Airborne Salt Spray—Techniques for Experimentation and Its Effects on Vegetation

Bruno C. Moser

Department of Horticulture, Purdue University, West Lafayette, IN 47907.
Grateful appreciation is extended to Duncan Blanchard, Atmospheric Sciences Research Center, State University of New York, Albany, for assistance and advice concerning the impingement sampler. Thanks are also extended to General Public Utilities Corporation and Jersey Central Power and Light Company for support of this work.

Construction of salt water cooling towers at nuclear power plants raises the question of possible environmental impact due to salt drift. Potential effects on vegetation are of particular interest.

Studies on the effects of airborne salt drift have been concerned mainly with problems associated with vegetation growing in coastal areas and along highways that are heavily salted during the wintertime. In both cases salt solution droplets generated either by the surf or automobile traffic are carried on the wind, eventually impinge on vegetation, and are absorbed by the foliage. Uptake of salt solutions by foliage is rapid and relatively efficient (5).

Although there are many reports in the literature of detrimental effects due to airborne salt, very few demonstrate quantitative relations between plant growth and measured airborne salt levels. Some exceptions are as follows: Lomas and Gat (7) demonstrated a relation between yield of citrus trees and measured airborne salt near the Mediterranean coast. They showed that levels of salt drift drop off rapidly with distance inland and that reduced yields were associated with high salt levels near the coast. Oosting and Billings (9) demonstrated a positive relation between airborne salt measurements and injury to plants growing along the North Carolina coast. Measurements of salt drift near Canadian highways also have been correlated with injury to evergreens during the winter season (6).

Typical "molding" effects on the growth habit of vegetation has been observed in coastal areas (4). It has been established that this one-sided growth is associated with excessive accumulation of chloride and sodium in tissue on the side of plants facing the surf or drift source. Because of this, coastal areas bordering large bodies of salt water are excellent natural laboratories in which to study the effects of salt spray drift. Droplets generated in the surf are swept inland by onshore winds (2). Once aloft, salt particles and droplets may come in contact with vegetation by sedimentation, impingement, or in rainfall. Impingement of windborne particles is by far the major means by which salt accumulates on the aerial portions of plants in coastal areas. Accumulation of salt by impingement also will most likely represent the greatest threat to vegetation growing in the wake of drift from salt-water cooling towers.

With the above discussion in mind, it was decided to approach the problem of potential effects that salt drift from cooling towers might have on vegetation by way of effects observed in the seashore environment. It was decided to approach the problem in two stages. First, to develop techniques to monitor levels of airborne sea salt occurring under coastal conditions and to observe effects of these levels on plants growing there. Secondly, to develop techniques to reproduce natural salt levels under more controlled experimental conditions and to use these controlled conditions to establish relations between time of exposure, airborne salt concentration, and plant response.

Techniques for airborne salt measurement.—Two techniques for measuring levels of airborne salt were developed; one to collect salt by impingement and the other by sedimentation.

Impingement sampler.—A modification of Blanchard's platinum wire loop (3) was used to determine salt collected by impingement. Monofilament nylon line (250 μm diameter) was strung over a metal frame in order to provide a larger target than the metal loop (Fig. 1). Under field conditions the target was hung from a support 1.52 m (5 ft) above the ground. At the end of each exposure the targets were removed from their supports and placed in wooden boxes with ribbing similar to a slide box. Each box held 10 such targets. The boxes were returned to the laboratory, 100 cm of monofilament line was cut from each rack and rinsed with 5 ml distilled water in a glass chromatography solvent trough. The resulting solution was then analyzed for sodium by flame spectrophotometry. Airborne salt concentrations ($\mu g/m^3$) experienced by each rack were then calculated by $C = Mr/At\bar{u}k$ in which C = air concentration of sea salt; M = mass of sodium collected (μg); r = ratio of sodium to total sea salt weight (3.25); A = exposed area of target (m^2), t = exposure time (min), $\bar{u}$ = average wind velocity during sampling period (m/min), k = collection efficiency (Average = 0.9) (3).

