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PREDICTION OF RADIONUCLIDE CONTAMINATION OF GRASS FROM FALLOUT-PARTICLE RETENTION AND BEHAVIOR

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ABSTRACT

Retention of large (44- to 188-μ) fallout-simulant particles by dense fescue grass approached 50% initially, but, from 1 hr to 1 day later, weathering processes decreased retention to 10%. A modified negative-exponential function characterized particle weathering over a 2- to 3-week period. Half-time for early weathering loss was 3 to 4 days, but retention approached an asymptotic level after 2 to 3 weeks, at which time 2% of the ground-surface deposit remained on vegetation. Particle deposits on leaf blades were readily removed by slight wind (<1 mph) and phytotaxic movements of the foliage. Axillary deposits, however, were not readily removed by wind and rain. Using Miller's contamination factor convention ($a_L = C_p/m$) and nuclide leachability, we predicted the ^{137}Cs contamination of fescue foliage (F_L) from fallout simulant independently according to the expression $F_L = a_L W_L$.

Surface nuclear detonations produce both worldwide and local fallout materials that may be hazardous to biological organisms. Precise definition of different kinds of fallout is difficult because many variables influence formation processes and distribution patterns. The properties of local* fallout from a given detonation depend on the kind of materials drawn into the fireball, the cloud-arrival time, and the particle size distribution, which is a result of the condensation of vaporized materials and the character of initial ejecta. Rather than distinct zonation, the deposits exhibit a gradation of particle size and radioactivity properties as a function of distance from formation. The variable nature of local fallout notwithstanding, the materials deposited in the vicinity of 7- to 30-kt test shots have certain consistent characteristics.[1] Deposits of 50- to 150-μ material were recorded 50 to 140 miles from ground zero. At least 50% of

*Conceptually a local deposit is regarded as a layer of particulate material that can be seen with the unaided eye.

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total fallout was in the 44- to 177-μ size class, and an appreciable quantity of the radioactivity was fixed to this fraction.

Fallout deposits from nuclear testing traditionally have been reported in terms of radiation intensity contours rather than mass loads, although the latter parameter would be more useful for the experimental determination of particle behavior and radiation exposure in specialized situations. Mass load has been estimated indirectly from mass-contour ratios, fallout specific activity, and intensity-contour ratios,[2,3] but these parameters are often unavailable, a factor which increases the difficulty of characterizing local fallout deposit. Assuming that volcanic eruptions produce particle clouds somewhat similar to those of nuclear detonations, Miller[4,5] and Miller and Lee[6] evaluated the deposition characteristics downwind from the Costa Rican volcano Irazu. As much as 8 g/sq ft/day was deposited 25 miles downwind from Irazu, and 90% of the particles were in the 44- to 175-μ size class. These measurements of particle travel and mass load represent minimal magnitudes because the cloud dimensions were somewhat smaller than those recorded for 7- to 30-kt surface tests.

Accumulations of local fallout are important radiologically because subsurface biological tissues may receive a considerable beta dose from surface deposits. The meristematic regions of plant apexes which reside within several millimeters of the surface will be particularly sensitive to the beta component. That biological effects to plants were manifested by beta radiation from local deposits is unclear according to field observations associated with projects Sedan, Palanquin, and Cabriolet. Damage from local fallout was attributed to the physical effect of dust in the Sedan test,[7] but plant effects at Palanquin and Cabriolet[8] were greater than would be expected from either dust deposits or cumulative gamma dose. Plants exhibited damage when the total beta dose was less than 200 rads. A mantle of dust covered the plants where effects were manifested, but mass load of the deposit was not reported.

According to a damage-assessment analysis, Brown and Pilz[9] calculated beta-to-gamma-dose ratios of 2 to 4 for average-dimension plant meristems at 1 m height. At 1 cm height the dose ratios were 10 to 20 depending on time of arrival. However, these calculations were based on uniform deposition, which ignores the specialized cases of particle retention and concentration, e.g., collection in plant crevices, a phenomenon that has been observed frequently.[4,10-12] The specific morphological characteristics not only affect particle concentration and dose to local tissues but also influence the magnitude of initial interception and the degree of retention as a function of time.

