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INTERCEPTION AND RETENTION OF SIMULATED COOLING TOWER DRIFT (100–1300 μm DIAMETER) BY VEGETATION*

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Abstract – A key issue concerning environmental impacts from cooling tower operation is the interception of drift by vegetation and the efficiency of plants in retaining the residue scavenged from the atmosphere. Chromated drift water, typical of the cooling towers of the Department of Energy's uranium enrichment facilities at Oak Ridge, Tennessee, was prepared using radiolabelled chromium. A portable aerosol generator was used to produce a spectrum of droplets with diameters (100–1300 μm) characteristic of mechanical draft cooling towers using state-of-the-art drift eliminators. Efficiency of interception by foliage varied according to leaf morphology with yellow poplar seedlings intercepting 72% of the deposition mass in contrast to 45% by loblolly pine and 24% by fescue grass. Retention patterns of intercepted deposition consisted of a short-time component (0–3 days) and a long-time component (3–63 days). Retention times, estimated from the regression equation of the long component, indicated that drift contamination from any deposition event may persist from between 8 and 12 weeks. In field situations adjacent to cooling towers, the average annual concentration of drift on vegetation at any distance remains relatively constant, with losses from weathering being compensated by chronic deposition.

INTRODUCTION

Ground level air concentration and deposition rates of drift are important source characteristics that aid in predicting the potential for environmental effects of cooling tower operation on terrestrial ecosystems. The current approach in drift assessment is to use source and transport parameters as input data into one of several drift transport models to predict the quantity of mineral residue present downwind from cooling systems (Schrecker *et al.*, 1975). The resulting model simulations provide estimates of instantaneous or long-term (average annual) deposition and air concentrations of drift along a distance gradient.

Predictions of drift deposition (average annual) from present models assume 100% interception by the substrate (soil surface). The potential for effects in plants should be proportional to the quantity of drift intercepted, retained and available for uptake through the foliage. Variations in initial interception between plant genera are related in part to diverse leaf morphologies. Because the contamination of foliage by cooling tower drift is partially by droplet sedimentation, methods for estimating initial interception and retention are assumed to be similar to techniques used in evaluating the fate of simulated fallout on plant species (Witherspoon and Taylor, 1970).

An aerosol, characteristic of the drift from several mechanical draft cooling towers, was produced by simulating the chemistry of the recirculating cooling water and generating droplets of known diameter sizes. The simulant was applied in a field study to determine the initial interception by plants and to estimate the retention efficiencies among several genera.

METHODS

A portable (backpack) drift simulator was designed and fabricated to generate a uniform aerosol of known droplet characteristics. The backpack droplet simulator was tethered by a 30 m pressure hose and electric cable from a stationary source of compressed gas and electric power. The aerosol (mist) was produced [illegible] the discharge volume controlled by forcing the [illegible] simulant through a full-cone spray nozzle [illegible] pressure of compressed gas during a specified [illegible] interval. Flow through the spray nozzle was a [illegible] of pressure, such that 0.75 l min^{-1} was discharged [illegible] 24 psi. Specific dosage of the simulant was [illegible] controlled by activating an electric timer motor [illegible] opened and closed a solenoid valve for a [illegible] interval, thus delivering a known quantity [illegible] throttling valve. By opening the solenoid valve [illegible] 100 ml of simulant was discharged. The aper[illegible] the nozzle were such that micron-size droplet[illegible] generated. Droplet size was measured, using [illegible]

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Table 1. Size and mass distribution of simulated drift droplets produced by a portable aerosol generator

Droplet diameter (microns)	% of sample by number	% of mass by diameter
100–200	4.50	0.10
201–300	9.33	0.74
301–400	19.29	4.23
401–500	14.47	6.74
501–600	20.58	16.99
601–700	16.40	22.78
701–800	7.08	15.03
801–900	5.14	15.86
901–1000	1.93	7.74
1001–1100	0.32	1.96
1101–1200	0.64	4.82
1201–1300	0.32	3.00

sensitive paper methods, and corrected for splash effect by calibration techniques described by Engelmann (1962). The simulated drift droplets ranged from 100–1300 μm in diameter with the greatest fraction by number (40%) and mass (55%) occurring in the 500–800 μm class (Table 1). The spectrum of droplets is representative of drift droplets expected at the stack discharges of some older natural draft and of mechanical draft cooling towers using current state-of-the-art drift eliminator designs (Wistrom and Ovard, 1973). Both the time interval (8 s) and pressure (24 psi) were controlled such that a desirable mass load (ml m^{-2}) of the drift simulant was obtained from calibration operations. The apparatus was calibrated by discharging water onto a dry cement pad, thus producing a wet outline of the deposition area. By varying the height of the spray nozzle above the ground, one could control the size (area) of the circle to be contaminated. The discharge volume (100 ml) released from a height of 1.5 m uniformly covered a circle ($\sim$1.12 m dia.) of 1 m^2.