Sedimentation sampler.—Salt deposition on vegetation by droplet and particulate fallout was measured with the technique described (11). The instrument consists of a quieting chamber in which a disposable petri dish is placed to collect the salt. The petri dish was exposed for a known length of time, capped, returned to the laboratory and rinsed with 5 ml of distilled water. By knowing

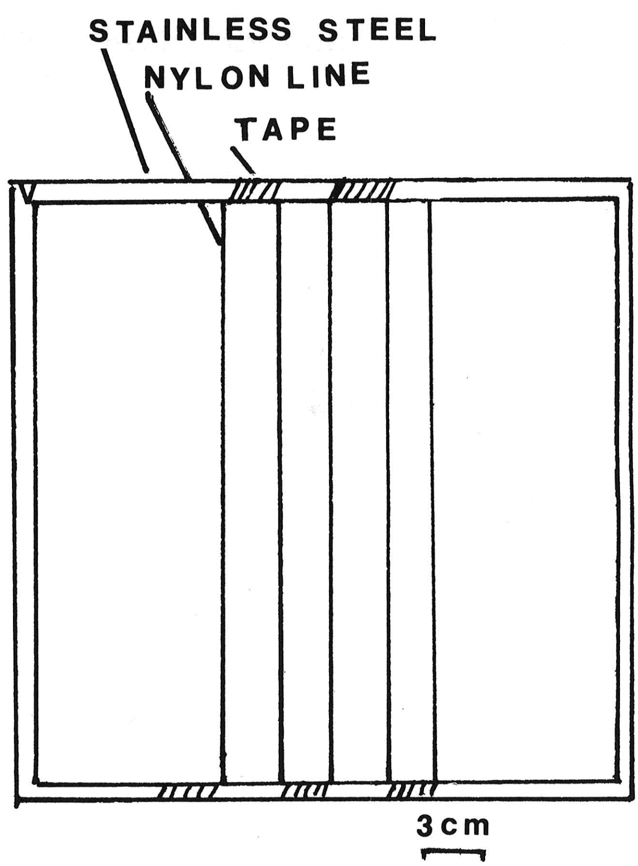

Fig. 1. Rack used to collect airborne salt droplets and particles deposited by impingement.

00031-949X/79000182$03.00/0

Exhibit INT391
June 26, 2012

the area of the petri dish, the time of exposure, and the amount of sodium in the dish it is a simple matter to calculate sedimentation rate of sea salt ($\mu g/m^2/sec$).

Salt impingement measurements and effects on native vegetation.—During the summer of 1971 a number of salt sampling stations were established in conjunction with an ambient salt monitoring program for the Forked River Cooling Tower Project (8). Sampling stations were established at different distances inland from the coast. Impingement samplers were used for this portion of the study and data was collected only when winds were blowing onshore. Exposure time of the targets varied from 0.5 to 5 hr depending on distance inland and salt load in the air. Wind speed was measured with a recording anemometer. Results of these measurements are presented in Fig. 2.

For most of the summer no detrimental effects could be observed on coastal vegetation even though concentrations of airborne salt were relatively high near the coast. However, on 28 and 29 June onshore winds from an offshore weather pattern resulted in heavy surf with salt levels three times higher than any measured during that summer. This high salt deposition resulted in visible salt buildup on exposed vegetation. Within three days of this incident widespread injury was observed on most plant material in a zone up to 375 m from the surf. The injury observed was foliar scorch and shoot tip dieback concentrated on the side facing the surf. Within 3 wk of this high salt occasion, new growth had resumed below the killed tissue and it developed normally in spite of repeated occurrences of salt levels similar to the average concentrations indicated in Fig. 2.

Sedimentation measurements.—Measurements of sedimentation rates of airborne sea salt were confined to the first 600 m inland from the surf line. This was done because visible effects of salt on vegetation were observed within this area and exposure times of samplers at greater distances inland were excessive. Exposure times of 1-2 hr were sufficient near the shore. Sedimentation samplers were placed in the same transect as the first two impingement samplers. Samples were collected only when winds were onshore and in the range of 8.1 to 16.1 km/hr (5 to 10 mph). Results of repeated measurements during the summer of 1972 are presented in Fig. 3 (11). Sedimentation rates were high near the surf and dropped off rapidly with distance inland. This data represents typical sedimentation rates to which coastal vegetation is exposed during onshore summer winds.

Reproduction of ambient conditions in wind tunnels.—Wind tunnel experiments were chosen to reproduce conditions of impingement similar to those experienced in nature. Wind tunnels such as those described in Fig. 4 were constructed on benches in a

