transport and human dosimetry of released radionuclides are not entirely multiplicative in form, nor are they completely composed of lognormally distributed input parameters. Moreover, the lognormal distribution per definition covers a range from zero to infinity. In a real physical system, however, most distributions are truncated by maximum and minimum values that cannot be exceeded. The analytical approach, described by Shaeffer (1979), does not take into account the potential effect of truncated distributions on the variability of model output.

The limitations presented by the analytical approach may be avoided by applying numerical methods. The Monte Carlo technique has been demonstrated to be a versatile numerical method for simulating the propagation of uncertainties in environmental models (O'Neill, 1973, Gardner et al., 1976, and Garten et al., 1978). This type of approach is based on the statistical properties of the model output when input parameters inserted in the model are selected at random from a prescribed distribution. In applying this technique to analyze potential uncertainties in model predictions, it must be assumed (as was assumed with the analytical approach) that the model is a correct formulation of reality, i.e., that correct input will produce correct output. However, unlike the analytical approach, any distribution and any level of truncation of these distributions can be prescribed for all input parameters, and the form of the model need not be restricted to a multiplicative chain. Nevertheless, because this procedure involves a large number of successive

computer simulations, applications can be time consuming and expensive in comparison with the analytical approach.

Description of the Dose Prediction Model and the Applied Data Base

For the current analysis the dose prediction model was adopted from the AIRDOS-EPA computer code developed at Oak Ridge National Laboratory (Moore et al. 1979) which comprises the Gaussian plume model for atmospheric transport of airborne effluents and the model given in the U.S. Nuclear Regulatory Guide 1.109 (US 1977) for terrestrial food chain transport. The dosimetric model was derived from an approach given by Dunning (1979). In this preliminary investigation the contamination of vegetation by wet deposited radionuclides was neglected. The primary data base for the input parameters involved in the dose prediction model was taken from an extensive review of the literature describing the statistical properties of environmental parameters occurring in the U.S. NRC Regulatory Guide 1.109 model (Hoffman and Baes 1979).

Propagation of Uncertainties in the Pasture-Cow-Milk-Man Pathway

The pasture-cow-milk-man exposure pathway was chosen for the purpose of this study because of the large quantity of information available on the distributions of values for the numerous parameters of importance to the calculation of dose resulting from radioiodine transported over this pathway. The thyroid dose to children (0.5-1.5 years of age) and adults was estimated for a unit activity release of elemental ^{131}I assuming an effective release height of 100 m and a receptor point 1000 m downwind of a point source. The analysis is restricted to the elemental form of ^{131}I because of the extensive literature available on the deposition properties of this physicochemical form. Other physicochemical forms of

^{131}I which may be released to the atmosphere from nuclear facilities are expected to be less readily deposited onto the surfaces of vegetation (Hoffman 1977).

With respect to atmospheric transport calculations, Pasquill stability class D was assumed along with a continuous wind blowing in one direction. The variability attributable to the dispersion coefficients was derived by Miller (unpublished) from experiments conducted at the Nuclear Research Center, Karlsruhe, Germany (Thomas et al., 1976; Thomas and Nester, 1976). Other environmental, metabolic, and physiological input parameters and their statistical properties used in the ensuing calculations are given in Table 1. The results calculated with the Monte-Carlo-simulation method are summarized in Table 2 and describe the frequency distributions of the thyroid dose D, the dose to air concentration ratio D/χ, and the dose to deposition rate ratio D/d. Typical representations of the frequency distribution of the thyroid dose to infants and adults resulting from a unit activity release of elemental ^{131}I is depicted in Figs. 1 and 2, respectively. The frequency distribution of the thyroid dose is highly skewed and can be approximated by a lognormal distribution. Under the assumptions made, the range of calculated doses varies by approximately three orders of magnitude. However, the probability of occurrence of the minimum or maximum calculated dose is very low. Generally, the values of 95% probability (X_{95}) and the 99% probability (X_{99}) of not being exceeded are, respectively, approximately a factor of 3-4 and 5-9 times the mean value ($\bar{X}$). The higher values are usually attributable to adults and the lower values to infants who have less variability in dietary habits.

