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# Absorption of Radionuclides by Aboveground Plant Parts and Movement within the Plant

**H. B. TUKEY, S. H. WITTWER, and M. J. BUKOVAC**

**Department of Horticulture, Michigan State University, East Lansing, Mich.**

The aboveground parts of plants readily absorb radionuclides from external spray applications. Entry occurs through the leaves, stem, fruit, and bark. The rate of absorption, extent of subsequent transport, and pattern of distribution within the plant is dependent upon the nature of the radionuclide and many internal and external factors. Not only are radionuclides absorbed by aboveground plant parts, but they may be lost therefrom into the external environment from leaching induced by rain and dew. Both acropetal and basipetal transport occur following application of $P^{32}$, $K^{42}$, $Rb^{86}$, and $Cs^{137}$ to aerial plant parts. This is in marked contrast to $Ca^{45}$, $Sr^{89}$, $Sr^{90}$-$Y^{90}$, $Ru^{103}$, and $Ba^{140}$. These latter radionuclides do not move freely from the absorbing aerial organ (leaf, fruit), and basipetal transport is negligible. The hazard exists that fission product radionuclides may be directly incorporated into plant tissues.

THE ROOT is commonly accepted as the principal nutrient-absorbing organ of the plant. However, Mayer (*25*) as early as 1874 demonstrated that ammonia was absorbed directly by the foliage of plants and influenced growth. Sulfur is absorbed as sulfur dioxide (*29*) from the atmosphere by leaf surfaces and is translocated and readily converted to organic forms (*40*).

A few years ago a very simple yet significant experiment was conducted in which bean seedlings were grown to maturity in solution cultures of only distilled water (Figure 1). The sole supply of nutrients for the plants was in solutions applied to the foliage. The life cycle of the bean plant was completed with all mineral nutrients being supplied through the foliage.

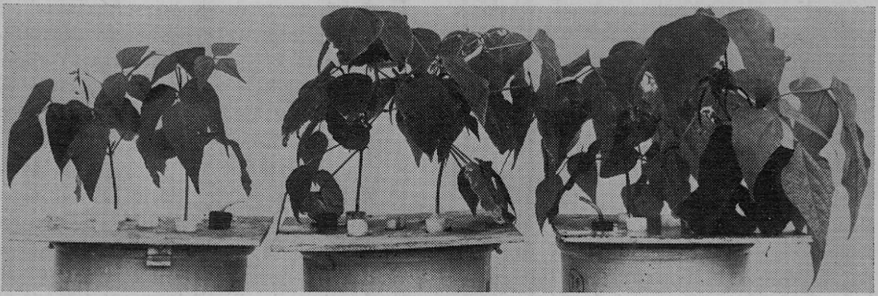

Figure 1. Bean plants grown with mineral nutrients supplied solely by foliar or nonroot feeding, as compared to root feeding

Left. Foliage sprayed weekly with a complete nutrient solution
Center. Sprayed daily with a complete nutrient solution
Right. Plants supplied with a complete nutrient solution (containing 1/10 the concentration of nutrients sprayed on foliage) through roots
Roots of plants in left and center cultures grown in distilled water

Recently, with the use of radioactive isotopes, it has been conclusively demonstrated that not only the leaves but also the bark and even the fruit can absorb nutrients (*42*). Fallout products from a nuclear detonation may be deposited upon the aboveground parts of plants and be absorbed by them, and therefore, it becomes of some concern to determine how and to what degree these contaminate materials may enter a plant, the nature and the amount of movement of these substances within the plant, and the extent to which they may be leached from plants once they are absorbed.

### *The Leaf as an Organ of Absorption*

The cuticle of the leaf is composed of a framework of cutin within which flat platelets of wax are embedded (*23*). The structure has been likened to a rubber sponge of cutin in which the holes are filled with wax. In a heavily cutinized leaf with unbroken cuticle, this layer is not easily penetrated by materials in solution (*45*). In some species of plants a heavy wax is extruded onto the leaf surface which may act as a significant barrier to penetration (*34*).

Such complete barriers to penetration, however, seldom exist in nature. Cracks and imperfections appear in the cuticle. Hydration of the cuticle causes expansion in which the wax platelets are spread apart so that permeability of the cuticle is increased. Hairs and other specialized epidermal cells overlie veins, and there are specialized surface veins in the leaf which are made up of parenchyma tissue with thin-walled cells which extend into the epidermis and provide excellent conduction into the leaf. Cuticular areas have been observed over the anticlinal walls of epidermal cells which are preferentially penetrated by water-soluble substances (*9*). In fact, in very young leaves, cutin may be absent over these areas. The damaging of epidermal hairs by brushing lightly with a soft brush or eroding the leaf surface by rubbing gently with a glass rod markedly increases penetration (*38*).

In addition, Roberts *et al.* (*31*) have shown from microchemical examination of McIntosh apple leaves that there is a relationship of cell wall constituents to penetration of water-soluble materials applied to the leaf surface. Pectinaceous substances are found in intermittent parallel layers in the outer walls of epidermal cells, interspersed with cutinized areas. Such pectinaceous materials form a continuous pathway extending from outside the leaf to the walls of vein extensions and from there directly into the vascular system of the leaf (*52*).

Also, Lambertz (*19*) has recently re-emphasized the importance of plasmodesma. He has found 2 to 200 and 60 to 800 protoplasmic strands per 50 square microns in the walls of epidermal cells. He has concluded that there may be 8000 to 9000 such strands in the outer wall of a single epidermal cell. The number increased to maximum during the day, and decreased at night. The number increased during the development of a young leaf until a maximum was reached in vigorous bright green leaves, and declined in number as the leaf yellowed. It appears that these strands of protoplasm end directly under the cuticle. Lambertz could not be certain that the cuticle did not plug some or all of these pore-like openings. Nevertheless, from general observation he ventured the opinion that they must be open.