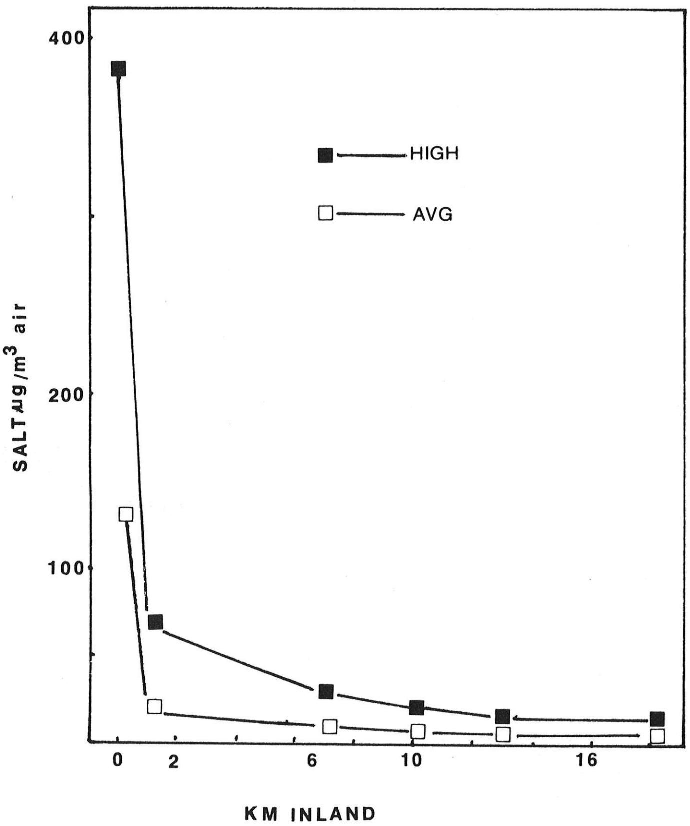

Fig. 2. Airborne sea salt concentration ($\mu g/m^3$) as affected by distance inland from the surf.

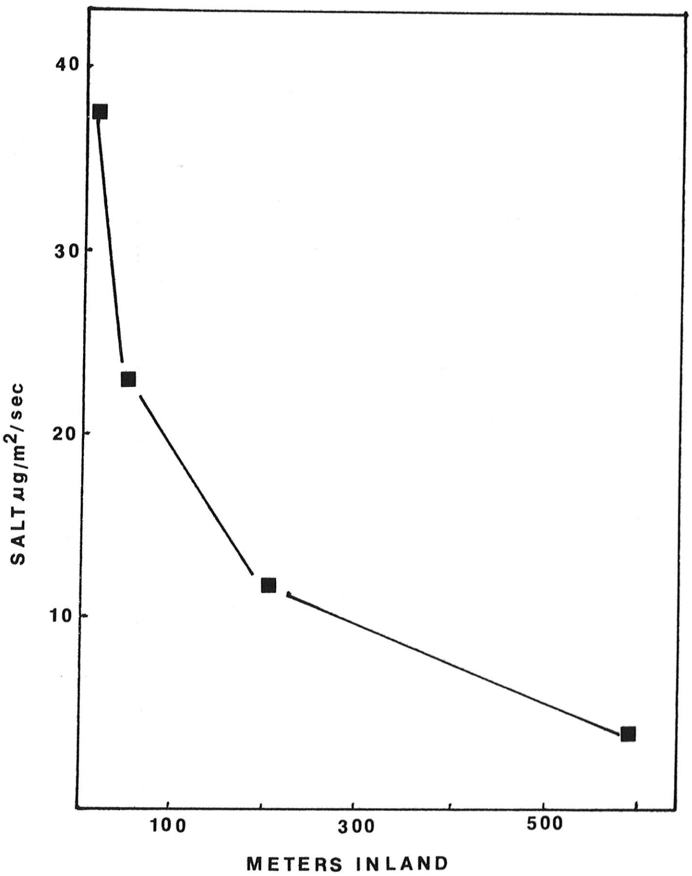

Fig. 3. Sedimentation rates of airborne sea salt as affected by distance inland from the surf.

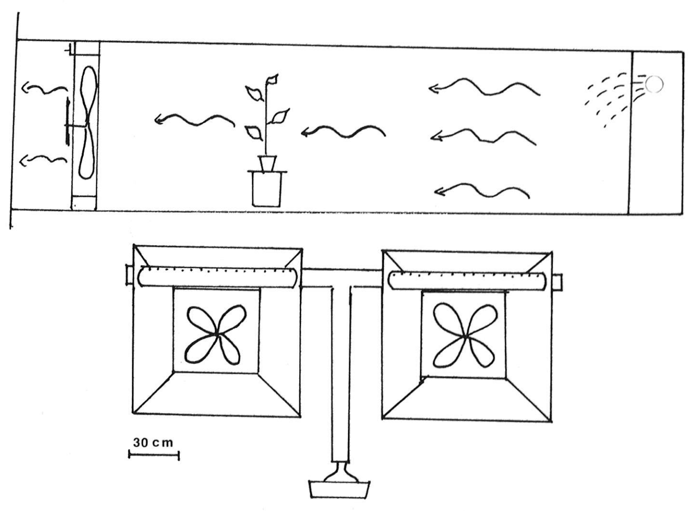

Fig. 4. Wind tunnel designed to conduct controlled airborne salt deposition and impingement experiments.

greenhouse at Rutgers University.

