Tabe 4. A comparison of errors in the modified Kusnetz method and the method presented here

		Modified Kusnetz Method t_0, t_x, t_1 (min)		Improved Method t_0, t_x, t_1 (min)		
		(10,47.5,52.5)	(10,57.5,62.5)	(10,50,60)	(10,50,80)	(10,50,110)
	Working Level					
Statistical Error	0.01 WL	7.3%	7.9%	5.4%	3.5%	2.7%
	0.001 WL	22.0%	25.0%	17.0%	11.0%	8.5%
	$R_1:R_2$					
Systematic Error *	1.0:1.0	-1.2%	+4.0%	+0.4%	+2.5%	+4.2%
	0.9:0.15	-0.4%	-2.2%	-0.9%	+0.6%	+1.2%
	0.7:0.5	-0.7%	+1.6%	-0.3%	-0.1%	+0.4%
	0.1:0.1	-4.9%	-2.3%	+1.2%	-0.3%	-1.7%
Normalizing Factor		K=150	K=130	K=13800	K=35500	K=55900

*For systematic errors, "+" indicates an overestimate of WL, while "-" indicates an underestimate.

low daughter concentrations. The statistical errors occurring in the integrated method in the (10, 50 and 80 min) time regime are half as large as those in the modified Kusnetz method. We conclude that the modified Kusnetz method is adequate for many applications, but that the method presented here can be used to obtain more precise results in situations where low concentrations of radon daughters are being sampled.

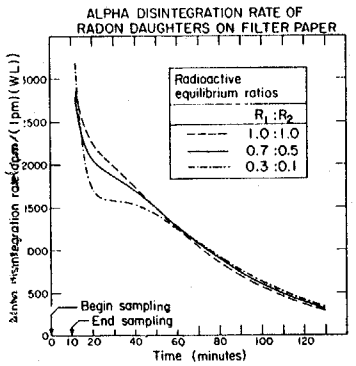

FIG. 1. α disintegration rate of radon daughters on a filter paper as a function of time. The decay rate is normalized by the WL sampled. The sampling time is 10 min. The three curves plotted correspond to three disequilibrium conditions.

$$R_1 = \frac{\text{Volume activity of } ^{214}\text{Pb (RaB)}}{\text{Volume activity of } ^{218}\text{Po (RaA)}},$$

and

$$R_2 = \frac{\text{Volume activity of } ^{214}\text{Bi (RaC)}}{\text{Volume activity of } ^{218}\text{Po (RaA)}}.$$

WILLIAM W. NAZAROFF
Energy and Environment Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720

References

Br72 Breslin A. J., 1972, "Monitoring Instrumentation in the Uranium Mining Industry". Unpublished report.

Co77 Courneya W. J., 1977, "Methodology—Radon Gas and Radon Daughters in Air Measurement", Adapted from Radiation Protection Bureau *Health and Welfare Canada Procedure.*

Ev69 Evans R. D., 1969, "Engineers' Guide to the Elementary Behavior of Radon Daughters". *Health Phys.* 17, 229–252.

Fe79 *Federal Register*, 1979, 2 July, 44, 38664–38670.

Ku56 Kusnetz H. L., 1956, "Radon Daughters in Mine Atmospheres—A Field Method for Determining Concentrations", *Ind. Hyg. Quart* 85–88.

Ma69 Martz D. E., Holleman D. F., McCurdy D E. and Schiager K. J., 1969, "Analysis of Atmospheric Concentrations of RaA, RaB and RaC by Alpha Spectroscopy", *Health Phys.* 17, 131–138.

Health Physics Vol. 39 (October), pp. 687–690
Pergamon Press Ltd., 1980. Printed in the U.S.A.

Potential Importance of Resuspension During Chronic Releases of Radionuclides to the Atmosphere*

(*Received* 13 *December* 1979; *accepted* 14 *March* 1980)

DURING chronic releases of radionuclides to the atmosphere, airborne concentrations and resulting radiation exposures are often calculated by assuming that the contributions from resuspended activity are negligible compared with the contributions from direct atmospheric transport [e.g. (Mo79)]. In this paper, models which have been proposed in the literature to describe the resuspension factor are used to predict air concentrations and exposures from resuspension during a long-term chronic release to the atmosphere. We find that the concentration from resuspension predicted by some of the models is larger than the contribution from direct atmospheric transport. This result casts doubt on the validity of the resuspension models and indicates the need for a re-examination of the values of the model parameters.