Although an organized transport system capable of rapid conduction of materials into the leaf may not always be present, the leaf is structurally well equipped to absorb materials through both the upper and lower surfaces. Wittwer and Teubner (*50*) have recognized what they term both intercuticular passage and intracuticular penetration.

In addition, the leaf area of a plant is considerable. Thus, a 12-year-old apple tree provides in its foliage, both upper and lower surfaces, an area of one tenth of an acre or approximately 10 times the spread of the branches of the tree (*41*). The leaf areas of plants in many sugar cane and pineapple plantations are sufficient in that the fertilizer needs can be completely supplied to these crops by foliar applications through the growing season.

### Absorption by Aboveground Parts Other Than Leaves

Entry of mineral nutrients through the bark of dormant deciduous trees occurred when cotton gauze saturated with solutions of radiopotassium or radiophosphorus was wrapped around tree branches (*41*). Radioactivity was detected in both the phloem and xylem stem tissues 18 inches above and below the point of application within 24 hours. This entry of nutrients through the bark and transport through the branches occurred during February and March even with temperatures below freezing. Similar applications made just as the buds were commencing to swell showed the material to move in through the bark and up the branches, to concentrate near the buds available for the flush of new growth. Entry was largely through leaf scars, cracks, lenticels, and longitudinal bark fissures. Rapid entry in the spring was associated with growth cracks that accompanied expansion of new tissues (*13*).

### Factors Affecting Entry of Radionuclides into Aboveground Parts

It may be anticipated that foliar absorption of radionuclides will be affected by external and internal factors. Temperature, light, the pH and the carrier of the treating solutions, and various additive chemicals, such as surfactants, may be important, as well as the species of plant involved, the morphological nature of the absorbing organ, and the nutritional status of the plant (*8*, *39*).

**Effect of pH and Ionic Carrier.** Rapidity of uptake of phosphorus through the leaves of the bean (*Phaseolus vulgaris*) has been studied with three carriers (*39*). The hydrogens of orthophosphoric acid were replaced by adjusting the pH of the treating solutions with the hydroxides of ammonium, sodium, or potassium. All phosphate salts were absorbed less effectively than orthophosphoric acid to which only a slight amount of ammonium, sodium, or potassium had been added (pH 2 to 3). The slowest penetration through the leaf was with monopotassium phosphate (pH 4 to 5). A mixture of the monosubstituted phosphates and orthophosphoric acid (pH 2 to 3) resulted in two- to tenfold increases in uptake through bean leaves as compared with other inorganic phosphates.

The effects of pH and ionic carrier on absorption of radiopotassium and radiorubidium by bean and tomato leaves were in marked contrast to those for radiophosphorus (*39*). Phosphate, citrate, and chloride were the accompanying anions, with pH levels of 2, 4, and 8. The absorption of rubidium was accelerated 10 to 20 times at a pH of 8, compared with a pH of 4 when phosphate was the carrier. In general for rubidium, both chlorides and citrates were less effective than phosphates. However, at similar pH levels and with the same carriers, potassium uptake when applied as the citrate at pH 8 was twice that of any other form.

**Effect of Surfactants, Solubility, Hygroscopicity, and Surface Moisture.** Leaf absorption of radionuclides may often be facilitated by the addition of a wetting agent to the formulation. Currier and Dybing (*9*) have reported an instance of a fourteenfold increase in foliar uptake of some herbicides when a surfactant was added. Certain detergents, however, will reduce the speed with which phosphorus is absorbed. Swanson and Whitney (*38*) have reported the formation of small necrotic areas on bean leaves from applications of phosphoric acid with a pH less than 3.0, resulting in greatly increased uptake. Barinov and Ratner (*1*) have shown that $H_3PO_4$ at a concentration of $0.1M$ altered the cutin and destroyed the protoplasm in epidermal cells so that materials entered the leaf more rapidly. At low concentrations ($0.066M$), where there was no injury to the leaf, entry was slower than for other phosphates.

Barinov and Ratner (*1*) have reported a latent phase of about 24 hours in the uptake of mineral substances through the leaves. They found the duration dependent on the solubility and the hygroscopic qualities of the applied materials, the pH, and the selective character of cellular protoplasm in relation to absorption of ions. Thus with solutions of $Ca^{45}Cl_2$, the latent period lasted 4 to 6 hours from the time of application, followed by rapid uptake of 56% in 24 hours and 84% in 72 hours. On the other hand, with $Na_2HPO_4$ the latent period was 24 hours, followed by only 2.8% uptake during the next 24-hour period, and 10% for the third 24-hour period. The latent period was longer for plants with a heavy cuticle. Soluble and hygroscopic salts had a shorter latent period and a more rapid uptake than less soluble and less hygroscopic materials. The latent period was not present when the leaf was rubbed lightly with a glass rod. Repeated drying and wetting of the leaf and of the applied material also favored uptake.

The presence of surface moisture has a significant effect upon the foliar absorption of phosphorus (Table I). Approximately twice as much $P^{32}$ was absorbed from a $20mM$ solution of $H_3P^{32}O_4$ placed on a bean leaf when the surface was kept moist as when it was allowed to dry. Absorption of $P^{32}$ was also increased by intermittent wetting of the treated area with distilled water (Table I). Phosphate absorption continued from the dry residue for several days after evaporation of the solvent, although the treating solution dried within a few minutes.

**Effect of Leaf Age and Portion Treated.** Young and rapidly expanding leaves are more efficient in absorption than are fully matured leaves, although all functional green leaves seem to serve as organs of absorption. Both sides of the leaf blade function in absorption. Approximately 50% more $P^{32}$ was absorbed through the upper surface of the bean leaf than the lower surface although the lower surface contains seven times (*12*) more stomata than the upper surface. Thus, it appears that phosphate entry is not facilitated by stomatal openings. Placement of the treating solution on the upper leaf surface at the tip, along the outer margin, and in the center along the mid-rib, gave only a slight increase in absorption when compared to similar positions on the under side of the leaf. On the other hand, application to the petiole resulted in very rapid uptake. However, the treating site on the leaf surface was of no importance in determining the final level of radiophosphorus which had accumulated in the roots 12 hours later.