The tunnels consist of 10-m-long frames over which 0.152-mm (6-mil) polyethylene is stretched. One end is open to the greenhouse and the other extends to the outside air. An exhaust fan located at the outside end draws air down the tunnel to create wind conditions. Variable speeds are possible through the use of a direct current motor on the fan. All experiments in this report were conducted under 9.7 km/hr (6 mph) wind conditions. Salt mist from collected sea water is generated at the greenhouse end of the tunnel by means of a spinning-disk humidifier. The mist is blown up the standpipe into a horizontal section of PVC pipe. A series of holes is located at 5-cm intervals across the top of the horizontal section which is sealed at the end by a large rubber stopper. Mist generated within this system forms a cloud within the pipe. Its only escape path is from the holes located in the horizontal section through which it flows. Mist forced from the holes is carried down the tunnel on the wind and blown out the back of the greenhouse. Rates of mist output can be altered by changing the hole sizes in the horizontal pipe. Stratification within the tunnel is minimal. This is probably due to the turbulence created by the slightly undulating sides of the tunnel when it is in operation.

Plants are exposed in the tunnel by placing them in racks located near the exhaust fan end.

Calibration of the tunnels with coastal conditions was achieved by placing an impingement rack in the tunnel at the same location as the test plants. A 1-hr exposure time was used after which targets were inspected both visually and chemically. Visual examinaiton was achieved by scanning one of the monofilament lines under a microscope and observing relative particle size and density. Chemical determination of sodium was achieved as described earlier. The results obtained are compared to similar targets exposed for 1 hr at different distances from the surf.

Figure 5 illustrates results of an expanded calibration run of two tunnels with different rates of mist output. Exposure times for the collection racks ranged from 1 to 48 hr. Results indicated that salt output is linear with time in both tunnels. When 1-hr runs were compared chemically and visually with those under natural conditions, it was found that the salt load and particle size distribution of the high-output tunnel were similar to those observed 50 m from the surf line. The salt load of the low-output tunnel was similar to observations 600 m inland from the surf.

Wind tunnel experiment with beans.—An experiment was run in the tunnels in order to see what effect such salt conditions would have on plants of bean cultivar Contender. Seeds were sown in 10-cm diameter pots and grown until the first trifoliolate leaf was visible. The plants were placed in each tunnel and the system was run for 48 hr. Weather conditions were 75 day and 65 F night temperatures with relative humidities of 60 and 80%, respectively. All plants were rinsed with distilled water and harvested 72 hr after the experiment began. The tissue was oven-dried, ground in a Wiley mill fitted with a 420-μm (40-mesh) screen, extracted with water, and analyzed for sodium and chloride. Extraction was carried out on 100-mg tissue samples. Three extractions (5 ml each) were made for 24, 12, and 8 hr each. Pooled samples were analyzed.

Results of this experiment are presented in Fig. 6. Uptake of both chloride and sodium was proportional to time of exposure to salt drift. Uptake of the salt by plants exposed in the low-output tunnel was minimal and no injury symptoms were observed. However, plants placed in the high-output tunnel showed symptoms of salt toxicity if they were exposed for 12 hr or more. Initial symptoms consisted of wilting of areas on the primary leaves. This was followed in a few days by necrosis of the previously wilted areas and chlorosis of the young trifoliolate leaves. The necrotic and chlorotic symptoms became more severe as time in the high-output tunnel