Description of Resuspension

Resuspension is defined as the entrainment into the atmosphere of radionuclides that were originally airborne but deposited on the ground surface. Resuspension is often described by means of a parameter called the resuspension factor, K, defined as

$$K(\text{m}^{-1}) = \chi_r(\text{quantity/m}^3)/\chi_s(\text{quantity/m}^2), \quad (1)$$

where χ_r and χ_s are the air concentration from resuspension and the ground-surface concentration, respectively. In order to account for the many factors influencing resuspension, such as downward migration of the deposited activity into the soil and other chemical and physical processes [e.g. (An75)], the resuspension factor is usually assumed to be a time-dependent quantity which decreases monotonically with time following deposition.

In the analysis presented here, we assume a constant continuous release to the atmosphere which results in a constant air concentration from direct transport, χ_0. We further assume that the deposition of resuspended activity can be neglected. From the definition of the resuspension factor in eqn (1), the resuspended air concentration, χ_r, at any time t during the release is given by

$$\chi_r(t) = \chi_0 v_d \int_0^t K(t-t') \exp[-\lambda(t-t')]\, dt', \quad (2)$$

where v_d is the deposition velocity, λ is the radioactive decay constant, and the release is assumed to begin at time $t = 0$. We note that χ_r is a monotonically increasing function of time during the release. At any time t, the importance of resuspension relative to direct atmospheric transport may be determined from the ratio $\chi_r(t)/\chi_0$, or, alternatively, from the ratio of total exposures given by

$$\psi_r/\psi_0 = \frac{1}{\chi_0 t}\int_0^t \chi_r(t')\, dt'. \quad (3)$$

Calculations

We have calculated the ratios χ_r/χ_0 and ψ_r/ψ_0 in eqns (2) and (3) during a long-term chronic release to the atmosphere by employing three empirical parameterizations of the resuspension factor reported in the literature.

A common form for the resuspension factor is

$$K(t) = K_0 \exp(-\lambda_k t) + K_e. \quad (4)$$

In the Liquid Metal Fast Breeder Reactor (LMFBR) impact statement (USAEC74), the assumed parameter values are $K_0 = 10^{-5}\,\text{m}^{-1}$, $K_e = 10^{-9}\,\text{m}^{-1}$, and $\lambda_k = 5.1\,\text{yr}^{-1}$. An analysis of the LMFBR model similar to the one presented here was previously given by Horst and Elderkin (Ho75a). In the Reactor Safety Study (NRC) model (USNRC75), eqn (4) was used with the same parameter values given above, except $\lambda_k = 0.68\,\text{yr}^{-1}$. A second parameterization due to Anspaugh *et al.* (An75) is

$$K(t) = K_0 \exp(-\lambda_k t^{1/2}) + K_e, \quad (5)$$

with $K_0 = 10^{-4}\,\text{m}^{-1}$, $K_e = 10^{-9}\,\text{m}^{-1}$ and $\lambda_k = 0.15\,\text{day}^{-1/2}$. The three proposed resuspension factors are shown in Fig. 1. It is obvious that the

*Research sponsored jointly by the U.S. Nuclear Regulatory Commission under Interagency Agreement DOE 40-550-75 and the Fuel Cycle Program Office, Savannah River Operations, U.S. Dept. of Energy, under Contract W-7405-ENG-26 with the Union Carbide Corp.

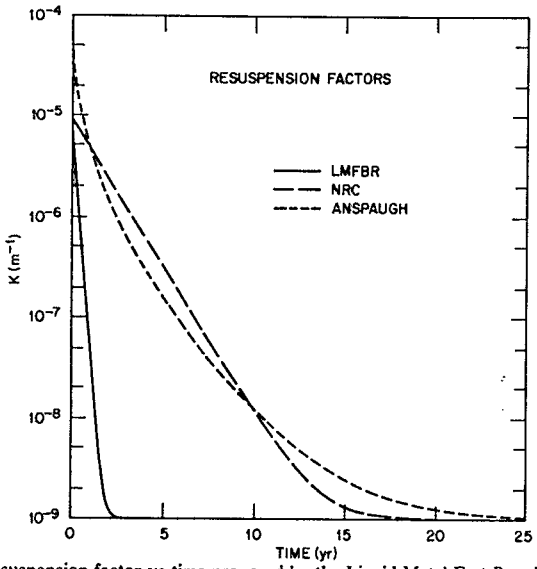

FIG. 1. Resuspension factor vs time proposed by the Liquid Metal Fast Breeder Reactor (LMFBR) impact statement, the Reactor Safety Study (NRC), and Anspaugh *et al.*

resuspended air concentration predicted during a chronic release will be much less using the LMFBR model compared with using the NRC or Anspaugh models.