**Table I. Effect of Presence of Surface Moisture on Foliar Absorption of $P^{32}$-Labeled Orthophosphoric Acid (*17*)**

| *Moisture Conditions at Site of Treatment* | *Per Cent Absorbed* | |
|---|---|---|
| | *Test I* | *Test II* |
| Kept moist | 43.1 | 35.0 |
| Moistened every 1.5 hours | . . . | 26.2 |
| Moistened every 3 hours | 27.6 | 23.2 |
| Moistened every 6 hours | 22.8 | 21.9 |
| Allowed to dry after initial treatment | 23.5 | 17.8 |
| Least significant difference at: | | |
| 5% | 9.0 | 11.5 |
| 1% | 11.0 | 13.9 |

**Summary of Factors Affecting Foliar Uptake.** A number of the factors known to influence foliar absorption, as illustrated by radiophosphorus, have been summarized by Wittwer and Bukovac (*49*) and are presented in Table II. The effects of pH and cation carrier when considered in the light of the ionic species and the degree of molecular dissociation which occurs particularly with phosphate, suggest an exchange mechanism in the entry of foliar-applied radionuclides. That absorption is active rather than passive would seem to follow from the positive effects of temperature, light, and sucrose. Diffusion as well as active absorption through the cuticle, and thence to the epidermal plasmodesmata proposed by Lambertz (*19*) provide most probable pathways for entrance through leaf surfaces.

**Effect of Foliar-Absorbed Nutrients upon Root Absorption.** Foliar applications not only add materials to the plant but may also influence root uptake from the soil. The increase in root absorption that often results from foliar applications of nutrients may come about by an increase of as much as 70 to 80% soluble sugars in the roots, and by greater root growth (*35*). Shereverya (*35*) concludes from his studies that, since roots utilize food and respire at the expense of photosynthetic products, therefore growth, absorbing surfaces, and absorption of mineral substances will all increase proportionately with intensity of photosynthesis.

**Table II. Summary of Factors Affecting Foliar Absorption of Phosphorus (*49*)**

| *Variable* | *Comments* |
|---|---|
| I. Treating Solution | |
| pH | Maximum absorption at pH 2.0–3.0 dependent upon cation |
| Carrier ion | Greater absorption with $NH_4$ than Na or K |
| Surfactants | No effect on absorption in plants easily wetted•<br>Facilitates absorption on difficult to wet plants |
| Sucrose | Depresses uptake for short periods (3–12 hours) in light and enhances absorption over long periods (>24 hours) in dark |
| Concentration | Greater total uptake with increase in concn. of applied soln., but reduced percentage absorbed of that applied |
| II. External Environment | |
| Temperature | Increases with temp. increase from 50°–70° F. At low temp., absorption is more effective through foliage than through roots |
| Light | Greater absorption in light than dark |
| Humidity | Increase in humidity results in increase in absorption |
| Time of day | Greater absorption obsd. during morning than evening hours |
| Nutritional status of plant | High levels in root media depressed foliar absorption |
| III. Leaf and Plant Characteristics | |
| Stomata | Absorption not related to no. of stomata on leaf surface |
| Site of application | Greatest absorption when applied to upper surface at base or on mid-rib of leaf blade<br>Absorption greater through upper than lower surface |
| Age of leaf | Absorption rates reduced with age |
| Presence of surface moisture | Greatly facilitates foliar absorption |
| State of plant development | Maximum benefits derived from applications during flower bud development and anthesis |

## *Leaching of Radionuclides from Aboveground Plant Parts*

If plants can absorb nutrients through aboveground parts, they may be able also to lose them through these same parts (*43*). As early as 1805, de Saussure (*10*) noted that water in contact with leaves contained alkaline salts. Many reports appeared sporadically in the literature suggesting that materials are leached from leaves by rainfall. This hypothesis has been subjected to experimental evaluation and confirmed, by allowing plants to absorb isotopically-labeled nuclides through their roots and then exposing them to simulated rainfall (foliar leaching) from a mist atomizer in a propagation chamber. The mist spray, after passing over the leaf for various intervals up to 24 hours, was collected in a funnel and channelled through an anion-cation exchange resin column which adsorbed the leached plant constituents (Figure 2). The leachate was eluted from the resin columns, variously precipitated, and analyzed for radioactivity. The following radioisotopes were included in the studies: $Na^{22}$, $Mg^{28}$, $P^{32}$, $S^{35}$, $Cl^{36}$, $K^{42}$, $Mn^{54}$, $Fe^{55-59}$, $Zn^{65}$, and $Sr^{90}$-$Y^{90}$.

**Leaching Losses from Leaves.** Losses were dependent upon the nature of the plant employed, the physiological age and the nutrient level, and the nature of the material leached. For example, young leaves of squash (*Cucurbita pepo*), bean (*Phaseolus vulgaris*), and corn (*Zea mays*) lost more of the root-absorbed $Ca^{45}$, $K^{42}$, and $P^{32}$ (3 to 4%) than did leaves of tomato (*Lycopersicon esculentum*) and sugar beet (*Beta vulgaris*) (0.8 to 1.5%). Older leaves lost as much as 75% of the previously root-absorbed potassium in 2 hours. Loss was a direct function of time. With leaves still attached to the mother plant, losses eventually reached several times the amount of nutrients originally found in the leaves, indicating a replenishment mechanism within the plant.