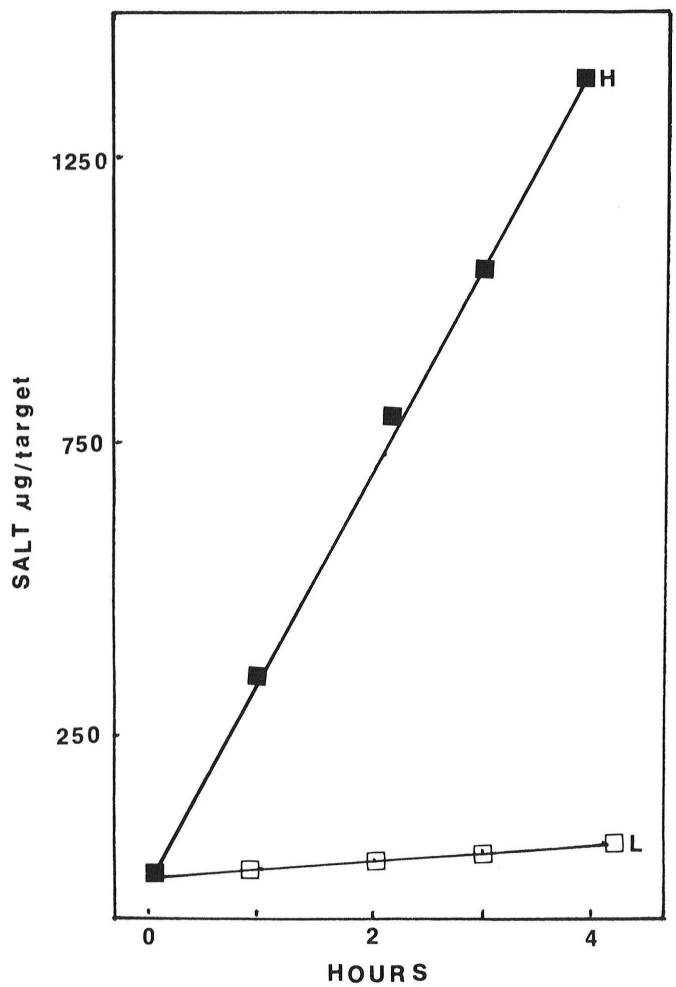

Fig. 5. Calibration run of two wind tunnels designed to reproduce airborne salt deposition and impingement conditions representative of 50 m (high output [H]) and 60 m (low output [L]) from the surf.

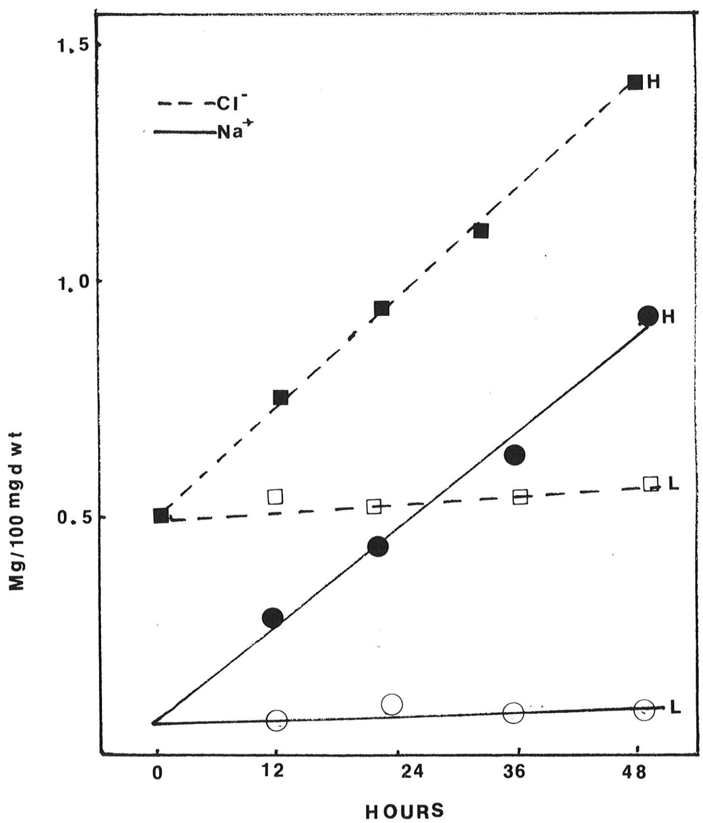

Fig. 6. Effect of exposure time on sodium and chloride concentration of bean leaf tissue. H and L represent high and low output tunnels described in Fig. 5.

increased.

Wind tunnel experiment with pines.—Experiments with white pine (*Pinus strobus* L.) and Japanese black pine (*Pinus thunbergii* P.) were carried out in the high-output wind tunnel. Four-yr-old plants of both species were exposed on 10 July for 48 hr and then removed and grown under greenhouse conditions for 2 mo.

Symptoms of salt toxicity were visible on white pine 20 days after exposure. This consisted of dieback of needle tips on the side of the plant that had faced the drift generator. No symptoms of toxicity were observed on the opposite side of the plant. At the end of 2 mo dieback on the injured side extended over most of the needles. Plants exhibited the characteristic "molded" pattern of growth observed under natural seashore conditions.

Plants of Japanese black pine exposed to the same salt drift and grown under the same conditions as the white pine showed no signs of injury at the end of the experiment.