Despite intensive efforts to characterize initial retention of fallout ash by plants[4-6] and long-term contamination from nuclear fallout debris,[1,7,8,13,18] there is limited information on the behavior of fallout materials in the relatively short interval after deposition (several hours to 1 week). Additional data on retention phenomenology would be useful for estimating plant contamination and species vulnerability to beta radiation. The results of initial retention and short-term coefficients of loss for simulated-fallout deposits in a tall fescue

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(*Festuca arundinacea* Shreb) meadow community are reported here. Mass load and particle diameter were consistent with the previously described requirements for local fallout in the vicinity of 7- to 30-kt nuclear tests and for reported deposition of fallout from a volcanic eruption. Evaluations for this magnitude of detonations obviously are very conservative relative to what might be expected from megaton-size explosions. Particle travel, mass load, and area coverage quite likely would be considerably different from multiple megaton-size detonations.[1]

Data on retention are evaluated according to Miller's[5] contamination-factor model to show correlation between predicted and observed vegetation contamination from local fallout. Relations of retention weathering and intraplant radiocesium movement are summarized and modeled to provide a means for estimating potential source terms that can be used as input for the vegetation–cow–man food chain.

PROCEDURES

Experimental Area

Extraneous plant material (litter and weeds) was removed from a 4-year-old stand of tall fescue 6 weeks before a fallout simulant was applied to the vegetation. A homogeneous cover of fescue grass developed by late July, at which time the plant density* was 17.4 g/sq ft ± 2.3 (standard error), and average canopy height was 30 cm. Two areas (each 2.5 by 5 m), with a 1-m wide border zone extending around each plot, were located for treatment. Walkways were established in this zone to avoid disturbing the contaminated plants during later sample collection. When the experiment was terminated after 3 weeks, plant density was 20.2 ± 1.9 g/sq ft, and the quantity of grass for intermediate dates of sampling was estimated by interpolation. Meteorological data (temperature, rainfall, dew point, wind velocity, and direction) were recorded continuously at a nearby (200 m distant) weather station.

Simulant Characteristics and Application

A fallout simulant was fabricated at the Stanford Research Institute by fixing low-level ^{86}Rb on two size classes of quartz sand. The simulant possessed physical characteristics similar to local fallout,[15-17] and the ^{86}Rb label expedited the measurement of sand retention and loss by the grass. Rubidium-86 was used because its half-life (18.7 days) and gamma emission (1.07 MeV) were convenient for following short-term particle movement on vegetation. Minimal occupational exposure and field-site contamination hazards resulted from the

*Plant density is expressed in terms of dry weight per area rather than in conventional terms of units of individuals per area.

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use of this isotope. Leachability was low (2% over 24 hr at a particle-to-water ratio of 1 to 100) because high temperatures during fabrication fused the isotope to the quartz. Two particle size classes (44 to 88 and 88 to 177 μ in diameter*) were used in the experiment to determine differential retention and loss parameters for both fine and coarse fractions associated with local fallout debris. At the time of simulant application, the ^{86}Rb activity density was 1.56 and 2.07 μCi/g for fine and coarse particles, respectively.

The simulant was released from a hopper–spreader apparatus that traveled on elevated girders at least 1 m above the vegetation canopy. At this height the particles approached maximum falling velocity before contact with the canopy. Rate of travel and simulant release were controlled remotely to minimize hazard to personnel during application. Uniformity and effectiveness of simulant application from such an apparatus have been reported elsewhere.[10,12] Two separate areas were contaminated with fine and coarse simulant particles during calm conditions in late afternoon. Ambient temperature averaged 89 ± 1°F and relative humidity was 78 ± 0.8% in the plant canopy.

Sampling and Radioassay

Particle mass load on an area basis was determined gravimetrically from randomly positioned plate collectors placed above the canopy. Similar plates were placed beneath the grass canopy, and initial grass retention at t_0 was determined by difference. Collecting dishes from beneath the canopy were recovered immediately after application, before weathering and redistribution of intercepted particles could occur.

Short- and long-term particle-retention characteristics were determined by radioassay of randomly collected subsamples of grass. To minimize accidental particle loss during the sampling procedure, we placed a plastic bag gently over small clusters of tillers and gathered it tightly around the tussock base before the plants were clipped. Ten replications were taken from each area at the respective sampling dates. The samples, still inside the plastic collection bags, were placed in uniform geometry cartons and assayed with a 3- by 3-in. crystal and Packard MCA-115. Only the 1.07-MeV gamma peak of the radiation spectrum was evaluated in the radioanalysis. Counting efficiency and physical decay were determined from a 1.05-μCi ^{86}Rb standard of similar geometry which was obtained independently from the Oak Ridge National Laboratory (ORNL) Isotopes Division.

*Hereafter, the 44- to 88-μ and 88- to 177-μ size classes are designated as fine and coarse particles, respectively.