By estimating the "dose-to-air-concentration ratio" or the "dose-to-deposition-rate ratio" (Table 2) the only effect on their frequency distribution is from the variability in the terrestrial food chain parameters, the dosimetric parameters, and the deposition parameters. But, because the coefficient of variability does not change substantially for these ratios, the meteorological dispersion parameters are indicated to be of less significance and less variability than other parameters involved in the above dose prediction model. Our calculations indicate that the total imprecision in the calculated dose is dominated especially by the variability attributable to the internal dose conversion factor and the milk transfer coefficient F_m. For adults, the variability in dietary habits, i.e., the milk consumption rate seems to be of importance.

The results listed in Table 2 were obtained by assuming truncation of the prescribed distributions for the various model input parameters at values assumed to be minimum and maximum extremes. To study the effect of a more severe truncation, a comparison was performed by assuming distributions to be truncated at the maximum and minimum observed values. The results of this comparison indicate no substantial differences in the frequency distributions produced by the model's responses. As shown in Table 3 there seems to be only a slight shift of the measures of central tendency (X_p, $\bar{X}$) to higher doses. The measures of dispersion, the standard deviation, however, tend to decrease with increased truncation of distributions for input parameters.

A comparison of the numerical results with analytical results (which require a slightly modified algorithm using only lognormally distributed input parameters) is given in Table 4. In this specific

case the results do not differ significantly. The reason for this apparent similarity is that the model analyzed with the Monte Carlo technique behaves approximately the same as the model analyzed with the analytic approach. Because of the relative insignificance of the contribution of contaminated soil to the thyroid dose from ^{131}I the model analyzed with the Monte Carlo technique approximates a multiplicative chain.

Discussion of the Results

From the results presented above it may be concluded that the imprecision inherent in the predictions for the pasture-cow-milk-man pathway is potentially large. This primarily reflects the variability in the values available for the environmental input parameters of the model. It should be noted, however, that the variability mentioned above is obtained in dose estimates by use of input parameter distributions derived from data available in the general literature which represents a variety of ecological conditions and may therefore not be directly applicable to any particular site. One might, therefore, expect the imprecision in dose estimates to be potentially lessened when the basic processes are better understood and when data bases become available on a site-specific basis. Because ecological conditions at a given site are expected to be less variable than the conditions represented in the general literature.

In principle, however, the uncertainties in model predictions can only be determined by a process referred to as model validation, i.e., a comparison of predictions with field observation. Conducting validation experiments is often difficult, because the required time and costs are

prohibitive and because the measurement of some quantities such as the internal dose is impractical. Therefore, even if validation studies are conducted dose assessments will *always* have an associated imprecision or range of predictions.

Final Remarks

What are the potential consequences of such imprecisions in dose assessment models, in the related aspects of radiation protection, and the legal problem of showing compliance with regulatory standards?

As long as the environmental levels of contamination or radiation exposure are far (several orders of magnitude) below regulatory standards, there should not be any substantial regulatory problems. But if the predicted doses approach regulatory limits, then the question "What is an acceptable probability of doses being greater than a regulatory standard?" becomes pertinent. The application of only maximum or upper-limit values in dose prediction models could be utilized, but this procedure has such a high potential for overestimation of doses that an artificially restrictive situation for regulatory purposes can be easily created. In fact, when predicted doses approach permissible levels, the imprecision associated with model predictions infers that it is impractical, if not impossible, to give absolute assurance that all individuals exposed to radionuclides will receive doses less than these standards. However, if the health risk associated with radiation levels allowed by such standards is sufficiently low, then even the health risk attributable to the few individuals potentially receiving doses in excess of these standards should be very small. Therefore, under such low-risk conditions, compliance with standards may be acceptably verified with dose prediction models using generic reference values for input parameters.