Shown in Fig. 2 are the values of χ_r/χ_0 during the first 2 yr of a chronic release as predicted by the three models using eqn (2). The calculations assume a deposition velocity $v_d = 1$ cm/sec and negligible radioactive decay. The values 0.64, 4.7 and 7.7 for χ_r/χ_0 given in the figure are the values at $t = 40$ yr for each of the models. This time corresponds to an expected operating lifetime of a nuclear facility. We find that the value of χ_r/χ_0 for the LMFBR model, while always less than unity, is not negligibly small. For the other two models, the predicted air concentration from resuspension is significantly greater than the concentration from direct transport beginning at times less than 1 yr. The values of the exposure ratio ψ_r/ψ_0 for each model calculated from eqn (3) are very similar to the curves for χ_r/χ_0 shown in Fig. 2.

Discussion

We have shown that application of models of the resuspension factor proposed in the literature to long-term chronic releases to the atmosphere results in air concentrations from resuspension which cannot be neglected compared with the concentration from direct atmospheric transport. Indeed, the resuspended air concentration predicted by two of the models is much greater than the concentration from direct transport. These results would seem to cast doubt on the validity of the models.

The contributions from resuspension relative to direct transport shown in Fig. 2 depend primarily on the assumed values of the deposition velocity v_d, the initial resuspension factor K_0, and the resuspension decay constant λ_k. If, for example, the proper values of v_d and K_0 were each a factor of 10 less than the values assumed in this analysis, the resulting resuspended air concentrations would be reduced by a factor of 100, and the models would predict that resuspension is negligible during the release. For dry deposition on grasslands, values of v_d ranging from about 0.02 cm/sec for relatively non-reactive gases to 0.2 cm/sec for small particulates and 4 cm/sec for reactive gases

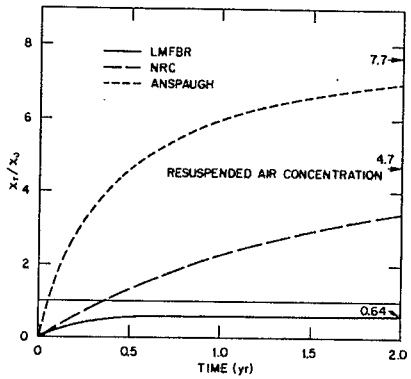

FIG. 2. Ratio of resuspended air concentration to concentration from direct atmospheric transport vs time during a chronic release to the atmosphere predicted by the three models for the resuspension factor shown in Fig. 1. The assumed deposition velocity is $v_d = 1$ cm/sec, and radioactive decay is assumed negligible. The numbers on the r.h.s. of the figure give the values of χ_r/χ_0 for each model at time $t = 40$ yr.

have been suggested (Mo79). For the parameters K_0 and λ_k, we note that the proposed values are based on measurements at the Nevada Test Site under conditions which are not likely to apply to non-desert locations in the U.S. For K_0, for example, Bennett (Be76) has suggested that measurements in New York on plutonium from atmospheric weapons testing set an upper limit of 5×10^{-6} m^{-1}, but that values considerably less than this are more realistic. With $K_0 = 5 \times 10^{-6}$ m^{-1}, the Anspaugh model gives a value for χ_r/χ_0 after 40 yr of 0.4, and the NRC model gives a value of 2.4. It is evident from the available data that λ_k is a particularly uncertain parameter in the models. The sensitivity of the resuspended air concentration to this parameter is seen from the difference between the curves for the LMFBR and NRC models in Fig. 2, which differ only in the value of λ_k.