The relative ease of leachability of several isotopes has been reported (*43*). Leached materials which were permitted to return to another nutritive medium were taken up by other plants growing in that medium. Comparisons of greenhouse-grown and field-grown crops show a higher salt concentration in the leaves of the former, which have not been exposed to the natural leaching actions of rain and dews (*43*).

In other experiments Long *et al.* (*20*) applied radiopotassium and radiorubidium to the roots of bean plants. The leaves were then leached for 4 hours. More potassium than rubidium was lost by the plants—namely, 70% $K^{42}$ and 14% $Rb^{86}$. The greatest leaching losses occurred from plants grown at a high nutrient intensity and leached in the dark.

**Leaching Losses from Fruit.** The fact that materials can be leached from leaves suggests that perhaps they can also be leached from fruit, especially from fleshy fruits, such as the strawberry (*Fragaria spp.*). To test this hypothesis, 0.02 ml. of $Sr^{90}$-$Y^{90}$ (10 $\mu$c./ml.) were placed on the peduncles of strawberry fruits in four stages of maturity, ranging from the immature to the very mature. After 2 days the fruits were detached from the plant and soaked in distilled water for 24 hours. The peduncles were not in contact with the water. At various intervals the water was replaced by fresh water and analyzed for radioactivity. Losses of carbohydrates from other fruits in similar stages of maturity by the same leaching procedure were also determined (*43*). Losses of approximately 75% of the previously applied radiostrontium occurred regardless of the stage of fruit maturity.

In contrast, losses of carbohydrates were least from immature fruit and greatest from very mature fruit. From green, immature fruits, only 4 mg. of carbohydrates, or 1.7% of the dry weight, were leached, whereas from fully ripe fruits the loss was 84 mg. or 6.0% of the dry weight. During the first 7 hours of leaching, losses of carbohydrates from mature fruit were relatively small, but steady, at the rate of about 1 mg. per hour. For the next 17 hours, losses increased progressively until they reached 7 mg. per hour during the final 2 hours of the experiment.

### *Comparative Distribution of Radionuclides Following Applications to Roots and Leaves*

Observations on the comparative distribution within the plant of radionuclides other than products of nuclear fission following application to roots and to leaves are useful in a consideration of the behavior of fission products. $P^{32}$ and $Ca^{45}$ are of interest in this connection.

**Comparative Uptake and Distribution of $P^{35}$ and $Ca^{45}$.** The highly mobile elements nitrogen (*47*), phosphorus, potassium, and rubidium (*5*) applied to aerial plant parts are readily translocated, both acropetally and basipetally, at a rate comparable to that which follows root absorption. Barinov and Ratner (*1*) have shown that the movement of phosphorus from the leaf into the rest of the plant is dependent in part upon the physiology of the plant. The presence of potassium in the solution aided in the outflow from the leaves of tomato, and the ammonium ion aided outflow in lettuce. A reduction in temperature from 26.3° to 11.3° C. markedly reduced the movement of materials out of the leaf into the rest of the plant.

Phosphorus accumulates rapidly in growing meristematic regions (*44*) such as root tips, vegetative growing points, flowers, fruits, seeds, and even embryos within seeds. In fact up to 95% of the phosphorus applied to tomato (*Lycopersicon esculentum*) foliage may be utilized by the plant (*44*). When $P^{32}$-labeled phosphoric acid was applied to the soil in a band in the root area, and this method of placement compared with applications to the aboveground parts during early flowering, the foliar treatments were far more effective per microgram of applied phosphorus as measured by that which accumulated in the developing tomato fruits (Table III). With the bean, the foliar applications were more than 25 times as efficient as

**Table III. Comparative Accumulation of Phosphorus in Developing Fruit of Bean and Tomato from Applications of Orthophosphoric Acid Containing $P^{32}$ (*44*)**

| *Part Treated* | *Phosphorus Accumulated in Developing Fruit*<br>*Micrograms* | *% of total* | *% of applied* |
|---|---|---|---|
| | BEAN | | |
| Foliage | 91 | 1.10 | 6.98 |
| Roots | 36 | 0.38 | 0.27 |
| | TOMATO | | |
| Foliage | 33 | 0.40 | 1.23 |
| Roots | 24 | 0.27 | 0.18 |

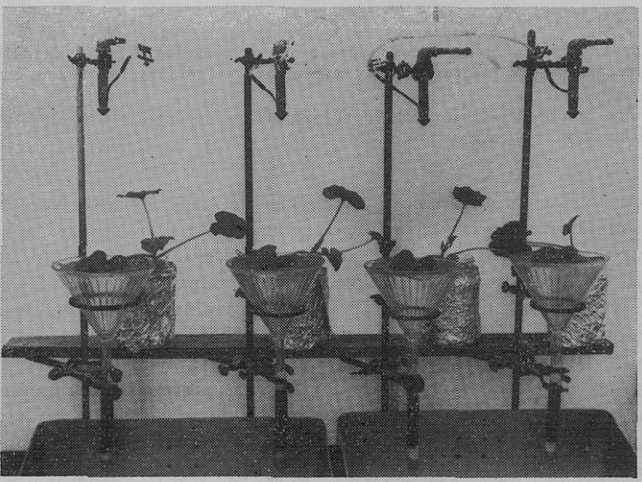

Figure 2. Method of leaching root-absorbed nutrients from young leaves by misting with a water spray

**Top.** Atomizing nozzles with water lines and air lines
**Center.** Plants in nutrient culture
**Bottom.** Collecting funnels and column of anion-cation exchange resins (*43*).

