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INTERCEPTION AND RETENTION OF A SIMULATED FALLOUT BY AGRICULTURAL PLANTS*

J. P. WITHERSPOON and F. G. TAYLOR, JR.
Radiation Ecology Section, Health Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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Abstract—Five species of agricultural plants were contaminated in the field with two particle size ranges of a quartz fallout simulant containing ^{86}Rb. Initial fallout interception and retention of particles up to 8 weeks was determined. Loss of fallout from foliage due to the weathering action of wind and rain (weathering half-lives) and loss due to weathering plus radiological decay (effective half-lives) were determined for all species.

The initial interception of smaller particles (44–88 μ dia.) by foliage was 2.5 times that of larger particles (88–175 μ dia.). Particle interception was correlated with leaf area and varied between species by a factor of 65 in terms of μCi ^{86}Rb/g foliage.

After rapid initial losses of fallout (67% lost the first week after deposition), differences in retention rates between species became non-significant. Retention times of the two particle size ranges were also found to be similar.

INTRODUCTION

THE INTERCEPTION and retention of fallout by plants leads not only to irradiation of plants but also to the entry of fission products into food chains. Since about 47% of the total dose from fallout is delivered during the first day (64% during the first week) following a weapon detonation, initial interception and early losses of fallout are critical events in determining dose to contaminated plants. A better understanding of these events should lead to improved evaluation of the short-term biological hazards involved in using nuclear devices for peaceful or military purposes.

Previous studies on retention of fallout particles by plants have been made at the Nevada Test Site following nuclear detonations,[1,2] in Costa Rico following the eruption of the Irazú volcano[3] and with artificial fallout under field conditions.[4,5,6] In most of these studies, however, the early losses of fallout from plants due to weathering (wind and rain) were not determined.

The purpose of this study was to determine initial retention and early losses of a fallout simulant by agricultural plants. Five species of plants were selected to represent a wide range of foliage shapes and surface conditions. Two ranges of particle size (44–88μ diameter and 88–175μ diameter sand) were selected to represent close-in fallout. Moreover, these particle sizes have been used in previous studies under field conditions.[5,6]

MATERIALS AND METHODS

Experimental plots

Two 10 by 10 m seed beds were prepared, and seed were planted the last week of May. Each seed bed consisted of two rows each of squash (*Cucurbita moschata*), soybeans (*Glycine max*), grain sorghum (*Sorghum vulgare*), peanuts (*Arachis hypogaea*) and Korean clover (*Lespedeza stipulacea*). Spacing of plants followed standard agricultural practice. Following seed planting, the plots were fertilized and maintained for weed control until the plants were 6 weeks old. Plant height at 6 weeks ranged from 25 cm (lespedeza) to 100 cm (sorghum).

Application of fallout simulant

Two fallout simulants consisting of quartz particles 44–88 μ dia. and 85–175 μ dia. containing ^{86}Rb sorbed at high temperatures[7] were obtained from W. B. Lane of the Stanford

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Research Institute. The ^{86}Rb concentrations at time of application were 2.04 and 2.81 μCi/g sand for the 44–88 μ and 88–175 μ sizes, respectively. The solubility of the ^{86}Rb was approximately 2% in distilled water (24 hr contact of 1 g of particles with 100 ml distilled water).

The small particles were applied to one 10 by 10 m plot and the larger size to the other plot by a technique developed at ORNL for fallout studies in a grassland.[5] In general, this technique consisted of running a modified fertilizer spreader containing the fallout simulant over the plot on a moveable track. Figure 1 shows the remote-controlled spreader and part of the overhead track with its supports. Both the speed of the spreader and an internal hopper opening can be controlled such that a desirable mass loading of particles (g/ft^2 soil) can be obtained from calibration operations with non-radioactive sand. The spreader (1.5 m above the soil) covered a strip of ground 1 m wide so that several runs were necessary to cover the entire plot.