Bennett (Be76) has proposed that the resuspension factor be redefined as the ratio of the resuspended air concentration to the ground-surface concentration in the top layer of the surface soil region, which is taken to be the top 1 cm. The resuspension factor is then assumed to be constant with time, but the resuspended air concentration can decrease with time as the deposited activity migrates below the top layer of the ground surface. From an analysis of uranium concentrations in soil and the atmosphere, Bennett recommends a resuspension factor of 5×10^{-9} m^{-1}. This resuspension factor results in values of χ_r/χ_0 and ψ_r/ψ_0 which are at most only 0.06 at the end of a 40-yr continuous release.

If the air concentration from resuspension predicted using eqn (2) is comparable to or largerthan the concentration from direct transport, it is important to note that the model itself is no longer valid, because it is then clearly incorrect to assume that the deposition of resuspended material can be neglected. If resuspension in fact contributes significantly to the total air concentration, then more sophisticated computational simulations of the atmospheric diffusion-deposition-ressuspension process are required, such as the models developed by Horst (Ho75b; Ho79).

In conclusion, the analysis presented here shows that if the respension factor is to be used in radiological assessments of long-term chronic releases to the atmosphere, further investigation into the proper values of the deposition velocity, initial resuspension factor, and resuspension decay constant is needed. The models for the resuspension factor which we have examined are applicable to such releases only if the values of some or all of these parameters are considerably less than the values proposed in the literature. Otherwise, more complex models which properly account for atmospheric diffusion, deposition, and resuspension are required. We also note that in the absence of a valid model for the resuspension factor, Horst (Ho75b; Ho79) has shown that resuspension can be conservatively accounted for by calculating air concentrations from direct atmospheric transport without depletion due to deposition.

D. C. KOCHER

Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

References

An75 Anspaugh L. R., Shinn J. H., Phelps P. L. and Kennedy N. C., 1975, "Resuspension and Redistribution of Plutonium in Soils", *Health Phys.* **29**, 571.

Be76 Bennett B. G., 1976, "Transuranic Element Pathways to Man", in: *Transuranic Nuclides in the Environment*, p. 367 (Vienna: IAEA).

Ho75a Horst T. W. and Elderkin C. E., 1975, "An Assessment of the Long-term Exposure Due to Resuspension—II", Pacific Northwest Laboratory Annual Report for 1974 to the USAEC Division of Biomedical and Environmental Research, Part 3, Atmospheric Sciences, Battelle Pacific Northwest Laboratories Rep. BNWL-1950 PT 3, p. 237.

Ho75b Horst T. W., 1975, "The Resuspension of Material Dispersed by Atmospheric Diffusion from a Point Source", Battelle Pacific Northwest Laboratories Rep. BNWL-1964.

Ho79 Horst T. W., 1979, "The Annual-Average Effect of the Deposition-resuspension Process on Airborne Contamination near the Surface", *4th Symp. on Turbulence, Diffusion, and Air Pollution*, p. 501 (Boston, MA: AMS).

Mo79 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", Oak Ridge National Laboratory Rep. ORNL-5532.

USAEC74 U.S. Atomic Energy Commission, 1974, "Liquid Metal Fast Breeder Reactor Program Proposed Final Environmental Statement", Rep. WASH-1535, Vol. II.

USNRCS75 U.S. Nuclear Regulatory Commission, 1975, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Appendix VI. Calculation of Reactor Accident Consequences", Rep. WASH-1400.

Health Physics Vol. 39 (October), pp. 690–694
Pergamon Press Ltd., 1980. Printed in the U.S.A.

Neutron Fluence to Dose Conversion Factors for Some Moderated Neutron Spectra

(*Received* 28 *December* 1979; *accepted* 11 *March* 1980)

Introduction

KNOWLEDGE of neutron fluence to dose conversion factors is essential for evaluation of neutron dose and dose equivalent for monitoring in reactor environments during normal as well as accident situations. For deriving these factors, use is made of neutron depth dose distributions in a homogeneous anthropomorphic cylindrical phantom with a radius of 15 cm and a height of 60 cm. In the calculations done by Auxier *et al.* (Au68), this cylindrical phantom was divided into 150 small volume elements with the thickness of each element being 3 cm. Ing and Makra (In78) used the data of Auxier *et al.* for deriving dose conversion factors for leakage neutrons from various critical assemblies and also for moderated neutron spectra. Later, Snyder (NCRP71) divided the cylindrical phantom into volume elements of thickness 2 cm and he took a larger number of neutron histories for doing these calculations. Singh *et al.* (Si78a, b; Si79a, b) used Snyder's result in their calculations of depth dose distributions for various critical assemblies and moderated spectra. In this paper, we have made a comparison of the fluence to dose conversion factor for the first layer of the phantom calculated by these two methods.