Acknowledgments

The authors would like to thank their colleagues J. H. Carney, R. H. Gardner, and R. V. O'Neill for computer code development and for assistance with data interpretation.

References

1. Aitchison, J., and Brown, J. A. C. 1969. *The Lognormal Distribution.* New York: Cambridge University Press.

2. Dunning, D. E. 1979. ^{131}I ingestion thyroid dose conversion factor for infants. In Hoffman, F. O. and Baes, C. F. (eds.) *A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides.* ORNL/NUREG/TM-282 (October 1979).

3. Gardner, R. H., Mankin, J. B., Shugart, H. H. 1976. *The COMEX Computer Code Documentation and Description.* Environmental Sciences Division Publication No. 888, EDFB/IBP-76/4.

4. Garten, C. T. Jr., Gardner, R. H. and Dahlman, R. C. 1978. A compartment model of plutonium dynamics in a deciduous forest ecosystem. *Health Phys.* 34 (June) pp. 611-619.

5. Hoffman, F. O. 1977. A reassessment of the deposition velocity in the prediction of the environmental transport of radioiodine from air to milk. *Health Phys.* 32 (May) pp. 437-441.

6. Hoffman, F. O. et al. 1978. An evaluation of uncertainties in radioecological models. Presented at the *12th Annual Symposium of the German-Swiss Fachverband fuer Strahlenschutz,* Norderney, Federal Republic of Germany.

7. Hoffman, F. O., and Baes, C. F. III (eds.). 1979. *A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides.* ORNL/NUREG/TM-282 (October 1979).

8. International Commission on Radiological Protection. 1978. *Radionuclide Release into the Environment: Assessment of Doses to Man.* ICRP Publication 29, New York, Pergamon Press.

9. Miller, C. W. 1979. Personal communication, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

10. Moore, R. E., Baes, C. F. III, McDowell-Boyer, L. M., Watson, A. P., Hoffman, F. O., Pleasant, J. C., and Miller, C. W. 1979. *AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides*. ORNL-5532.

11. O'Neill, R. V. 1973. Error analysis of ecological models in radionuclides in ecosystems. *Proceedings of the Third National Symposium on Radioecology*, May 1971, Oak Ridge, Tennessee, CONF-710501-P2.

12. Shaeffer, D. L. 1979. *A Model Evaluation Methodology Applicable to Environmental Assessment Models*. ORNL-5507.

13. Shaeffer, D. L., and Hoffman, F. O. 1979. Uncertainties in radiological assessments — a statistical analysis of radioiodine transport via the pasture-cow-milk pathway. *Nuclear Technol.* 45 pp. 99-106.

14. Stocum, W. E. 1970. Variability in the parameters used to predict dose to the thyroid from the ingestion of ^{131}I in milk. IN *Environmental Surveillance in the Vicinity of Nuclear Facilities*, Proceedings of a Symposium sponsored by the Health Physics Society.

15. Thomas, P., Hubschmann, W., Konig, L. A., Schuttelkopf, H., Vogt, S., and Winter, M. 1976. *Experimental Determination of the Atmospheric Dispersion Parameters over Rough Terrain. Part 1. Measurements at the Karlsruhe Nuclear Research Center*. KFK-2285.

16. Thomas, P., and Nester, K. 1976. *Experimental Determination of the Atmospheric Dispersion Parameters over Rough Terrain. Part 2. Evaluation of Measurements*. KFK-2286.

17. U.S. Nuclear Regulatory Commission, Calculation of annual doses to man from routine releases of reactor effluents for the purpose of evaluating compliance with 10 CFR 50, Appendix I. *Regulatory Guide 1.109*. Revision 1, October 1977.