Before sanding operations, thirty plastic tubs (18 cm dia. openings) were placed between rows on each plot as a check on mass loading. The simulant was applied between 8.30 and 9.30 p.m. on 14 July under dry conditions (68% relative humidity) with 0–0.5 mph winds.

Sampling

Plant samples were taken the day before simulant application for determination of foliage area and weight per soil area. Immediately following contamination three 0.25 m^2 samples of each species in each plot were randomly selected, clipped and bagged for radiometric analyses. These samples were used to determine initial reception of the fallout simulant. Afterwards, three samples per species per plot were collected at intervals of 0.5, 1.5, 7, 14, 21, 28, 35, 42, 49 and 56 days following simulant application. Each sample was oven dried at 100°C for 24 hr, then the ^{86}Rb activity of foliage was measured in a Packard gamma spectrometer with an Armac scintillation detector.

Weather data

A small weather station was located 200 m from the experimental plot. Wind speed was recorded at 20 min intervals by a low inertia anemometer located 2 m above ground surface. Precipitation was recorded at 20 min intervals daily from midnight to midnight.

RESULTS AND DISCUSSION

Initial interception of the fallout simulant

Initial mass loading, as determined by deposition of particles in plastic tubs, was 5.70 ± 0.7 g/ft^2 soil (11.6 μCi ^{86}Rb/ft^2) for the 44–88 μ particles and 6.57 ± 0.6 g/ft^2 (18.4 μCi ^{86}Rb/ft^2) for the 88–175 μ particles. This mass loading was probably lower than that for close-in fallout following a large yield weapon detonation. CLARK[8] estimated a mass loading of 15.7 g/ft^2 at a distance of 77 miles from a 10^4 KT surface detonation.

Foliage area and biomass at the time of particle deposition are given in Table 1. Three species had a relatively dense foliage coverage such that the ratio of foliage area to soil area exceeded one. Growth habits, however, differ greatly in these species. The large surface area of squash foliage (1.7 m^2/m^2 soil) is due to large individual leaves, and a relatively prostrate growth habit. The large foliage area (3.1 m^2/m^2 soil) of soybeans is due to its bushy growth habit with many layers of relatively small leaves. Sorghum (1.2 m^2/m^2 soil), like corn, has many broad, lance-shaped leaves and a vertical growth habit.

Table 1. Foliage area and dry weight of plants at time of fallout simulant application. (Values are mean ±1 S.E.)

Species	Foliage area/ soil area (m^2/m^2)	Foliage wt./ soil area (g/m^2)
Squash	1.72 ± 0.4	68.59 ± 14.4
Soybeans	3.11 ± 0.4	122.91 ± 11.3
Sorghum	1.25 ± 0.2	57.96 ± 9.0
Peanuts	0.91 ± 0.03	47.87 ± 2.1
Lespedeza	0.51 ± 0.02	20.27 ± 1.0

Following the notation of MILLER,[3] the initial concentration of the fallout simulant on foliage may be expressed by a foliage contamination factor, a_i, such that

$$a_i = C_i^\circ / m_i \qquad (1)$$

where C_i° is the quantity in μCi of radionuclide initially intercepted per g dry weight of foliage,