A chromate-based corrosion inhibitor (9 ppm chromium) is used in the recirculating cooling water of several mechanical draft cooling towers at the Oak Ridge Gaseous Diffusion Plant (Fowlkes, 1973). Therefore, it was desirable to simulate the water chemistry for the interception–retention study. After calibration to a desirable mass load (ml m^{-2}), radiolabelled sodium chromate ($Na_2{}^{51}CrO_4$) was added to the cooling water as a tracer. Experimental units were individual pot cultures (2 yr old), each containing a fescue grass sward (*Festuca arundinacea* Schreb.), a loblolly pine seedling (*Pinus taeda* L.), or a yellow poplar seedling (*Liriodendron tulipifera* L.). Two pots each of fescue grass and loblolly pine were arrayed in a circle within each of twenty-five 1 m^2 plots. Yellow poplar seedlings were placed only in 12 plots. Filter discs of known area (268 cm^2) were also placed in the center of each plot and contaminated concurrently with the plants to determine the initial deposition. The pot cultures were arranged so that the foliage of individual plants did not obstruct the receptor surface of adjacent plants or the filter disc within the treatment plot. The drift simulant (mist) was released above the canopies of each pot culture by acute exposures under calm conditions. Immediately following application, four plants of each species were randomly selected and clipped into plastic bags to determine the initial interception of the drift simulant. Subsequent collections were made periodically during an eight-week period to determine the retention of drift on foliage. Initial mass loading of the simulated drift was 100 ml m^{-2} which resulted in a deposition of 90 $\pm$ 5 μCi^{51}Cr m^{-2}.

Samples of grass foliage and recirculating water samples from the diffusion plant cooling towers were prepared for spectral resolution by energy dispersive x-ray techniques and photographed using a scanning electron microscope to determine the sites of drift contamination and the size distribution of the drift particles. Elemental analyses for the water samples were obtained from the residue of recirculating water droplets which had been evaporated to dryness, whereas the actual particles (residue) on the upper and lower surfaces of the grass foliage were analyzed.

Actual drift contaminated plants (grass) within 0.05-m^2 plots were collected near the Oak Ridge Gaseous Diffusion Plant cooling towers, removed to the laboratory, and leached with distilled water to simulate throughfall of one to six inches (2 to 15 cm) of rain. Water aliquots were analyzed using an atomic absorption spectrophotometer for mineral residue (total chromium) which had been removed. Loss rates were then determined from linear regression analysis for each component (foliage and litter).

RESULTS AND DISCUSSION

Following the notation of Miller (1967), the initial concentration of the drift simulant on foliage may be expressed by a foliage contamination factor a_i such that

$$a_i = C_i/m_i, \qquad (1)$$

where C_i is the quantity in μCi of radionuclide initially intercepted per gram dry weight of foliage, and m_i is the quantity in μCi of drift simulant deposited per square meter of soil surface area. The fraction, F, of drift that is initially intercepted by foliage is given by

$$F = a_i W_1, \qquad (2)$$

where W_1 is the biomass (dry weight) of foliage in g m^{-2} of soil surface.

Species with high ratios of leaf surface area to soil surface area (leaf area index—LAI) [illegible] greater interception efficiencies than species with [illegible] foliage area. For example, yellow poplar and [illegible] seedlings in this study, with area indices between [illegible] 2.85, intercepted 72 and 64% of the deposit[illegible], respectively, whereas fescue grass, with a [illegible] index of 2.3, intercepted 24% (Table 2). The [illegible] contamination of yellow poplar leaves [illegible] a function of the orientation of foliage [illegible] to