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RESULTS AND DISCUSSION

Mass Deposit and Initial Retention

The initial mass deposit of particles over open ground area was 11.0 ± 0.5 and 9.2 ± 1.0 g/sq ft for fine and coarse particle, respectively. This mass load approximates the quantity of surface deposit which could be expected in the form of local fallout for intermediate weapon yield according to predictions from mass-contour models[1] and measurements of volcanic ash debris.[6] Initial retention at t_0, as determined by difference of particle deposit above and below the grass canopy, is given as 5.0 and 1.8 g/sq ft (Table 1) for the fine and coarse size classes, respectively. A substantial fraction (45% fine and 20% coarse) was retained in the grass canopy during this short time interval, but the quantity had diminished by a factor of 3 for both size classes 1 hr later (Table 1).

These data indicate substantial particle loss from vegetation shortly after contamination, and the timing of the first observation greatly influences the magnitude of initial retention values. Nearly 50% retention has been observed here (Table 1) and elsewhere[11] when measurements are made immediately after deposition. However, approximately 10% retention on grass has been reported when measurement is delayed 1 hr to 1 day after deposition. Specific examples are 11% for fescue at 1 hr (Table 1), 9% for sorghum at 12 hr (fine particles[12]), and 11% average for primary volcanic deposit on Costa Rican grasses.[6] Operationally, it seems advisable to distinguish between absolute t_0 and delayed retention (1 to 12 hr postcontamination). Herein, initial retention and/or weathering are designated as the phenomena occurring from absolute t_0 to 1 hr and effective retention as that occurring from 1 hr to several weeks.

Retention data of different size-class particles (Table 1) are based on slightly dissimilar simulant-application rates, 11.0 vs. 9.2 g/sq ft for fine and coarse material, respectively. Strict comparison of absolute retention would require adjustment of one set of data (e.g., the coarse-size-class values × 11.0/9.2), thereby increasing coarse retention by 20%. Average retention (Table 1, column 12) would increase by less than 6%. This adjustment was not made, however, because the effect on subsequent evaluations of relative retention would be negligible.

Continuous Weathering Function

A continuous weathering function is an important parameter used in generalized mathematical models of landscape contamination.[18,19] Although often an oversimplification of retention phenomenology, such functions describe the transitory foodstuff contamination and potential radiation hazard in extensive agricultural systems. For the 17-day interval, the best fit of the composite fescue data was to a negative-exponential model (Fig. 1a) of the form

$$Y = \alpha + (1 - \alpha)e^{-\lambda t} \quad (1)$$

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Table 1

MASS, ^{86}Rb ACTIVITY, AND SAND RETENTION BY FESCUE FOLLOWING CONTAMINATION WITH FINE AND COARSE FALLOUT SIMULANT

Time, days	Fescue mass,* g/sq ft†	Fine particles (44 to 88 μ)				Coarse particles (88 to 177 μ)				Average retention‡		Cumulative precipitation, in.
		^{86}Rb activity		Retention		^{86}Rb activity		Retention				
		μCi/g†	μCi/sq ft	g/sq ft	%	μCi/g†	μCi/sq ft	g/sq ft	%	g/sq ft§	%	
0.0	17.4 ± 2.3			5.0	45.4			1.8	19.6	3.4	33.7	0.0
0.042 (1 hr)	17.4 ± 2.3	0.153 ± 0.013	2.65	1.7	15.4	0.071 ± 0.006	1.24	0.60	6.5	1.15	11.4	0.0
0.75	(17.5)	0.117 ± 0.022	2.05	1.35	12.3	0.069 ± 0.005	1.21	0.61	6.6	0.98	9.7	0.0
1.83	(17.7)	0.062 ± 0.008	1.10	0.75	6.8	0.061 ± 0.006	1.08	0.56	6.1	0.66	6.5	0.53
2.88	(17.9)	0.074 ± 0.006	1.32	0.94	8.5	0.037 ± 0.002	0.67	0.36	3.9	0.65	6.4	0.80
5.85	(18.3)	0.018 ± 0.002	0.34	0.27	2.4	0.030 ± 0.001	0.55	0.33	3.6	0.30	3.0	1.03
6.88	(18.5)	0.015 ± 0.001	0.28	0.23	2.1	0.025 ± 0.001	0.46	0.29	3.2	0.26	2.6	1.03
17.0	20.2 ± 1.9	0.009 ± 0.001	0.18	0.22	2.0	0.010 ± 0.0007	0.21	0.19	2.1	0.20	2.0	2.42

*Oven-dry weight. Initial and final quantities measured. Intermediate quantities (in parentheses) estimated by interpolation.