Reproduction of ambient conditions in sedimentation chambers.—An experimental system that would reproduce conditions of salt fallout similar to those occurring in the absence of wind also was desirable.

Sedimentation chambers such as those described in Fig. 7 were constructed for this purpose (11). The chamber is a wooden frame 1 m square at the base and 1.5 m high. Polyethylene (0.152-mm = 6-mil) is stretched over the frame with a resealable flap for entrance to the chamber. Salt drift is generated by a spinning-disk humidifier positioned below the chamber. Mist is blown up a PVC pipe (9.5 cm diameter) and exits through holes located in the sides of a cap at the top. The particles then settle to the bottom of the chamber. Sedimentation rates are determined by placing petri dishes in the bottom of the chamber for known time intervals and measuring the amount of salt collected. Salt output can be varied by changing the size of the exit holes in the cap. Figure 8 illustrates the effect that exit hole size has on output. Rates of output under these conditions are similar to sedimentation rates near the ocean (Fig. 3). The base of the chamber will accommodate 9 pots of plants during an experimental run.

Salt uptake and relative humidity.—Because of the hygroscopic nature of sea salt particles one might assume that relative humidity could affect rates of salt uptake by leaves. In order to investigate this possibility, bean plants were misted with sea salt and placed in growth chambers maintained at either 60 or 80% relative humidity (10).

Groups of plants were removed at different times, the foliage was rinsed, and the leaf tissue was analyzed for chloride. Effects of these two humidity conditons on salt uptake are illustrated in Fig. 9. Higher levels of chloride were absorbed by plants maintained under high humidity. Uptake of chloride extended over the entire experimental time under high humidity whereas at low humidity uptake occurred only during the first 4 hr. Microscopic examination of leaf surfaces revealed droplets under high humidity and crystals under low humidity.

DISCUSSION AND CONCLUSIONS

The impingement sampler offers a simple technique for determining air concentration and vertical deposition rates under field conditions. It has a relatively high collection efficiency for particles larger than 3 μm (1) and operates isokinetically. Since the target is a series of vertical rods, changes in wind direction during the sampling period do not alter collection efficiency or target size. Field measurements using this technique show that salt

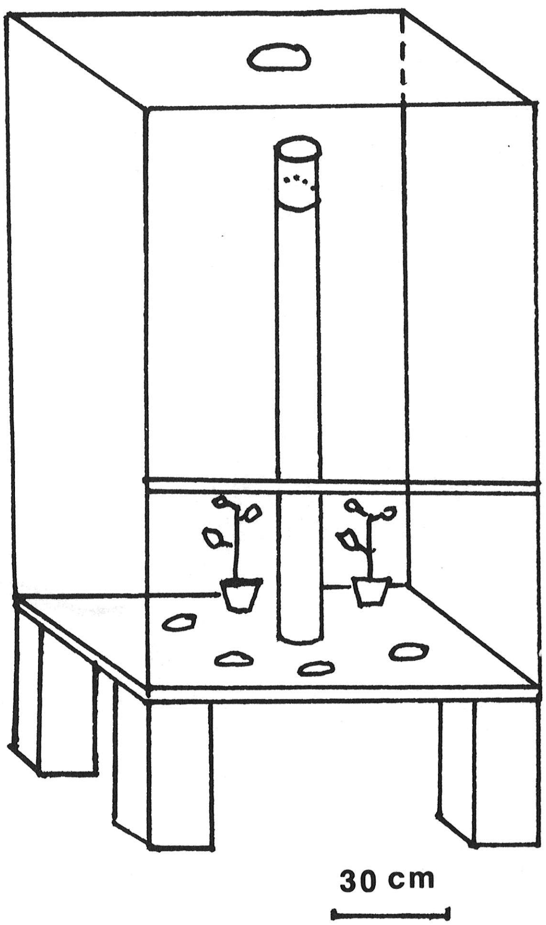

Fig. 7. Sedimentation chamber designed for conducting controlled experiments.