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Table 2. Initial interception of simulated drift by vegetation

	m_i (μCi m^{-2}) ±1 SE	C_i (μCi g^{-1}) ±1 SE	a_i ($C_i m_i^{-1}$)	W_1 (g m^{-2}) ±1 SE	F ($a_i W_1$)	LAI (m^2 m^{-2})
Fescue grass	89.6 ± 4.7	0.1831 ± 0.04	0.0020	118.69 ± 20.2	0.2374	2.30
Loblolly pine	89.6 ± 4.7	0.2239 ± 0.05	0.0025	181.99 ± 23.1	0.4550	2.85
Yellow poplar	89.6 ± 4.7	0.8877 ± 0.15	0.0099	72.57 ± 9.9	0.7184	4.00

m_i = initial deposition
C_i = initial interception per gram foliage
a_i = contamination factor
W_1 = plant density
F = fraction of initial deposition intercepted
LAI = leaf area index (m^2 m^{-2}).

the deposition path in addition to the greater leaf area of the receptor. It has been shown that the fraction of contaminant initially intercepted by herbage is related to an uptake coefficient (μ), dependent on biomass density, with experimental values of μ ranging from 2.3 to 3.3 m^2 kg^{-1} among grasses (Chamberlain, 1970). In the present study uptake coefficients were computed and found to be comparable to Chamberlain's results, with values of 2.27 and 3.3 m^2 kg^{-1} for fescue grass and loblolly pines, respectively. On the other hand, the uptake coefficient for yellow poplar was 17.49. Among yellow poplars the ratios of leaf surface area to biomass were two to three times greater than for fescue grass and loblolly pines, suggesting that the area of the receptor was independent of biomass in determining the fraction of initial interception. Surface characteristics, such as pubescence or roughness, seem insignificant to initial interception in this study since the surfaces (texture) of the foliage among the three genera are similar. The retention of the drift simulant by the three species resulted in a two-component curve (Fig. 1), which was resolved into a short-time or initial loss phase (0–3 days) and a long-time (3–63 days) component.

The majority of the initial contaminant (60–75%) was lost by all species during the first three days following contamination. Since the chromate tag was water soluble, and there was no rainfall event (Table 3) prior to the harvest at three days postapplication, the initial quantities lost (~75%) were likely in coalescing dew droplets which fell from the foliage by gravity flow. Loss of the remaining simulant (~25%) over the long-time component (3–63 days) showed no correlation to rain events or quantity of precipitation (Table 3). Chamberlain (1970) suggested that leaching of radioactive aerosols from foliage by rain was not the major mechanism of field loss. It has been demonstrated experimentally that plants are capable of releasing trace metals into the atmosphere (Beauford *et al.*, 1975). Such a release or field loss is due primarily to cuticle weathering, resulting from surface abrasion and leaf bending induced by various stresses. The trace contaminants released are likely contained in salt particles, wax rodlets or cuticular and other surface fragments (Beauford *et al.*, 1977). It is hypothesized in this study that a significant fraction of the remaining simulant (25%) removed over the long-time component (3–63 days) was released from the plants in this manner. The rates at which these materials (surface fragments) are removed can be enhanced by rain, dew, and wind. Linear regression analyses were performed on chromium-51 concentrations through the time period of 3–63 days postapplication to estimate residence times of the remaining fraction (Fig. 1). Retention half-times of the remaining fractions were four weeks for loblolly pines and yellow poplars and six weeks for fescue grass. Less than 1% was estimated to remain on loblolly pines and yellow poplar seedlings at seven weeks (Fig. 1a) compared to the same quantity on fescue grass at eleven weeks (Fig. 1c). The ratios of the slopes of the regression curves suggest that loss rates are the same for loblolly pines and fescue grass, whereas the loss rate from yellow poplar [illegible] times greater than the loss from the pines [illegible] grass. A test for parallelism of the regress[illegible] revealed that the slopes were not statistically [illegible] from each other ($P < 0.05$). However, because [illegible] differences in initial interception (Table 2) [illegible] initial loss between the species (Fig. 1) [illegible] pooled slope for the estimation of half[illegible] rejected. The flat laminar surface of the yellow [illegible] leaves provided an excellent receptor for [illegible] interception but afforded little chance for [illegible] retaining the solubilized residue of the [illegible] contrast, both fescue grass and loblolly p[illegible] effective in trapping the initial deposit[illegible] yellow poplar (Table 2).