†Plus or minus 1 standard error of mean.

‡Average retention includes data for both fine- and coarse-particle fractions.

§Unadjusted average of columns 5 and 9.

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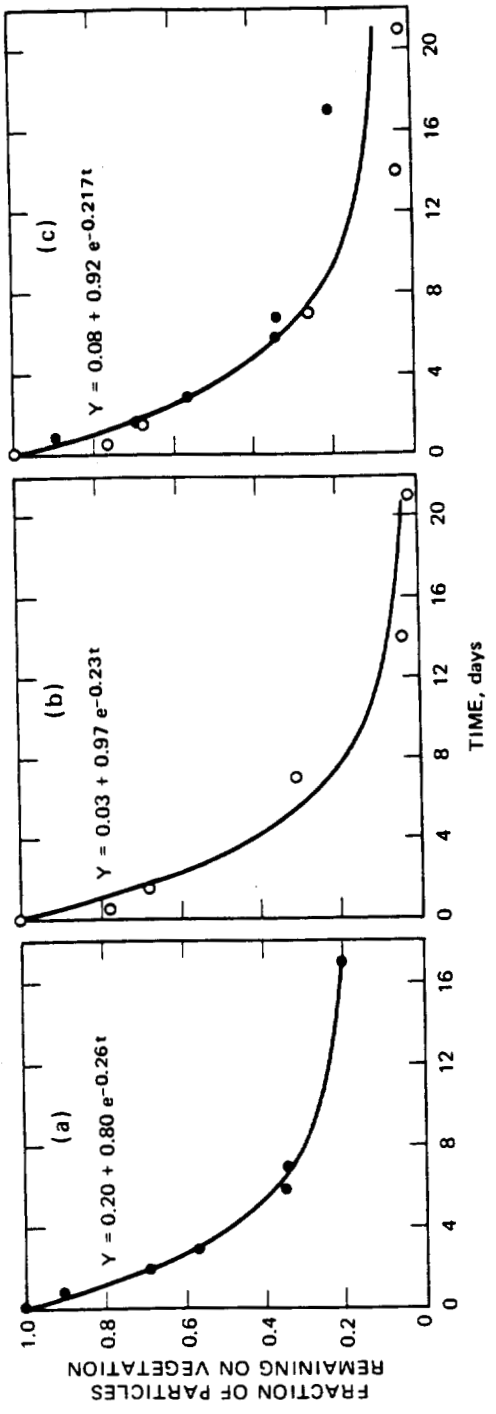

Fig. 1 Average effective particle retention by fescue (●) and sorghum (○) grasses. Data are normalized to express t + 1 hr as initial retention. (Sorghum data provided by Witherspoon.[20])

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In effect, the α parameter is a weighting function that dominates the expression of retention during the early period of weathering (small t values) but exerts less influence as time passes (large t values). High α values portray considerable deviation from the normal negative-exponential model ($y = ae^{-\lambda t}$) and indicate multicomponent weathering processes, the individual components of which are discussed in the next section. Other retention data on sorghum[20] are also fitted to the same model (Fig. 1b), and the α and λ parameters for fescue, sorghum, and composite grass are given in Table 2. Relatively low standard errors for the α and λ parameters indicate that the continuous-function model adequately

Table 2

COMPARISON OF α AND λ PARAMETERS FOR DIFFERENT SETS OF DATA BY THE CONTINUOUS-FUNCTION WEATHERING MODEL (EQ. 1), NEGATIVE-EXPONENTIAL PARTICLE RETENTION

Test data	α*	λ*
Fescue	0.195 ± 0.02	0.261 ± 0.02
Sorghum†	0.029 ± 0.07	0.227 ± 0.06
Composite grass	0.081 ± 0.05	0.217 ± 0.03

*Plus or minus standard error of the parameter estimates.
†Sorghum data from Witherspoon.[20]

describes partial retention for fescue grass. Higher standard errors for sorghum and composite grass reflect a less satisfactory fit of the model to the data. High variance of the parameter indicates that a zero value could be expected within the limits of error of the estimate; thus for these cases the best fit deviates little from an unmodified negative-exponential model. The λ parameters, however, were less variable in all test cases. Since the λ values are similar for different species of grass and the α parameters appear to be species dependent, the generalized model (Eq. 1) could be applied in the widespread evaluations of particulate-fallout retention on grass if an experimentally determined array of α values could be provided as input data for vulnerability assessments. In addition, if different species-related α and λ parameters were used, the model could also describe the time-dependent retention phenomena for vegetation types other than grass.