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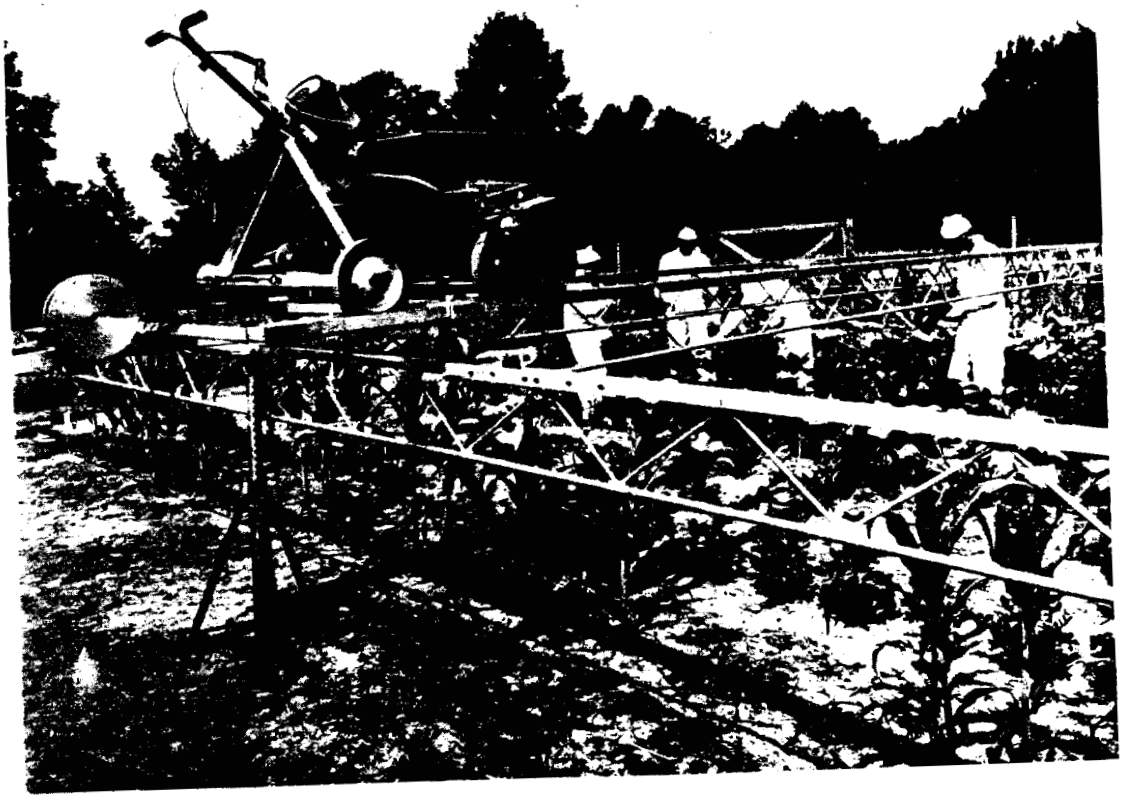

FIG. 1. Remote control spreader for sand application and movable track with supports. Personnel are sampling plants. The fallout simulant is visible as light shaded areas on foliage and soil.

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Table 2. Initial retention of simulated fallout particles by crop plants

Species	C_i° (μCi/g foliage)	m_i (μCi/ft^2 soil)	a_i (ft^2/g)	w_1 (g foliage/ft^2)	F ($a_i w_i$)	F_B/F_A
Squash	A* 2.568	18.46	0.139	6.37	0.885	1.41
	B 2.275	11.61	0.196		1.248	
Soybean	A 1.876	18.46	0.101	11.41	1.152	0.89
	B 1.047	11.61	0.090		1.027	
Sorghum	A 0.380	18.46	0.020	5.38	0.108	4.53
	B 1.058	11.61	0.091		0.489	
Lespedeza	A 0.180	18.46	0.010	1.88	0.019	3.95
	B 0.460	11.61	0.040		0.075	
Peanuts	A 0.238	18.46	0.013	4.45	0.058	1.69
	B 0.252	11.61	0.022		0.098	
						$\bar{X} = 2.49$

*A = 88–175 μ diameter particles.
B = 44–88 μ diameter particles.

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and m_i is the quantity of μCi of radionuclide deposited per ft^2 of soil surface area.

The fraction, F, of fallout that is initially intercepted by foliage is given by

$$F = a_i W_i \tag{2}$$

where W_1 is the biomass of foliage in g/ft^2 of soil surface area.