Table 1. Compilation of environmental, metabolic, and physiological data assumed for calculating the thyroid dose to infants (0.5-1.5 years of age) from an intake of ^{131}I via the pasture-cow-milk-pathway

Parameters	Unit	Type of distribution[a]	Mean	Standard deviation
Atmospheric dispersion parameter, σ_z	m	L	120.9	12.4
Air-grass-transfer factor, V_D	$m^2/kg \cdot s$	L	0.12	0.0059
Weathering half-life, T_w	days	L	10.4	3.38
Growing time for pasture grass, t_e	days	T	29.8	5.80
Density normalized interception fraction, r/Y_v	m^2/kg	L	2.0	0.96
Soil-plant-concentration ratio, B_v	--	L	0.35	0.65
Surface soil density, P	kg/m^2	L	213.0	23.4
Time between harvest and consumption (pasture grass) t_{hf}	days	T	0	0
Time between harvest and consumption (stored feed) t_{hs}	days	T	90.7	30.9
Fraction of time that cows on pasture, f_p	--	N	0.42	0.19
Fraction of feed that is fresh forage, f_s	--	N	0.43	0.12
Milk transfer coefficient, F_m	days/liter	L	0.01	0.0064
Total feed consumption rate of a cow, Q_F	kg/day	N	15.9	2.54
Time between milk production and consumption, t_f	days	T	2.9	1.2
Wind velocity, $\bar{u}$	m/s	U	3.0	0.29
Milk consumption rate for infants, U_m	liter/year	L	278.4	58.0
Thyroid mass, m	g	L	1.98	1.0
Fractional uptake for thyroid, f	--	L	0.31	0.091
Biological half-life, T_B	days	L	18.7	22.2

[a] L = lognormal; N = normal; T = triangular; U = uniform

Table 2. Statistical analysis of the pasture-cow-milk-man pathway using the Monte Carlo simulation approach with nontruncated best estimate input parameter distributions for a unit activity release (1 Ci) of ^{131}I

(No wet deposition, 100% occurrance of wind blowing in one sector combined with stability class D)

		X_p[a]	$\bar{X}$[b]	s.d. (c.v.)[c]	X_{99}[d]
Annual thyroid dose D (mrem/yr)	infants[e]	150	870	1140 (130)	5800
	adults	7	40	59 (148)	300
Dose to air concentration ratio D/χ (mrem m^3/pCi·yr)	infants[e]	1500	7045	9380 (133)	44500
	adults	40	321	494 (154)	2580
Dose to deposition rate ratio D/d (mrem m^2day/pCi·yr)	infants[e]	0.10	1.37	2.18 (159)	12.4
	adults	0.005	0.064	0.12 (192)	0.63

[a] X_p = most probable value of the distribution.

[b] $\bar{X}$ = mean value of the distribution.

[c] s.d. = standard deviation; in parentheses, the coefficient of variation (c.v.).

[d] X_{99} = value with a 99% probability of not being exceeded.

[e] Infants of 0.5-1.5 years of age.

Table 3. Comparison of models response using best estimate input parameter with nontruncated vs. truncated distributions

	Distribution of the input parameter	X_p[a]	$\bar{X}$[b]	s.d.[c]	X_{99}[d]
Annual thyroid dose to infants D[e]	nontruncated	150	870	1140	5800
(mrem/yr)	truncated[f]	200	1010	1140	5400
Dose to air concentration ratio (infants) D/χ	nontruncated	1500	7045	9380	44500
(mrem m^3/yr·pCi)	truncated[f]	2000	8030	8870	42000

[a] X_p = most probable value of the distribution.

[b] $\bar{X}$ = mean value of the distribution.

[c] s.d. = standard deviation.

[d] X_{99} = value with 99% probability of not being exceeded.

[e] Infants of 0.5-1.5 years of age.

[f] Truncation performed at minimum and maximum observed value.

Table 4. Comparison of results gained from the numerical and analytical method

		X_p[a]	$\bar{X}$[b]	s.d.[c]	X_{99}[d]
Annual thyroid dose to infants (mrem/yr)	numerical method	150	870	1140	5800
	analytical[e,f] method	250	1065	1310	6150

[a] X_p = most probable value.