Inclusion of a constant term (α) in the weathering function implies that particle retention will never reach zero, especially over an interval of at least several months. Therefore, in the long-term contamination assessments, it may be necessary to use two negative-exponential functions, the early component being governed by a 3 to 4 day half-time retention (Fig. 1) and the later component (post 1 week) being characterized by a longer half-time retention.

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Perhaps the frequently used 14-day half-time value would be meaningful for the long-term component.

Multicomponent Weathering

Component loss of fallout particles from plants is evaluated when there is reason to believe that several factors independently influence retention. For

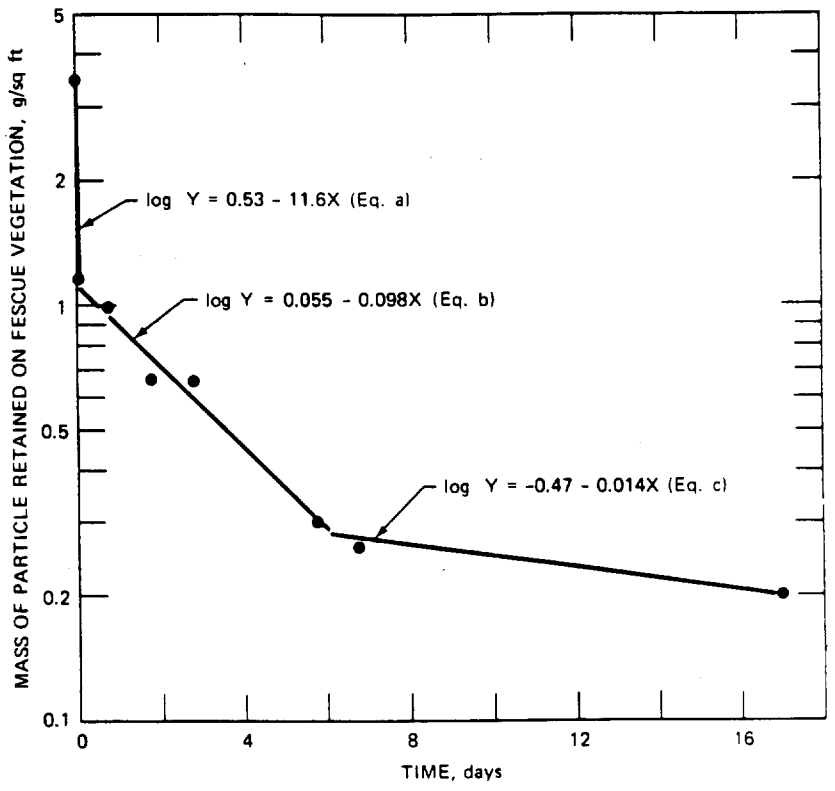

Fig. 2 Log-normal regression equations describing component particle retention by fescue.

example, weathering of particles from grass plants for initial particle retention on leaf-blade surfaces is different from that for retention in axillary crevices. Although the exact details of independent weathering processes are not well understood, several distinct components are evident for the fescue data (Fig. 2). When the data were fitted to a semilogarithmic regression model of the form

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$$\log Y = a + bX \quad (2)$$

two log normal equations (Fig. 2, Eqs. b and c) described effective retention for days 0 to 6 (in practice here, the t + 1 hr value is considered day 0) and days 6 to 17. The low-rate coefficients (b) were 0.098 and 0.014 for early and late time intervals, respectively. The difference of a factor of 7 in the loss rate for early and late intervals strongly indicates that dissimilar mechanisms affect retention on fescue and sorghum. No outwardly apparent effects were caused by moderate rainfall and low wind velocity; thus particle retention is influenced by a complex of environmental and vegetative factors that presently are poorly understood.

Extremely rapid weathering during the first hour (3.4 to 1.2 g/sq ft, Fig. 2) characterized the initial component of loss. Described in log-normal terms, the loss-rate parameter (Fig. 2, Eq. a) was 11.6, a value two to three orders of magnitude greater than the loss-rate values derived for effective retention. However, one should place only limited confidence in this parameter of the initial weathering interval since the function is described from merely two data points.

In terms of potential radiation damage to plants from local fallout, one can expect extremely rapid weathering of the early arriving, highly radioactive, but promptly decaying products. Rapid exponential loss of particles, coupled with the substantial early radioactive decay, would minimize the contact beta dose to sensitive plant parts. Approximately 10% of the fallout, however, may be effectively retained 1 hr postdeposition; and the loss rate of this fraction diminishes more slowly throughout a several-week period, thereby allowing appreciable beta exposure to plant parts in direct contact with the particles.