Table 2 gives initial retention values of the fallout simulants for all plants. The F values for 44–88 μ particles ranged from 0.07 for the small-leaved lespedeza to 1.2 for squash. For the 88–175 μ particles, F values ranged from about 0.02 for lespedeza to 1.1 for soybeans. Values of $F > 1$ were obtained for squash and soybean plants. The area of foliage per unit soil area (Table 1) exceeded unity due to the bush-like form of these plants, and particles had a tendency to fall in at an angle between layers of foliage such that more particles per unit foliage area were intercepted by these species. For all plants, F values for the smaller particles averaged about 2.5 times greater than those for the larger particles. The greatest differences in interception of small versus large particles were found in lespedeza and sorghum in which interception of 44–88 μ particles was about 4–4.5 times greater, respectively, than that of 88–175 μ particles. These species have very smooth leaves, and it is probable that the larger particles had a greater tendency to roll off during deposition. The least difference in interception of small versus large particles was found in soybeans. The highly layered foliage structure and villous leaf surfaces were slightly more effective in trapping larger particles ($F = 1.1$) than the smaller ($F = 1.0$) particles.

Figure 2 illustrates the pattern of 88–175 μ particle deposition on the individual leaf types. A slight vee-shape on leaves of sorghum, lespedeza and peanut caused particles to roll in toward the midvein and orient in a line along the length of the leaf. Particle distribution on squash and soybean leaves was more uniform due to small hairs on the surface and along veins.

Plants with large foliage surface areas tended to show smaller interception differences between particle sizes. Figure 3 shows the relationship between F values for the two particle size ranges and foliage area. Maximum retention differences occurred when the ratio of foliage area to soil area was less than one. This may represent a "bounce" effect where heavier particles, with greater deposition velocities, tend to bounce off of small leaves but fall back on larger leaves. Deposition velocities of the largest particles (175 μ) were about seven times greater than those of 44 μ particles.[8] Particles up to about 100 μ in diameter would have reached terminal velocities in this case.

The average F value for 88–175μ particles in the case of these crop plants was 1.5–2.2 times greater than values for small oak and pine trees under similar deposition conditions.[6] The foliage contamination factor, a_i, ranged