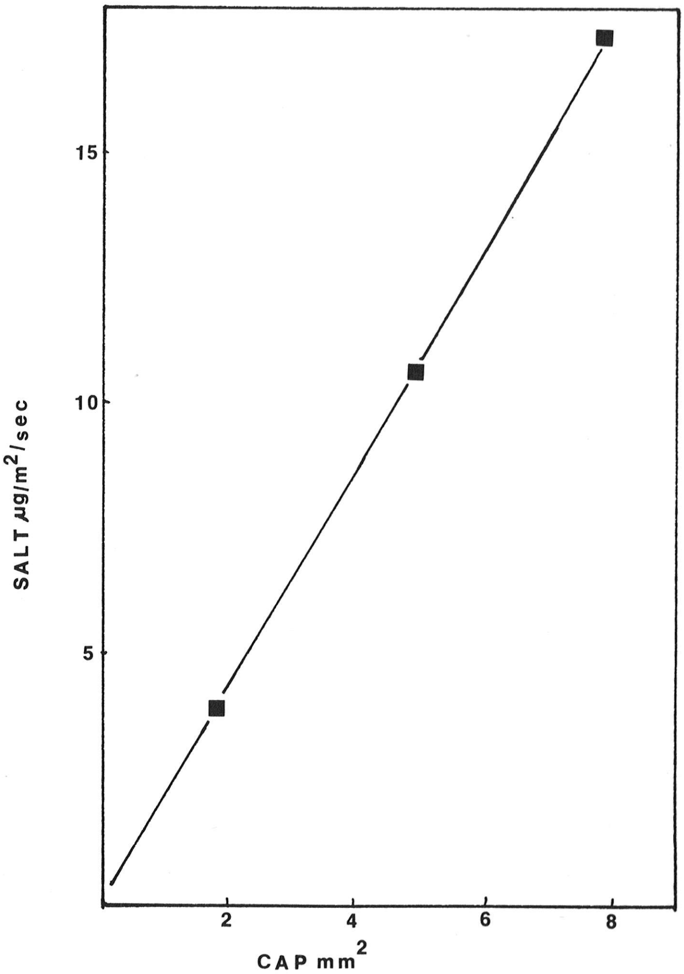

Fig. 8. Effect of column cap aperture on rate of salt output by sedimentation chambers.

concentratin (Fig. 2) and particle size drop off rapidly within the first 600 m inland from the surf. Beyond that there is a more gradual decline in salt load further inland. No observable effects of salt drift on vegetation were noticed at sampling sites beyond 8 km inland.

Native vegetation growing within the first 600 m inland periodically shows typical acute toxicity symptoms of foliar necrosis, shoot tip dieback, and "molded" growth habit. This type of injury seems to be associated with occasional periods of high onshore winds which continue for 24 to 48 hr rather than the typical sea breeze effect (Fig. 2). It appears that native vegetation growing within the first kilometer will tolerate the normal ambient levels, while the occasional short-term exposure to high levels results in acute injury which is readily noticeable. Chronic effects of long-term exposure to the lower levels are not known. This would suggest that since, in nature, it is the occasional high salt level which is most limiting to native plant growth, the same may be true for potential effects of salt drift from cooling towers. For this reason it will be important to know what the highest short-term salt deposition rate and air concentration level will be in addition to long-term levels, when assessing potential effects on vegetation.

Salt will accumulate rapidly on vegetation under windy conditions. This accumulation by impingement may be several times that which accumulates by simple sedimentation. For this reason measurements of air concentration and vertical deposition are as significant as sedimentation measurements when assessing potential effects on vegetation. This is particularly true under windy conditions.

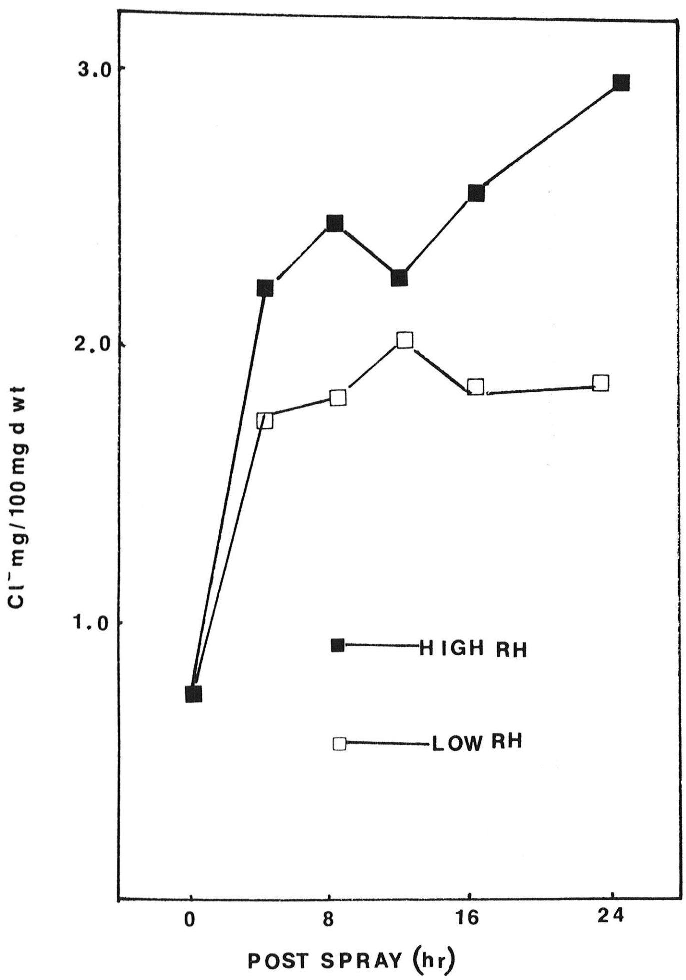

Fig. 9. Effect of relative humidity on chloride uptake into bean plants sprayed with sea salt.