Differential particle weathering can be attributed to the combined effects of meteorological factors (wind, rain), leaf morphology (pubescence), and plant habit (crevice, niche). Wind-induced weathering was considered nominal in this experiment because of atmospheric calms during application and because wind speeds in the grass canopy (at a height of 20 cm) were very low during the 17-day period. Wind speeds ranged from 0 to 1.5 mph and averaged 0.3 mph based on extrapolations from wind-profile data obtained 10 cm above the vegetation.

The low-magnitude wind speeds probably were effective in the initial dislodgement of particles from horizontally positioned leaf blades immediately following interception. Thereafter wind-induced weathering was negligible because particles had become trapped in the axillary crevices of the grass shoot. Neither were loss rates affected appreciably by moderate quantities of rainfall occurring as light showers. One-inch cumulative precipitation over days 2 to 4 caused no significant deviation from the established trend of particle loss for the composite data (Fig. 2). An additional 1.4-in. steady rainfall at day 12, the midregion of the slow-loss component, did not enhance particle removal.

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Vegetation Influence

Long-term retention of fallout particles is strongly influenced by plant-habit and leaf-surface features.[4,12,13] The junction of blade and sheath in grasses is a particularly effective collector[10] because the V-shaped leaf-blade structure channels particles into the crevice between sheath and stem. Rainfall and wind-induced flexing movements further impact the particles within the sheath. The principal mode of removal is associated with growth and development of internal leaf tissue whereby adhering particles are carried upward by the elongating central axis. It follows, then, that particle retention would be directly related to growth, perhaps as a mirror image of the generalized exponential growth function. Retention results (Fig. 1) indeed suggest such a negative-exponential loss rate for particle losses not conspicuously related to moderate meteorological events. Although central-axis growth rate was not measured in the present study, perhaps in future retention experiments it would be advisable to examine the correlation between central-axis elongation and fallout-particle decontamination, especially for maize and cereal-grain crops.

Contamination-Factor Analysis

Data on particle retention (Table 1) allow the calculation of contamination factors, as derived by Martin[14] and Miller,[5] for successive intervals after contamination. Particle mass load (m) and foliar retention (C_p) from Table 3 were determined experimentally, and contamination factors (a_L) were calculated according to the relation

$$a_L = C^0_{p/m} \tag{3}$$

This expression allows an estimation of time-dependent vegetation contamination in future situations based on knowledge of plant density and soil-surface fallout deposits and assuming that the affected plant communities exhibit similar retention characteristics. For a single fallout deposit, then, maximum retention and contamination factors are observed at t_0 and decrease thereafter (Table 3). Retention at t + 1 hr is taken as t_0, and the a_L factors for fescue were 0.009 and 0.004 for fine and coarse materials, respectively. Within 2 days the values had decreased by a factor of 2 and at t + 1 week by a factor of 4, but they changed very little during the second week of the field observation. Effective weathering had occurred within 1 week; thereafter the slower particle loss rate predominated.

The contamination-factor expression originally was derived in connection with project Sedan and later was applied to volcanic fallout deposits around volcano Irazu in Costa Rica. Miller and Lee[6] reported retention values and determined a_L factors (Table 3) for Costa Rican grasses which compare favorably with those reported here. The a_L factors herein derived for tall fescue

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Table 3

FESCUE FOLIAR-RETENTION (C_p) AND CONTAMINATION-FACTOR (a_L) PARAMETERS ALONG WITH CENIZA-ARENA-ASH CONTAMINATION FACTORS FOR COMPARISON

	Fescue retention and contamination factors						Ceniza-Arena-ash contamination factors and exposure conditions[6]	
	Fine particles			Coarse particles				
Time, days	Effective retention, g/sq ft	C_p,* g/g	a_L,† sq ft/g	Effective retention, g/sq ft	C_p,* g/g	a_L,† sq ft/g	a_L, sq ft/g	Deposition conditions‡
0.042 (1 hr)	1.7	0.098	0.0089	0.60	0.034	0.0037	§	
0.75	1.35	0.77	0.0070	0.61	0.035	0.0038	0.001	Dry, P
							0.05 to 0.1	Wet, S
1.83	0.75	0.042	0.0038	0.56	0.032	0.0035	0.07 to 0.002	Dry, S
							0.05	Damp, P
2.88	0.94	0.052	0.0047	0.36	0.020	0.0022	0.015	3-in. rain with recurring deposition
5.85	0.27	0.015	0.0014	0.33	0.018	0.0020	§	
6.88	0.23	0.012	0.0011	0.29	0.016	0.0017		
17.0	0.22	0.011	0.0010	0.19	0.009	0.0010	0.003 to 0.005	3.5-in. rain with recurring deposition

*C_p is grams of particles per gram of foliage.