**Table IV. Transport of $P^{32}$ and $Ca^{45}$ across Graft Unions of Apices of Forced Lateral Shoots from Two Tomato Plants (*Lycopersicon esculentum*) (*4*)**

| | *Days after Treating* | | | | | |
|---|---|---|---|---|---|---|
| | *$P^{32}$, C.P.M.* | | | *$Ca^{45}$, C.P.M.* | | |
| *Plant Part Analyzed* | *6* | *12* | *Means* | *6* | *12* | *Means* |
| 5-cm. segment of lateral of treated plant | 682 | 1,462 | 1,072 | 4,012 | 12,659 | 8,336 |
| 5-cm. segment containing graft union | 470 | 1,075 | 772 | 669 | 2,929 | 1,799 |
| 5-cm. segment of lateral of nontreated plant | 302 | 609 | 456 | 58 | 34 | 46 |
| Fruit of nontreated plant | . . . | 129 | . . . | . . . | 0 | . . . |
| Least significance difference at: | | | | | | |
| 5% | | | 375 | | | 2,611 |
| 1% | | | 519 | | | 3,611 |

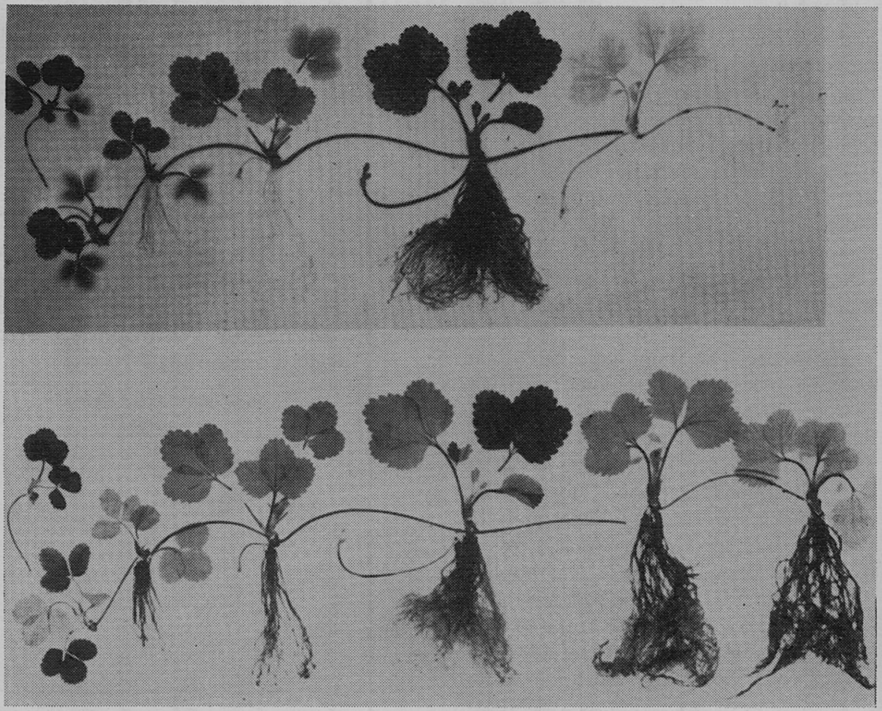

Figure 3. Distribution of $Ca^{45}$ from a root application to second runner plant of strawberry

Upper. Autoradiogram of entire runner series showing translocation of $Ca^{45}$ from roots of treated plant (center) back towards the first runner and parent plant (far right) and out to younger runners (left)

Lower. Photograph of entire strawberry plant from which autoradiogram was prepared Dark leaves had upper surface exposed (*28*)

those applied to the root medium, in terms of phosphate uptake based on the percentage applied.

In contrast to the free movement of phosphorus within the plant and its efficient absorption by aerial plant parts, calcium, strontium-yttrium, barium, and ruthenium do not move freely from the absorbing organ, and basipetal transport is negligible (*6*, *14*). Downes (*11*) found slight downward (basipetal) translocation of $Ca^{45}$ from the leaves to the roots of the onion (*Allium cepa*), but Norton (*28*), working with the strawberry (*Fragaria spp.*), found little or no movement from treated leaves. Following application to the roots of the mother plant, active upward transport of $Ca^{45}$ occurred. Lateral movement then followed into the stolons and aerial parts of daughter plants. The almost complete absence of basipetal transport, however, into the roots of daughter plants was striking (Figure 3). Obviously, as revealed by the radioisotope technique, the roots of the runner plants must depend upon their own absorption for a source of calcium.

The peanut (*Arachis hypogaea*) plant has provided another example of limited calcium movement. Bledsoe *et al.* (*3*) demonstrated that a calcium supply is necessary in the pegging zone for normal fruit development. Studies with $Ca^{45}$ showed that the calcium absorbed by the plant roots is not translocated to developing fruits once they are established in the ground, and that the fruit must thereafter depend upon securing its own supply of calcium from the soil.

**Movement of $P^{32}$ and $Ca^{45}$ Across a Graft Union Involving Reversed Polarity.** Different compounds may move within the plant through different tissues. Inorganic compounds are commonly thought of as moving in the xylem, whereas many organic compounds, especially carbohydrates, move in the phloem. Simultaneous movement of $P^{32}$ and $C^{14}$ in opposite directions within the phloem has been reported by Chen (*7*).

To study further the movement of different nuclides, observations have been made on the transfer of $P^{32}$ and $Ca^{45}$ across a graft union involving reversed polarity. Bukovac *et al.* (*4*) forced the lateral shoots from young tomato plants. They then grafted shoots together terminally from each of two plants so that the polarities of the two portions were in reverse position to each other. To one plant of a grafted combination $P^{32}$ was applied through the roots by addition to one of the plants in the grafted combination in the soil medium. To other combinations $Ca^{45}$ was similarly applied to one of the plants. Assays were then made at various hourly and daily intervals of the following portions of the plants: a 5-cm. stem section of the treated plant immediately adjacent to the graft union, a 5-cm. section through the graft union, and a 5-cm. stem section of the nontreated plant immediately adjacent to the graft union.