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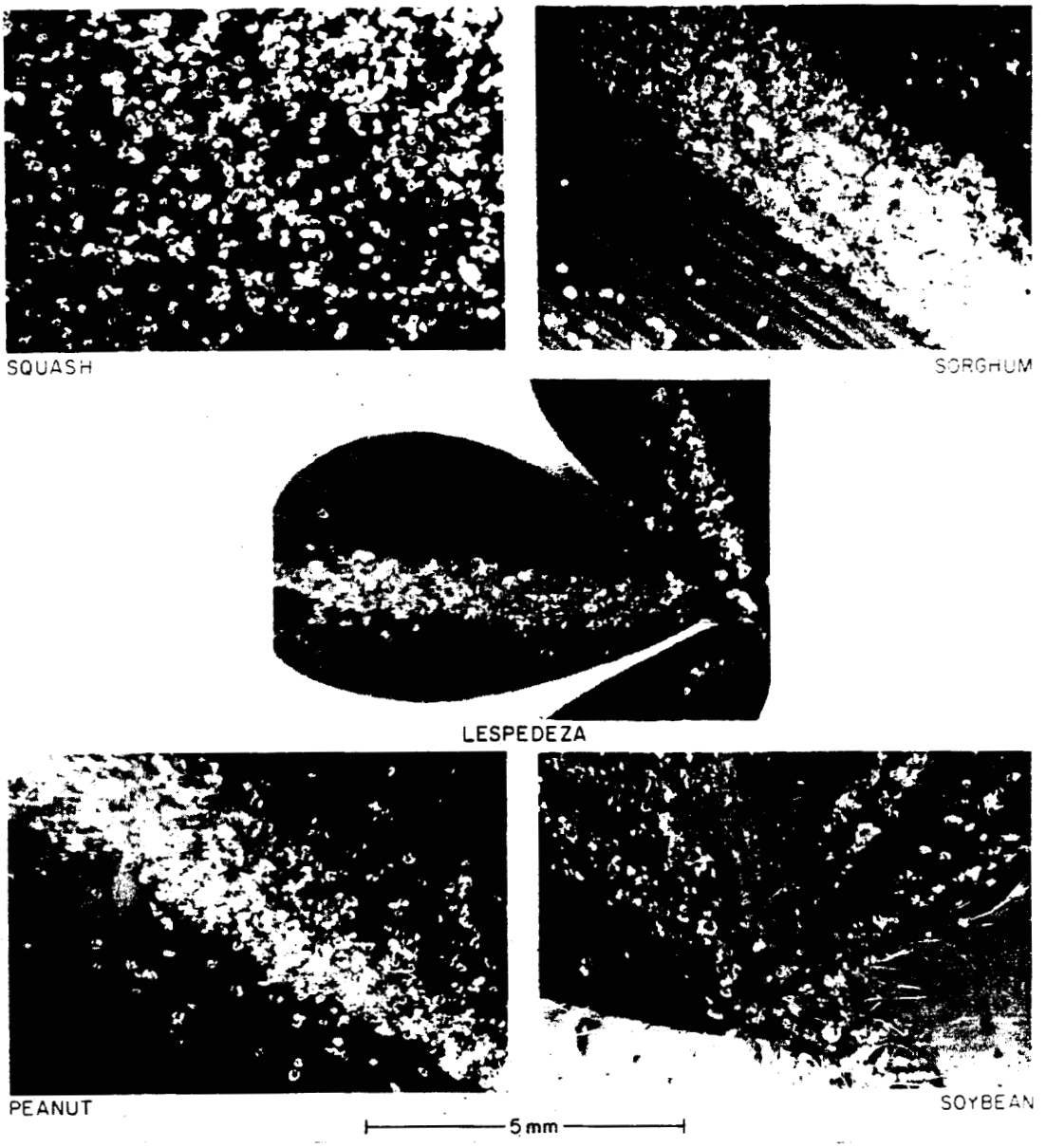

FIG. 2. Detailed photo showing initial orientation of 88–175 μ particles on the different types of foliage. Note the troughing effect in sorghum, lespedeza and peanuts.

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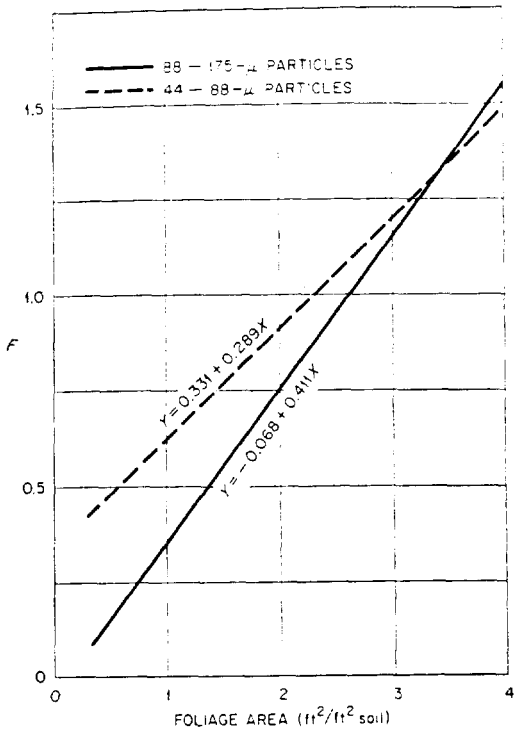

FIG. 3. Linear regressions of F, fraction of fallout initially intercepted, on foliage area.

from 0.01 to 0.19 in this study. These values are higher than reported values from NTS fallout fields.[3] Samples for the latter, however, were usually collected several days after initial contamination or after some loss of particles due to weathering.