†a_L is C_p/m, where m is 11.0 ± 0.5 and 9.2 ± 1.0 g/sq ft for fine and coarse deposits, respectively.

‡Variable fallout deposition is designated as P, short-period unweathered deposit, and S, multiple, long-period, weathered deposit.

§No comparable data.

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ranged from 0.004 to 0.007 at days 1 and 2 under dry conditions (80% relative humidity and no wind). The Ceniza-Arena a_L factors derived by Miller and Lee for an equivalent period ranged from 0.001 to 0.07 for dry conditions and from 0.05 to 0.1 for wet conditions. Good agreement obviously exists among the results from the two different assessments of foliar retention and for the calculated contamination factors irrespective of initial mode of fallout deposition. It seems that dense vegetation in subhumid or humid climates demonstrates similar patterns of early retention.

It is likely that total radionuclide transfer to plant parts would be greatly influenced by fallout-particle distribution in the canopy. In a subhumid environment, however, plant structures can assimilate much of the nuclide that is leached from fallout materials and transferred to plant surfaces. This argument is verified by using the derived a_L for coarse particles (0.0039) to predict ^{137}Cs contamination of fescue for the 10- by 10-m plots tagged in August 1967, in which a prediction of grass contamination is compared with an independent observation of radiocesium assimilation by the fescue community.[10] The fraction retained by the vegetation canopy is estimated from Miller's plant-retention relation:

$$F_L = a_L w_L \tag{4}$$

when a_L is 0.004 and w_L is 65 g/sq ft, the plant density at the time of contamination. F_L is 0.254, which, when multiplied by the activity-application rate (2.06 mCi/sq ft), is the total ^{137}Cs contamination of foliage [i.e., $F_L = 2.06 \times 0.254 = 0.523$ mCi/sq ft (expressed in terms of activity content of vegetation)]. It was observed from laboratory tests that 15% of the radiocesium will leach from the particle in an aqueous system. If the leachate is assimilated directly by vegetation, then, 0.523 mCi/sq ft × 0.15 = 78 μCi/sq ft is the activity of vegetation shortly after contamination. The observed radiocesium content of vegetation[10] at t + 8 days was 78 μCi/sq ft, showing a remarkably good agreement between that predicted from contamination-factor parameters and that measured after the contamination event. It can therefore be concluded from this analysis of a field test that foliar contamination-factor expression coupled with fallout leachability provides a good estimation of vegetation contamination in a grass community.

Source-Term Evaluation Model

Estimation of radiological hazards, from either direct particle deposit or nuclide assimilation, depends on identification of a source term or entry of the contaminant into the food chain. At least four different source terms (Fig. 3: compartments P, E, I, and F) can serve as the initial input for the grass–cow–man food chain. Dissimilar contamination phenomena and contaminant behavior patterns are manifest for each source term. Short-term hazards