The results, shown in Table IV, indicate an interesting difference in behavior between $P^{32}$ and $Ca^{45}$. Thus, 6 days after treatment, twice as much $P^{32}$ was found on the treated side of the graft union as on the nontreated side. While the accumulation of $P^{32}$ was progressively greater on the treated side of the union after 12 days, there was, nevertheless, apparent movement of $P^{32}$ across the union into the nontreated plant.

On the other hand, $Ca^{45}$ was effectively blocked by the reversed graft union. Thus, even after 12 days, the amount on the nontreated side of the union was very small—perhaps within the range of experimental error—while there was considerable accumulation of $Ca^{45}$ on the treated side. In graft unions which did not involve a reversal of polarity, acropetal transport of calcium was not impeded.

The nonpolar or downward transport of $Ca^{45}$ has been induced in the bean plant with mild anesthetization with diethyl ether (*6*). Similarly transport of both calcium and iron in tomato, peach, and apple apparently followed foliar sprays of 2,3,5-triiodobenzoic acid and maleic hydrazide (*18*).

### Uptake of Fission Products by Aboveground Plant Parts

**Comparative Absorption and Transition of $Sr^{90}$, $Ca^{45}$, and $Ba^{140}$ in Tomato, Beet, and Bean Plants.** Of the several products of nuclear fission (*32*) following an atomic blast, strontium is present in relatively large amounts, and is readily taken up by plants from contaminated soil (*15*, *21*, *22*, *36*). Strontium toxicity symptoms have been reported by Long *et al.* (*21*, *22*) on corn (*Zea Mays*), radish (*Raphanus sativus*), and bean (*Phaseolus vulgaris*) plants grown in soil which had been collected in proximity to such a blast. At the same time, Biddulph and Cory (*2*) in studying injury to *Portulaca oleracea* growing at the site of a blast, found a striking inverse relation between total calcium content and fission product radioactivity. They concluded that the injury which they observed was due to disruption of the calcium absorption mechanism of the plant. Spinks *et al.* (*37*) have reported 1.4 $\mu$c. of $Sr^{90}$-$Y^{90}$ and $P^{32}$ per seed as a lethal dosage for wheat, barley, and sunflower. Accordingly, it may be that the injury to plants from fission products may result from either the intensity of radiation or from the chemical nature of the fission compounds *per se* which interfere or compete with the absorption of elements essential for plant growth.

Martin (*24*) in a series of experiments studied the absorption and translocation

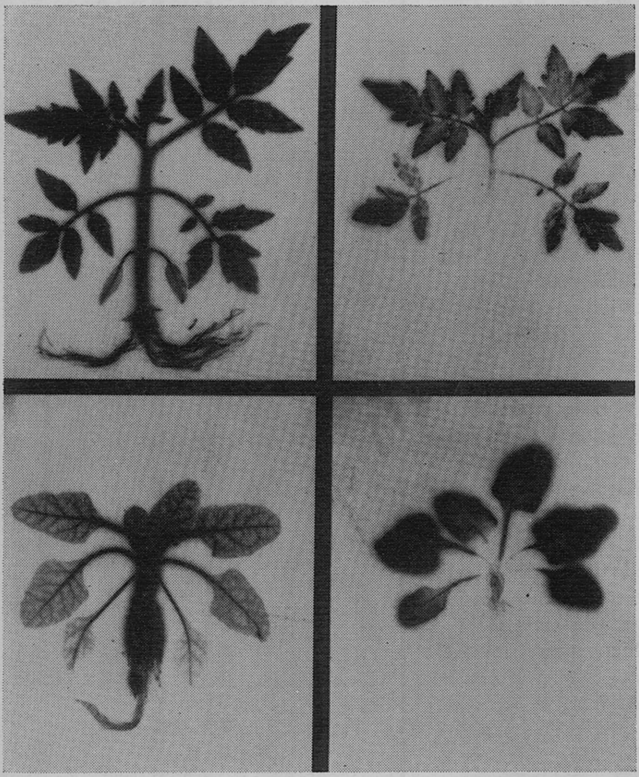

Figure 4. Autoradiograms of tomato (top) and beet (bottom) plants harvested 96 hours after treatment with $Sr^{89}Cl_2$

Left. $Sr^{89}$ applied to roots
Right. $Sr^{89}$ applied to leaves
Note absence of basipetal transport (*24*)

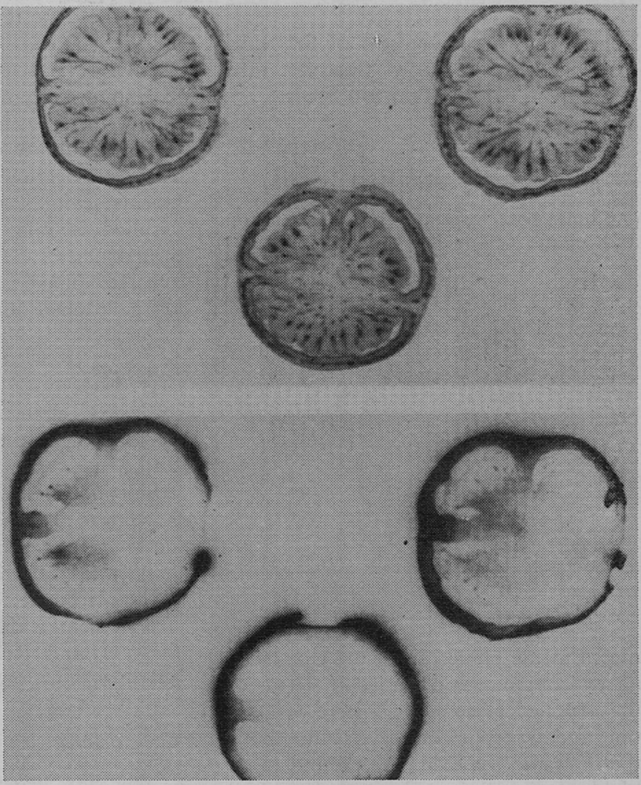

Figure 5. Distribution of $Sr^{90}$ in tomato fruit 36 hours after application to surface of intact epidermis

Top. Autoradiograms of fruit cross sections
Bottom. Photographs of same sections
Actual fruit diameter 7 to 8 cm. (*24*)

of radiostrontium, radiocalcium, and radiobarium when applied both to roots and to aboveground parts of tomato (*Lycopersicon esculentum*), beet (*Beta vulgaris*), and bean (*Phaseolus vulgaris*) plants. In agreement with other reports (*2*, *15*, *21*, *22*, *27*, *32*) all these were absorbed by plant roots and translocated to the aboveground parts (Figure 4). The upward transport of strontium was found to be greater than that of barium, but both elements tended to accumulate in the vascular tissue (*24*). Tomato fruits accumulated relatively little strontium. This was probably associated with low calcium requirements of tomato fruits.