Retention of the fallout simulant

No rain occurred for 6 days following application of the fallout, so the samples taken at 12 and 36 hr after deposition reflected losses due to wind only. Figure 4 shows average retention of particles by all plants and average wind speeds up to 36 hr after initial deposition. During the first 12 hr (overnight), the plants lost an average of 18.5% of the initial contamination. Wind speed averaged 0.5 mph over this period. Losses for the next 24 hr period also averaged 18.5% with an average wind speed of 1.1 mph. In terms of particle size, losses from plants from 0 to 12 hr ranged from 3 to 35% ($\bar{X} = 21.1\%$) for 44–88 μ particles and 9.5–26% ($\bar{X} = 15.8\%$) for 88–175 μ particles. For the 12–36 hr period, losses ranged from 1.2 to 33.5% ($\bar{X} = 15.4\%$) for smaller particles and 7.7–34.0% ($\bar{X} = 21.6\%$) for larger particles. Thus, during the first 12 hr when wind speed averaged only 0.5 mph, average loss of small particles was greater than loss of large particles by a factor of 1.3. For the 12–36 hr period, when wind speed averaged 1.1 mph, average loss of large particles was 1.4 times greater than loss of small particles. It apparently took a windspeed between 0.5 and 1.1 mph to remove some of the larger particles in the 88–175 μ range.

The concentration of a radionuclide on fallout-contaminated foliage, $C(t)$ as a function of time after fallout is usually approximated by

$$C(t) = C_i^{\circ} e^{-\lambda p t} \tag{3}$$

where λp is the effective decay constant for the radionuclide and is equal to $0.693/T_p$. The effective half-life, T_p, of the radionuclide on foliage is given by

$$T_p = T_r T_w / T_r + T_w \tag{4}$$

where T_r is the radioactive half-life (18.7 days for ^{86}Rb) and T_w is the weathering half-life due to the action of wind and rain.

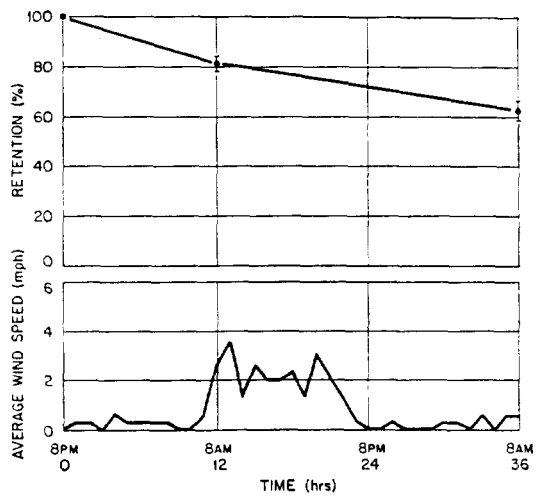

FIG. 4. Percent of initial fallout reception retained and wind speeds for 36 hr following fallout application. Retention values are averages for all plant species.

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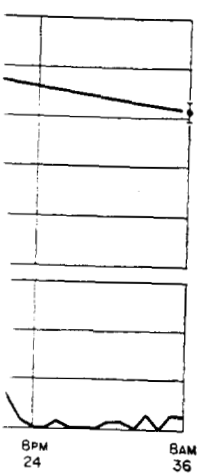