Fescue foliage was examined using [illegible] electron microscope to determine the [illegible] contamination and size characteristics [illegible] ticles. Both upper and lower surfaces of [illegible] examined from samples collected at 60 [illegible] Drift particles observed were either [illegible] particulates or droplets which subseq[illegible] leaving the mineral residue. Particle de[illegible] upper surfaces (Fig. 2a) of leaves collecte[illegible]

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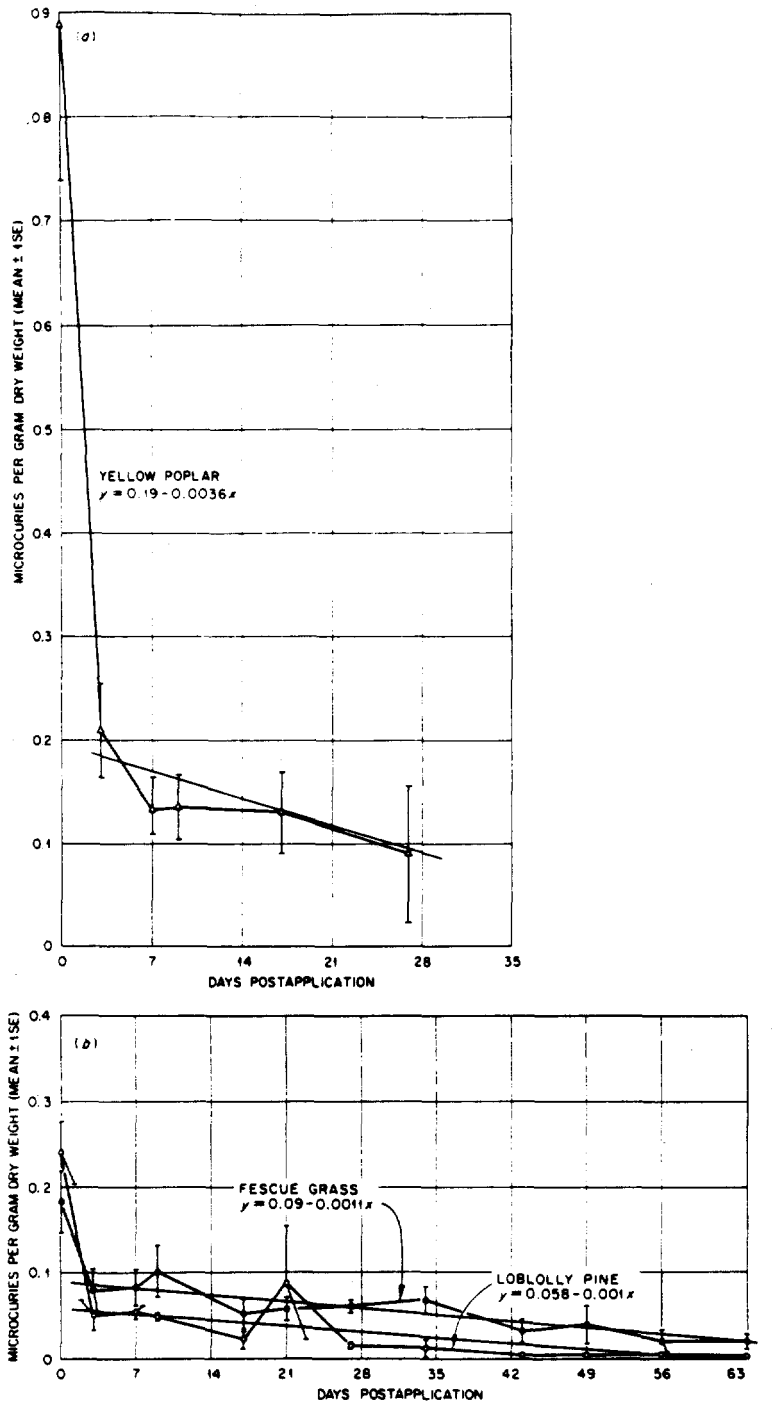

Fig. 1. Retention of chromium-51 on vegetation up to 9 weeks post-application. Each data point represents the mean (n = 4) at each sample period. Bars denote ± 1 standard error.