Generally, Martin (*24*) found that absorption of strontium was proportional to its concentration in the nutrient solution. Accumulation in tomato and beet tissues was almost equivalent to the normal calcium content. Such high concentrations, however, produced typical symptoms of strontium injury and were toxic to all three plant species. Beets accumulated more strontium in the tops than beans and tomatoes, and were less sensitive to strontium toxicity. When the applied strontium was chelated with (ethylenedinitrilo)tetraacetic acid (EDTA), absorption was greater in tomato plants low in calcium.

In contrast to the free movement upward and the high accumulation of strontium from a root application, the movement of strontium from the site of a foliage or fruit application was either very slight or completely lacking (Figures 4, 5). Tomato fruits which were 6 to 7 cm. in diameter were painted with a solution of $Sr^{90}$-$Y^{90}$–labeled strontium chloride. Each fruit received approximately 0.25 $\mu$c. After 36 hours, the fruits were harvested, peeled, cut into thin sections, dried, and placed on x-ray film for 7 days. The resulting autoradiograms showed absorption of radiostrontium through the skin of the fruit (Figure 5) in considerable amount, but without accumulation in any particular tissue. No transport out of the fruit into other tissues was detected.

Bean (*Phaseolus vulgaris*) and beet (*Beta vulgaris*) plants showed a somewhat greater downward movement of $Sr^{90}$-$Y^{90}$ than did tomato (*Lycopersicon esculentum*) plants, but in neither was the amount more than a trace of that applied. Chelation of strontium with EDTA did not increase translocation away from treated tomato leaves and fruits.

These findings are in agreement with results reported by Rediske and Selders (*30*), who exposed bean roots to solutions containing radiostrontium for a period of time and then withdrew the strontium supply. They found that once strontium had been deposited in a tissue, such as a leaf, there was no significant redistribution even when a comparatively high concentration gradient occurred.

Although the discussion concerning strontium in this paper is largely from the point of a contaminant, strontium has been shown by Vlamis and Jenny (*46*) to alleviate a calcium deficiency disease of Romain lettuce (*Lactuca sativa* var. *longifolia*) perhaps by partial substitution for calcium. And a peculiar chlorosis of Red Elberta peach trees (*Prunus persica*) in New Jersey, which failed to respond to several common nutrient elements applied to either soil or foliage, was reported by Wolf and Cesare (*51*) to be completely corrected within 2 weeks following applications of strontium chloride.

**Effect of pH and Fruit Development on Accumulation of $Sr^{89}$, $Sr^{90}$-$Y^{90}$, and $Ru^{103}$ in Tomato Fruits.** Johns (*16*) applied sprays of $Sr^{89}$ (0.5 $\mu$c per ml.) at three different levels of pH to the entire aboveground parts of fruiting tomato plants. Applications were made to one lot of plants shortly after the fruits had set (1 to 2 cm. in diameter), and to another lot of plants when the fruits were 5 to 8 cm. in diameter, but still green.

On the basis of the total radioactive contaminant sprayed onto the plants, and the amount recovered in the flesh and seeds of the tomato fruits after re-

**Table V. Incorporation of $Sr^{89}$ and $Ru^{103}$ from Foliage Sprays into Developing Tomato Fruit**

(As influenced by pH of treating solution and maturity of fruit when treated)

| | *Fruit Size, Cm.* | | |
|---|---|---|---|
| | *1–2* | *5–8* | |
| *pH* | *Radioactivity, %* | | *Mean* |
| | $Sr^{90}$ | | |
| 2.0 | 4.0 | 3.0 | 3.5 |
| 4.0 | 1.0 | 4.0 | 2.5 |
| 6.0 | 2.6 | 3.0 | 3.0 |
| Mean | 2.5 | 3.4 | 3.0 |
| | $Ru^{103}$ | | |
| 2.0 | 2.3 | 0.9 | 1.6 |
| 4.0 | 1.3 | 0.2 | 0.8 |
| 6.0 | 1.0 | 0.2 | 0.6 |
| Mean | 1.5 | 0.4 | 1.0 |

moval of the epidermis of the ripe fruit, an expression was obtained in terms of that applied as to the per cent absorption and transport into the fruit. Both the flesh and the seeds were found to be highly radioactive, and as much as 1 to 4% of the total radioactivity sprayed onto the plants was recovered in the developing fruits (Table V). The pH of the radiostrontium sprays did not influence accumulation in the fruit (Table V). Also, radiostrontium accumulated both in fruits approaching maturity and fruits in the initial stages of growth.

Similar results were obtained with radioruthenium ($Ru^{103}$), however with less recovery in the mature fruit (Table V). Although both $Sr^{89}$ and $Ru^{103}$ show little mobility within the plant or basipetal transport, they are absorbed directly by tomato fruits and accumulate in considerable quantities in the edible portions of the fruit following foliar applications. Thus, a potential food contamination hazard exists in the direct absorption by fruit crops of the constituents of atomic fallout.