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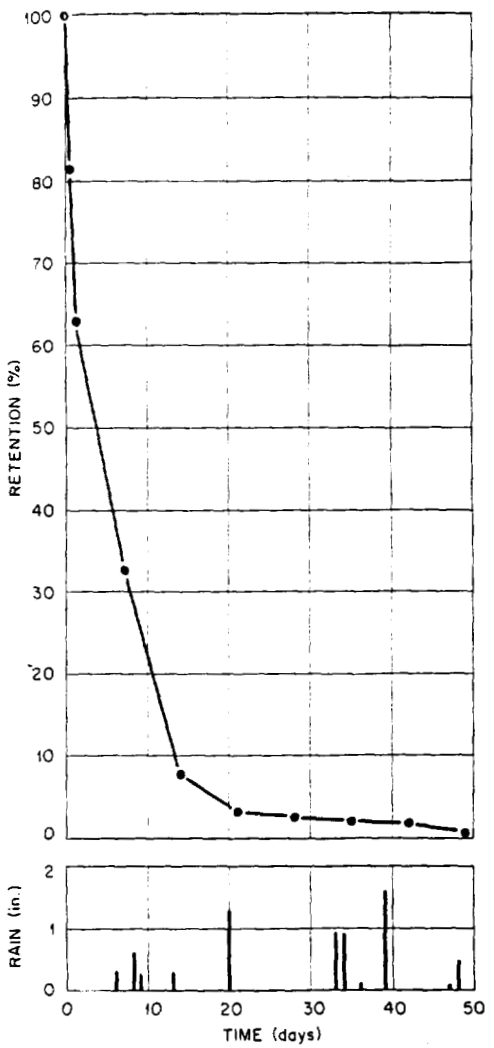

FIG. 5. Percent of initial fallout interception retained and amount of rainfall up to 49 days following fallout deposition. Retention values are averages for all plant species.

Retention curves, however, cannot be adequately expressed in terms of a single effective half-life. Rapid particle loss rates during the first week and subsequent rate changes due to weathering imply that retention data should be compartmentalized into appropriate time components for half-life analyses.

In this study four time components were used for calculation of half-lives. Linear regression analyses were performed on ^{86}Rb concentrations on foliage through time periods of 0–1.5, 1.5–14, 14–28 and 28–56 days. Weathering half-lives, T_w, were estimated from these linear expressions. Effective half-lives were then determined using equation (4).

Figure 5 shows the average retention by all plants of the fallout simulant. Both particle size ranges were included. This curve approximates the shape of individual retention curves for each species and each particle size range. The amount and time of rainfall during the study are also shown in Fig. 5. Eleven rain periods were recorded, and total rainfall was 6.96 in. The initial drop to $63 \pm 3\%$ at 1.5 days in the retention curve is due to loss of particles only by wind action. Wind speeds up to 6 days, time of the first rain, averaged 1.7 mph (7 mph max) during the day and 0.3 mph (2 mph max) during the night. It is likely that maximum losses due to wind action occurred during the first 2 or 3 days following deposition and that most of the loss of particles from 1.5 to 7 days was due to a 0.25 in. rain on the sixth day. After the second week, and three rains totaling 1.08 in., average retention was $7.9 \pm 1.6\%$. One intense rain (1.4 in.) on the twentieth day caused another sharp drop in retention down to $3.3 \pm 1.0\%$. After the third week the loss rate became relatively constant and subsequent rains had little effect on the quantity of fallout remaining on foliage.

Weathering half-lives for each species, each particle size range and for the four time components are given in Table 1. When plant species were averaged, there was no statistically significant difference between T_w values for the two particle size ranges due to wide variations in T_w values for individual species. For example, sorghum foliage was very effective in trapping 44–88 μ particles which funnelled down the angular leaves into leaf axils. This resulted in large T_w values for this species after 2 weeks. The hairy leaves of squash and soybeans were also relatively effective in retaining the smaller particles during this period. Species differences in T_w values of the 88–175 μ particles were less pronounced. Sorghum foliage, for example, was not as effective in retaining this particle size range.

The T_w values for the 14–28 day component averaged between 16 and 26 days in this study. MARTIN and TURNER[2] reported T_w values of

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Table 3. Weathering half-lives (T_w days) for simulated fallout particles on crop plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\bar{X}$ all plants
			44–88 μ Particles			
0–1.5	2.46	2.09	2.77	5.06	1.40	2.76 ± 0.71
1.5–14	7.21	7.29	6.62	8.43	8.36	7.58 ± 0.35
14–28	42.00	17.51	35.29	17.71	18.12	26.13 ± 4.71
28–56	39.00	45.66	272.76	32.11	32.68	84.44 ± 46.28
			88–175 μ Particles			
0–1.5	1.62	1.47	4.10	1.33	2.88	2.28 ± 0.53
1.5–14	7.36	7.19	7.43	15.71	7.55	9.05 ± 1.64
14–28	15.06	15.97	19.43	16.07	14.07	16.12 ± 1.03
28–56	56.50	34.72	38.36	29.46	38.33	39.47 ± 5.20