[b] $\bar{X}$ = mean value.

[c] s.d. = standard deviation.

[d] X_{99} = value with 99% probability of not being exceeded.

[e] Root uptake is not taken into account.

[f] Values adopted from Hoffman and Baes, 1979.

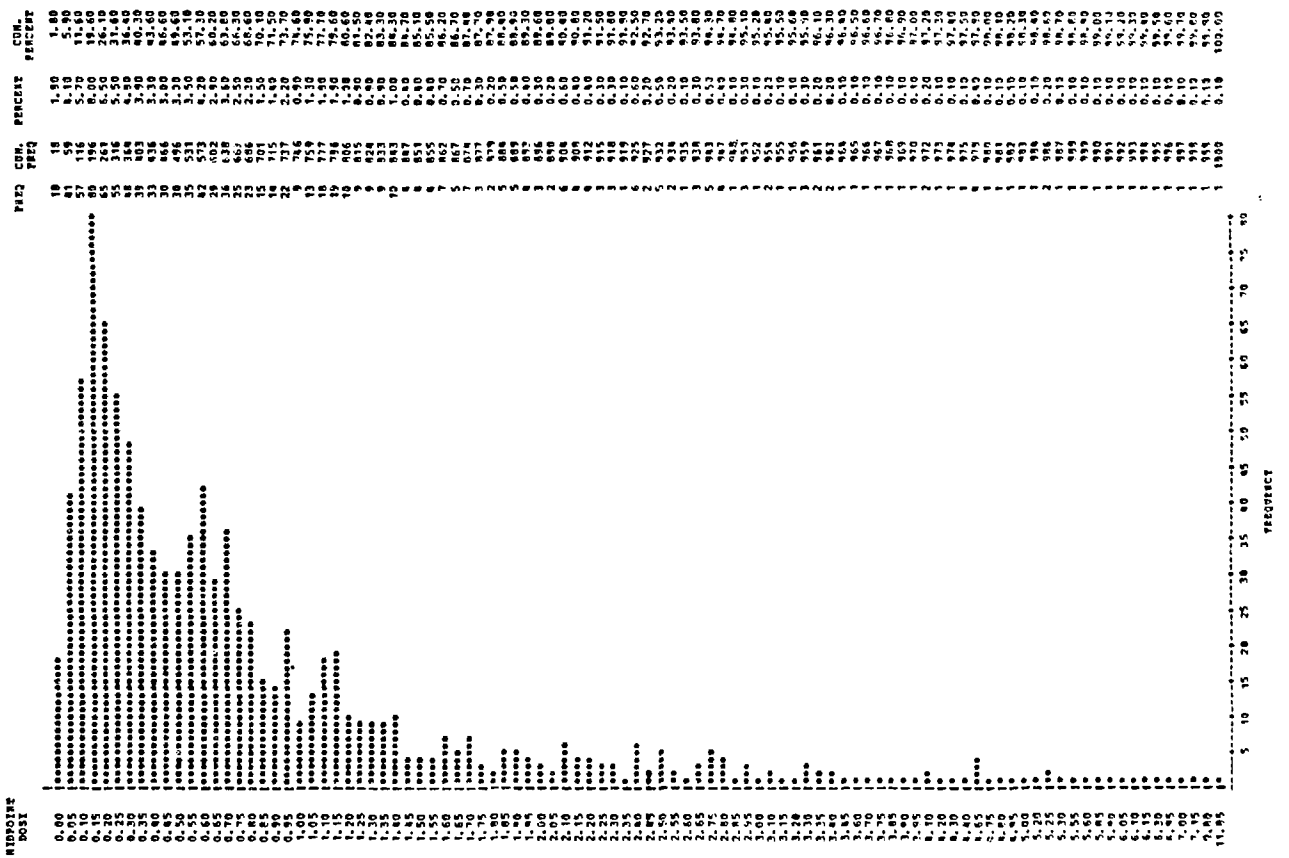
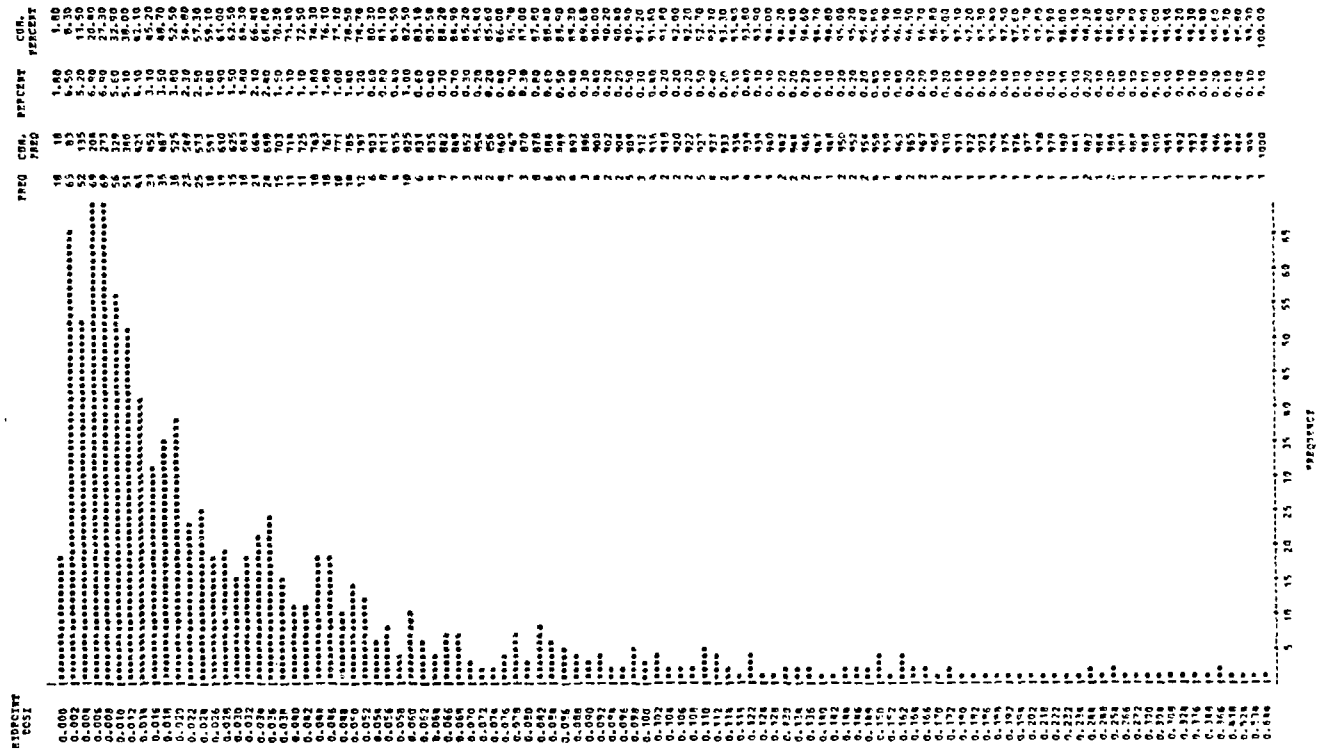


Fig. 1. Frequency distribution of the annual thyroid dose to infants from an intake of ^{131}I via the pasture-cow-milk pathway subsequent to a unit activity release (1Ci) to the atmosphere. (No wet deposition, 100% occurrence of wind blowing in one sector assumed).



Annual thyroid dose (rem/yr)

Fig. 2. Frequency distribution of the annual thyroid dose to adults from an intake of ^{131}I via the pasture-cow-milk pathway subsequent to a unit activity release (1Ci) to the atmosphere. (No wet deposition, 100% occurrence of wind blowing in one sector assumed).