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Table 3. Precipitation events and quantity of rainfall during the field study

Days postapplication of simulant	Precipitation (cm)
3	2.41*
5	0.91
9	2.54
18	0.30
25	1.27
33	1.02
46	4.45
50	1.02

* Rain event occurred following harvest of plants.

much less than on the lower surfaces (Fig. 2b), and at 300 m particle density on both surfaces was less than the corresponding surfaces at 60 m. Recirculating cooling water (RCW), evaporated to dryness, deposited residue similar in size (6–40 μm dia.) and configuration (Fig. 2c) to the deposits (5–50 μm dia.) observed on the foliage. To test whether the foliage deposits were actually drift derived, energy dispersive X-ray analyses were made on the drop residue (Fig. 2c) and compared by similar analyses to spectral characteristics of foliar deposits (Fig. 2b). Energy dispersive X-ray analysis showed that particles on the foliage contained elements common to the chemistry of the RCW drop (Na, Mg, Si, S, Cl, K, Ca and Fe). Each of these elements would be expected to occur in the RCW following concentration by several cooling cycles or in the make-up water. All particles examined did not contain the full spectrum of elements. Analyses of washed and unwashed leaves from control areas did not produce emissions spectra. This suggests that the concentration of specific elements in individual drift droplets may not be equivalent to the concentration maintained in the recirculating water. This finding is important in calculating the drift emissions since a common assumption in cooling tower drift estimates is that the drift droplets contain the same mineral concentration as the circulating water. The low density of deposits on the upper surfaces of the leaves suggests a field loss due to weathering. The chromium maintained in the RCW for corrosion inhibition could not be detected by the X-ray analyses as the concentration (9 ppm) is below the limit of detection (0.1 to 1%) by the energy dispersive technique.

A laboratory study was conducted to demonstrate the removal of drift (chromium) from plant materials by water. Differences in chromium concentration between foliage and litter in a previous study had suggested that there were more exchange sites associated with the litter than with the live foliage (Taylor *et al.*, 1975). It was hypothesized that the differences in concentration between live foliage and litter were related to the chemical properties of chromium rather than the physical trapping of the chemical residue. Drift deposited as hexavalent chromium on foliage should remain relatively water

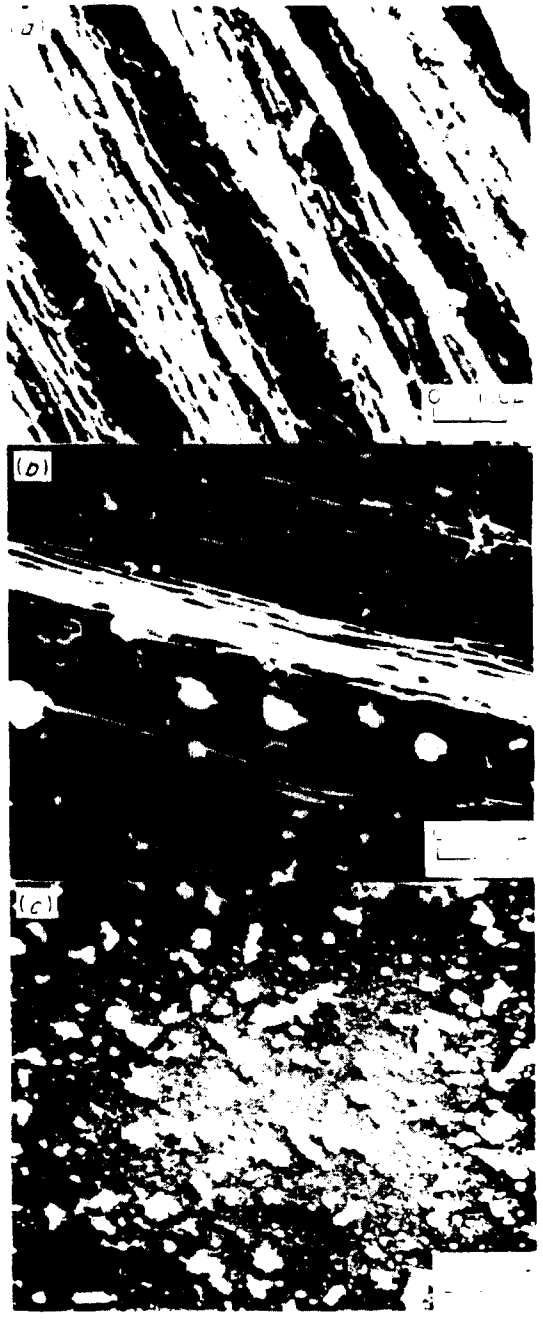

Fig. 2. Electron micrographs of drift depos[illegible] surface of fescue foliage; (b) lower surface [illegible] aligned along a vein; (c) deposits from recircula[illegible] water evaporated to dryness. Particle diameter[illegible] 5–50 μm.

soluble, whereas the deposition on litter w[illegible] be reduced to the less soluble trivalent spe[illegible] numerous organic particles and subseque[illegible] to the decaying mat. The litter mat would [illegible] greater potential for sites of chemical redu[illegible] increased area of foliage fragments and p[illegible]