The use of wind tunnels to assess potential effects of airborne salt takes into account the importance of both impingement and sedimentation. The results indicate that it is possible to reproduce various conditions of salt load and wind such as exist in nature near the ocean or potentially near salt-water cooling towers. Because of the control over wind velocity, salt load, and precipitation it is possible to look at effects of salt drift under reproducible conditions. Plants can be grown in the tunnel for some time since adequate light enters through the polyethylene.

The effect of salt drift on beans exposed in tunnels of different salt level indicates relations between salt load, exposure time, and plant response. The results indicate that exposure of bean plants to 100 μg sea salt/m^3 for only 12 hr will result in acute injury whereas exposure to 10 $\mu g/m^3$ for 48 hr has no detrimental effects.

Exposure time and degree of injury can be correlated with both sodium and chloride levels in the tissue (Fig. 6). Thus, both time of exposure and air concentration must be considered when investigating the effects of airborne salt. The results also suggest that it should be possible to establish critical levels of chloride in tissue which will produce various effects in plants. Once this had been established for a given plant, such as Contender bush bean, that plant could be used as a biological monitoring system. By monitoring chloride level in the foliage, one would know if the concentration was approaching a critical level and appropriate measures could then be taken to prevent this.

Experiments with pines in the wind tunnel verify the ability of this system to produce effects on plants similar to those observed in nature. The difference in sensitivity of the two species offers the researcher an opportunity to study reasons for selective tolerance.

Results of sedimentation measurements made near the ocean (Fig. 3) have been used to calibrate the sedimentation chamber technique (Fig. 8). This system will be used to investigate effects of salt fallout independent of the wind vector.

The relative humidity variable is important in evaluating the potential effects of salt drift. Uptake brought about by high humidity conditions (Fig. 9) must be taken into account. Conditions of relative humidity in areas surrounding cooling towers will certainly play a role in potential effects of salt drift.

The above report outlines techniques for making airborne salt measurements, for reproducing given levels of salt under semi-controlled conditions, and for carrying out experiments on plants. With this as a base it is hoped that future work can concentrate on a quantitative approach to salt drift effects on vegetation.

LITERATURE CITED

1. BLANCHARD, D. C. 1964. Sea-to-air transport of surface active material. Science 146:396-397.
2. BLANCHARD, D. C., and A. H. WOODCOCK. 1957. Bubble formation and modification in this sea and its meteorological significance. Tellus 9:145-158.
3. BLANCHARD, D. C., and L. ZYZDAK. 1972. Variations in aitken and giant nuclei in marine air. J. Phys. Oceanogr. 2:225-262.
4. BOYCE, S. G. 1954. The salt spray community. Ecol. Monog. 24:26-67.
5. BUKOVAC, M. J., and S. H. WITTWER. 1957. Absorption and mobility of foliar applied nutrients. Plant Physiol. 32:428-435.
6. HOFSTRA, G., and R. HALL. 1971. Injury on roadside trees: leaf injury on pine and white cedar in relation to foliar levels of sodium and chloride. Can. J. Bot. 49:613-622.
7. LOMAS, J., and F. GAT. 1967. The effect of wind-borne salt in citrus production near the sea in Israel. Agric. Meteorol. 4:415-425.
8. MOSER, B. C., and R. L. SWAIN. 1971. Environmental effects of salt water cooling towers—potential effects of salt drift on vegetation. Report to Jersey Central Power and Light Company. 45 pp.
9. OOSTING, H. J., and W. D. BILLINGS. 1942. Factors effecting vegetational zonation on coastal dunes. Ecology 23:131-142.
10. SWAIN, R. L. 1973. Airborne sea salt: some aspects of the uptake and effects on vegetation. M.S. Thesis, Rutgers University. 140 pp.
11. WILLIAMS, D. J. 1974. Airborne sea salt—some effects on plant growth. Ph.D. Thesis, Rutgers University. 154 pp.