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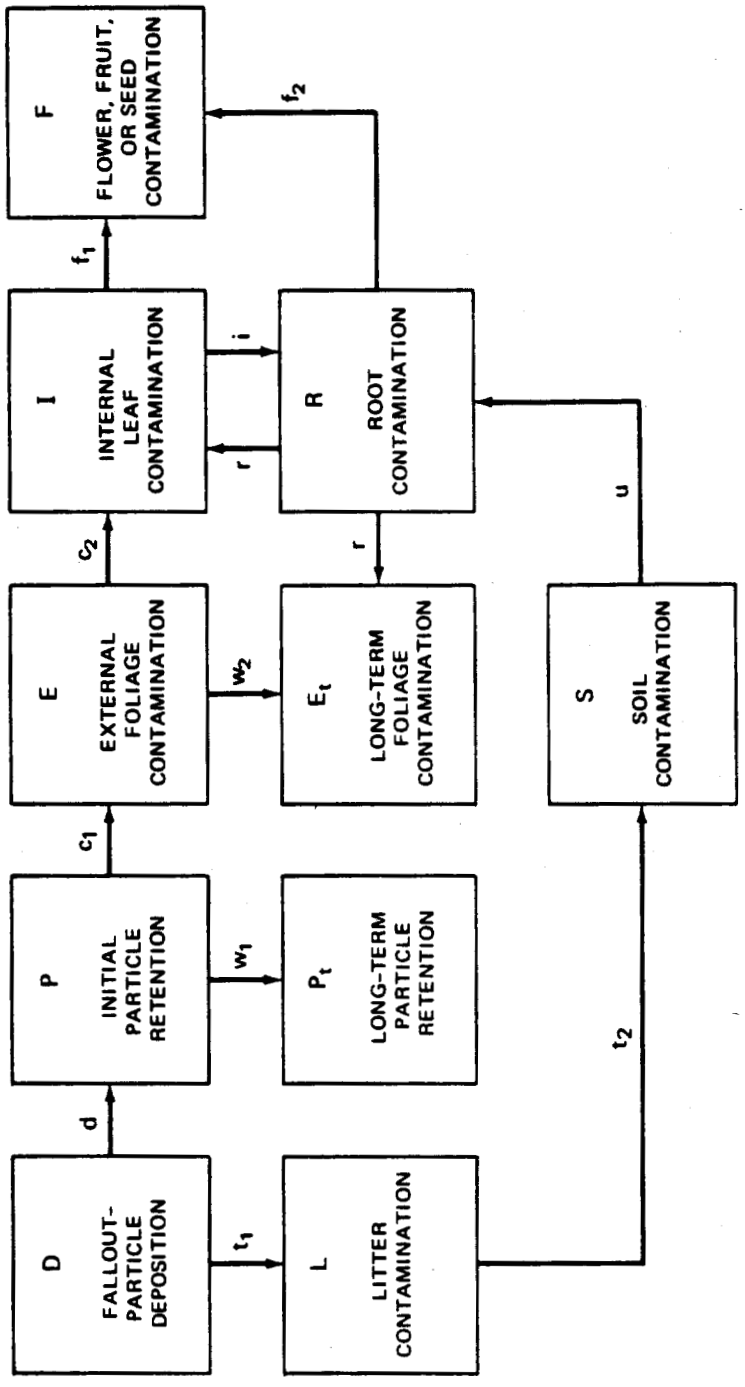

Fig. 3 Source-term relations of fescue grass after contamination with fallout-simulant particles. Transfer coefficients are evaluated in Table 4.

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Table 4

TRANSFER FUNCTIONS FOR SOURCE-TERM EVALUATION MODEL

Transfer functions	Definitions	Values for fescue grass	Source
d	= f(m), initial fraction of fallout mass load	0.10	Experimental
t_1	= 1 − d	0.90	Calculated
t_2	= f(L), fraction moving from litter to soil	0.01	Inferred from litter decomposition rate (Koelling and Kucera[23])
w_1	= Particle weathering function = 1 − P where $P = \alpha + (1-\alpha)e^{-\lambda t}$	$\alpha = 0.2$ $\lambda = 0.26$	Regression of particle retention on time
c_1	= f(P), fraction of nuclide movement from particle to foliage	0.15	Measured aqueous leachability
w_2	Nuclide weathering function = 1 − E where $E = \alpha + Be^{-\lambda t}$	$\alpha = 0.27$ $B = 1.59$ $\lambda = 0.052$	Regression of nuclide retention on time
c_2	= f(E), fraction of nuclide movement from external to internal plant parts	0.10	Inferred from Levi[21] (bean plants)
i	= f(I), fraction of internally assimilated nuclide movement to roots	0.25	Experimental
r	= f(R), fraction of root contaminant moving to current season's growth	0.4	Assumption
f_1	= f(I), fraction of leaf nuclide moving to seed	0.1	Inferred from Levi[21] (bean plants)
f_2	= f(R), fraction of root nuclide moving to seed	0.1	Assumption
u	= f(S), fraction of soil nuclide taken up by plant	0.001	Inferred from Nishita et al.[22]

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would be related to particle deposition and retention on foliage, whereas long-term problems could derive from assimilation and equilibration of the nuclide in the plant community. The model couples interrelations among principal source terms in order to estimate contamination potentials as a function of time, particle behavior, and intraplant nuclide movements. Transfer and weathering functions (Table 4) are used to predict the fate of radiocesium applied in the form of fallout-simulant particles to a fescue meadow. For subhumid environments, importance of the source term proceeds in Fig. 3 from left to right (compartments P to I) according to the approximate time sequence: P, 1 to 10 days; E, 7 to 100 days; I, 3 months to several years; F, any time interval prior to seed production. In practice, the model will predict the character and extent of contamination at successive intervals after fallout deposition. Knowledge of deposition forms, fallout behavior, and source-term magnitudes will foster more-intelligent decisions concerning grazing of pastures in the event of widespread contamination from nuclear explosions.

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