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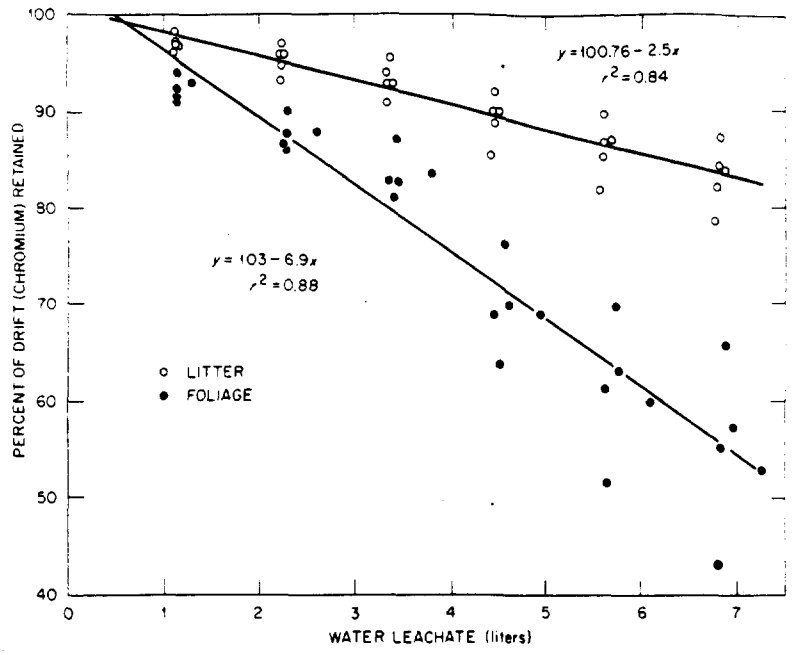

Fig. 3. Retention of drift on fescue foliage and litter from 0.05 m^2 plots, following application (soaking) of water equivalent to form one to six inches of rain (1.27 l. = 1 in).

Fescue grass (foliage) and litter were collected from 0.05 m^2 plots near the cooling towers of the Oak Ridge Gaseous Diffusion Plant and covered with water to simulate quantities equivalent from one to six inches (2.5–15 cm) of rain. The leachate (throughfall) was analyzed for chromium removed by each treatment and the resultant retention data summarized by linear regression analysis. The content of drift in the leachate indicated that the loss rate of chromium from grass foliage was two to three times greater than losses from litter (Fig. 3). Approximately 7–9% of the total was removed from foliage with each successive treatment in comparison to only 3% from the litter. Since the total quantity of drift on the foliage and litter was the result of chronic deposition, the residue being removed is likely the fraction remaining after the rapid initial loss depicted in Fig. 1. These data support the hypothesis that the difference in concentration between foliage and litter is likely related to a differential solubility of chromium in two oxidation states (Cr^{3+} and Cr^{6+}) with subsequent field losses due to removal by a combination of surface fragments and solubilized drift residue.

The interception and retention data of this study were derived from an experiment in which the distribution of droplet diameters and water chemistry was representative of cooling tower water. Since water lost from a cooling tower in the form of drift is primarily deposited by sedimentation and impaction, it is suggested that much of the earlier experimental data from fallout studies (Milbourn and Taylor, 1965; Chadwick and Chamberlain, 1970; and Witherspoon and Taylor, 1970) are amenable to estimate the fraction of drift intercepted by vegetation. However, caution must be used to draw any inference as to retention efficiencies of "drift" since retention will be element specific depending on water chemistry of the recirculating water of the cooling system and subsequent uptake and absorption by foliage. Under conditions of chronic drift deposition the level of contamination (foliar concentration) will depend on the balance between losses from weathering phenomena (including the release of plant fragments), dilution by new growth, and uptake by plants. Periodic sampling at Oak Ridge, Tennessee, has verified the relatively constant level of chromium drift contamination with distance (Taylor *et al.*, 1975, 1976).

These results are relevant to assess drift effects in vegetation from operating and proposed plants where drift deposition to the environs has been estimated by dispersion model techniques. The estimates of initial interception probably represent the worst case examples, since they are derived from a droplet distribution characteristic of stack discharges rather than the point of impingement, and represent estimates for individual plants without influence of a canopy. Consequently, an assessment of potential drift effects in vegetation, incorporating these results, would provide conservative estimates.

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