Table 4. Effective half-lives (T_p days) for simulated fallout particles on crop plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\bar{X}$ all plants
			44–88 μ Particles			
0–1.5	2.17	1.88	2.41	3.98	1.30	2.35 ± 0.51
1.5–14	5.21	5.25	4.89	5.81	5.78	5.39 ± 0.17
14–28	12.94	9.57	12.22	9.09	9.20	10.60 ± 0.72
28–56	12.64	13.27	17.50	11.82	11.89	13.42 ± 1.09
			88–175 μ Particles			
0–1.5	1.49	1.36	3.36	1.24	2.49	1.99 ± 0.41
1.5–14	5.28	5.19	5.32	8.54	5.38	5.94 ± 0.64
14–28	8.34	8.61	9.53	8.64	8.03	8.63 ± 0.29
28–56	14.05	12.15	12.57	11.44	12.57	12.56 ± 0.50

28 days (^{89}Sr) and 13–17 days (^{131}I) for Sedan fallout on plants from 5 to 30 days following detonation. Weathering half-lives of simulated fallout (^{134}Cs) on oak and pine trees were 25 and 21 days, respectively, during a period of 7–33 days after deposition.[6] Thus, it appears that T_w values for many different kinds of vegetation, in different geographical regions, may be quite similar after rapid initial losses during the first week or two.

When effective half-lives, T_p's, are compared (Table 4), differences between species become even smaller. The relative short T_r of ^{86}Rb (18.7 days) compared to some of the long T_w values reduced differences between species to non-significance.

Effective decay constants (Table 5) reflected only slight differences between particle size ranges and between species. Again, low λp values for sorghum reflected the ability of this species to retain particles. Relatively smaller λq's for peanuts and lespedeza during the 1.5–14 day component were due to a foliage phenomenon common to legumes. From late afternoon until morning, leaves of these species close up. This closure tended to reduce particle losses induced by wind and rain during this period.

It is obvious that concentrations of radionuclides of fallout-contaminated plants can be expected to decrease at rates significantly faster than would be predicted on the basis of radiological decay. This is especially true during the first day or two after deposition. Although large differences in initial interception existed between species and between particle size ranges, they became non-significant after about 1 week of exposure to wind and rain. Plants with grass-like foliage, such as sorghum, with an

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Table 5. Effective decay constants (λp day^{-1}) for simulated fallout particles on crop plants

Time component (days)	Squash	Soybean	Sorghum	Peanuts	Lespedeza	$\bar{X}$ all plants
			44–88 μ Particles			
0–1.5	0.319	0.368	0.287	0.174	0.533	0.336 ± 0.07
1.5–14	0.133	0.132	0.142	0.119	0.120	0.129 ± 0.004
14–28	0.053	0.072	0.057	0.076	0.075	0.067 ± 0.004
28–56	0.054	0.052	0.039	0.059	0.058	0.052 ± 0.004
			88–175 μ Particles			
0–1.5	0.463	0.508	0.206	0.559	0.278	0.404 ± 0.06
1.5–14	0.131	0.133	0.130	0.081	0.129	0.121 ± 0.01
14–28	0.083	0.080	0.073	0.080	0.086	0.080 ± 0.002
28–56	0.049	0.057	0.055	0.060	0.055	0.055 ± 0.002

efficient particle trapping mechanism may be exceptions. The particle size distribution over the size ranges used was not known. The 88–175 μ particle size range may have contained a large percentage of particles in the lower portion of this range. This would tend to minimize differences in retention values between the two size ranges used in this study.

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