Results and Discussion

The results for spectra [from (In78)] from seven critical assemblies and 37 neutrons spectra degraded through low and high Z shields are presented in Tables 1–4. In these tables all the values of $\bar{D}n$ include the γ dose contribution from (n, γ) reactions in the phantom. (It may however be noted that $\bar{D}n$ values given by Ing and Makra (In78) account only for charged particle dose.) It is seen from the tables that there is no significant differences in the values of $\bar{D}n$ and $\bar{H}$, i.e. total neutron dose per unit fluence and dose equivalent per unit fluence respectively, calculated by the two methods. But the neutron generated γ dose per unit fluence, i.e. $\bar{D}\gamma$ is 30–50% higher than values calculated by Singh *et al.* based on the Snyder phantom.

In Table 5, we have compared calculated values with the mean values of γ dose for the Viper reactor measured by various participating laboratories during the Fourth IAEA Intercomparison Experiment on Nuclear Accident Dosimetry, Harwell, 1975 (Gi76). Mean values of γ-ray doses measured in free air and on phantom, values of neutron fluence, thermal and greater than 0.4 eV, measured by various participating laroratories along with standard deviation in the measured values are given in Table 5. γ-Ray doses as measured on the phantom should be equal to the sum of the free air γ dose and the dose due to neutron generated γ-rays. γ-Ray doses were derived from neutron fluence values (in free air) by using appropriate fluence-to-dose conversion factors. For thermal neutrons the factor is 4×10^{-12} Gy n^{-1} cm^2 which is same for the Auxier as well as the Snyder phantom. Fluence-to-dose

Table 1. Dose-fluence conversion factors for seven selected critical assemblies

Critical Assembly	Based on Auxier Phantom				Based on Snyder Phantom			
	$\bar{D}n \times 10^{11}$ Gy n^{-1}cm^2	$\bar{H} \times 10^{11}$ Sv n^{-1}cm^2	$\bar{D}_\gamma \times 10^{11}$ Gy n^{-1}cm^2	$\bar{Q}$	$\bar{D}n \times 10^{11}$ Gy n^{-1}cm^2	$\bar{H} \times 10^{11}$ Sv n^{-1}cm^2	$\bar{D}_\gamma \times 10^{11}$ Gy n^{-1}cm^2	$\bar{Q}$
Jezbel	3.3	32.0	0.22	10	3.4	30	0.16	9
Godiva	3.1	31.0	0.23	10	3.0	28	0.17	9
Flat top	1.7	18.5	0.30	11	1.5	15	0.20	10
HPRR-I	2.7	26.5	0.25	10	2.7	25	0.18	9
HPRR-II	2.3	20.3	0.29	9	2.1	18	0.23	8
HPRR-III	1.9	20.4	0.29	11	1.9	18	0.20	10
Viper	1.1	10.0	0.32	10	1.1	9	0.22	9

Table 2. Dose-fluence conversion factors for light water moderated spectra

Nature of critical assembly		Based on Auxier Phantom				Based on Snyder Phantom			
		$\bar{D}_n \times 10^{11}$ Gy n^{-1}cm^2	$\bar{H} \times 10^{11}$ Sv n^{-1}cm^2	$\bar{D}_\gamma \times 10^{11}$ Gy n^{-1}cm^2	$\bar{Q}$	$\bar{D}_n \times 10^{11}$ Gy n^{-1}cm^2	$\bar{H} \times 10^{11}$ Sv n^{-1}cm^2	$\bar{D}_\gamma \times 10^{11}$ Gy n^{-1}cm^2	$\bar{Q}$
Fissile H_2O solution spherical Geometry of radius	10 cm	2.6	24	0.26	9	2.8	24	0.19	9
	30 cm	2.5	23	0.27	9	2.8	24	0.19	9
	50 cm	2.5	23	0.27	9	2.8	24	0.19	9
Fission neutrons through light water shield of thickness	10 cm	2.5	22	0.28	9	2.7	23	0.19	9
	20 cm	2.8	24	0.26	9	3.1	26	0.19	8
	30 cm	3.1	26	0.25	8	3.4	28	0.18	8
	50 cm	3.5	28	0.24	8	3.6	29	0.17	8