**Absorption and Distribution of $Sr^{89}$ and $Cs^{137}$ in Several Food Crops.** Middleton (*26*) has pointed out that of the long-lived fission products, $Sr^{89}$, $Sr^{90}$-$Y^{90}$, and $Cs^{137}$, are considered to present the major hazard to consumers of agricultural crops. Foliar absorption and incorporation into edible portions of wheat (*Triticum sativum*), potatoes (*Solanum tuberosum*), beans (*Phaseolus* spp.), cabbage (*Brassica oleracea capitata*), sugar beets (*Beta vulgaris*) and Swedes (*Brassica napobrassica*) takes place at varying degrees according to the stage of maturity of the plant and the plant type. The data (*26*) are also compatible with our conclusions that strontium is redistributed in plants to only a small extent. In fact, seeds and fruits as well as underground parts are relatively free from contamination if they develop after the deposition of strontium on the foliage occurs. Cesium, however, is absorbed and readily translocated to developing organs and to the roots, and this is in direct contrast to its relatively low availability from the soil through root absorption. Plants exposed to normal rainfall lost up to 85% of the applied isotope. Thus, a considerable proportion of the $Sr^{89}$ and $Cs^{137}$ sprayed on the foliage was afterward washed off or leached out by rainfall.

## Summary

Several elements have been classified as to their ease of absorption by leaves and the extent of their mobility (*49*). Absorption halftime values range from a few hours to several days. All elements, however, were absorbed. On the other hand, not all absorbed nuclides were transported out of the treated leaves. These include the fallout products $Sr^{89}$, $Sr^{90}$-$Y^{90}$, and $Ru^{103}$, which under most conditions are immobile.

## Conclusions

The significance of foliar absorption of fallout products, including $Sr^{89}$, $Sr^{90}$, and $Ru^{103}$, by food crops near areas of atomic blasts is apparent from reports of high levels of radioactivity in the tops and little if any in the roots (*33*). Similar to calcium, strontium and ruthenium are readily taken up through aboveground plant parts, but are not translocated out or downward into other parts of the plant. Cesium-137, also a component of fallout, is both quickly absorbed by plant foliage and translocated to all other plant parts (*26*). The complete decontamination of various edible aboveground plant parts by surface washing or by peeling is thus precluded except as these substances may be leached from them by other means. The immobility of strontium and ruthenium, however, lessen the possibility of their accumulation in roots and other below ground parts and in tissues which develop subsequent to foliar absorption of these contaminates. However, this does not preclude contamination from root uptake.

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# Dietary Considerations of the Radionuclide Contamination of Nonmilk Foods

**R. H. WASSERMAN and C. L. COMAR**

**Department of Physical Biology, N. Y. State Veterinary College, Cornell University, Ithaca, N. Y.**

**Several factors and concepts that may contribute to an understanding of the food contamination problem with Sr$^{90}$ and Cs$^{137}$ are reviewed. In this country at the present time, milk and milk products contain the highest relative proportion of these fission products; however, nonmilk foods, especially vegetables and cereals, contribute more Sr$^{90}$ to the total diet when considered as an entity. In the future, assuming no further testing, nonmilk foods will become even more important as sources of Sr$^{90}$ for the reasons discussed. Since Cs$^{137}$ in milk and meat arises from a similar precursor (bovine serum), and since there is no apparent discrimination between these compartments, the relative contribution from these two major dietary sources of Cs$^{137}$ is not expected to change with time. The variability in the radionuclide content of foods was emphasized by reference to the "Minnesota wheat" situation of several months ago.**

AT THE PRESENT TIME, milk and milk products, on the average, are the largest single contributors of environmental radiocontamination to the diet of man in this country. However, nonmilk foods, when considered as an entity, may represent the source of from 40 to 60% of the Cs$^{137}$ and Sr$^{90}$ ingested by the human. Under certain conditions and at future times, nonmilk foods may well assume an even greater relative significance in this respect.

For an understanding of processes that determine relative routes of entry, a brief description of the mechanism of radionuclide transfer may be in order as well as an indication of levels of Cs$^{137}$ and Sr$^{90}$ in various foods. Mention will also be made of factors that alter the magnitude of radionuclide intake from nonmilk and milk sources.

In the present discussion, emphasis will be given to Sr$^{90}$ and Cs$^{137}$, since these are the radionuclides of most concern. At early times after the release of nuclear debris, Sr$^{89}$ would represent a significant fraction of the total activity and its general metabolic behavior would follow that of Sr$^{90}$. Since Sr$^{89}$ has a physical half life of 54 days, its importance would rapidly decrease with time. Radioiodine and radiobarium are also major sources of radioactivity immediately after nuclear detonation but, because of their short half lives, 8 and 13 days, respectively, their primary dietary vector to man is in fluid milk following consumption of surface-contaminated vegetation by the grazing animal. Other

**Table I. Summary of Sr/Ca Observed Ratios**

[Sr/Ca observed ratio as defined by Comar *et al.* (*2*) = Sr/Ca in product ÷ Sr/Ca in precursor]

| *Species* | *Precursor → Product* | *O.R.* | *Range* | *Ref.* |
|---|---|---|---|---|
| Man | Diet→bone | 0.25 | 0.17–0.54 | (*11*) |
| Man | Diet→milk | 0.10 | 0.08-0.13 | (*7*) |
| Sheep | Diet→bone (meat)[a] | 0.24 | 0.15–0.31 | (*11*) |
| Goat | Diet→bone (meat)[a] | 0.23 | . . . | (*14*) |
| Goat | Diet→milk | 0.09 | . . . | (*14*) |
| Cow | Diet→bone (meat)[a] | 0.20 | . . . | (*15*) |
| Cow | Diet→milk | 0.10 | 0.09–0.16 | (*11, 15*) |
| Rat | Plasma→fetus | 0.6 | 0.55-0.65 | (*13*) |
| Rabbit | Plasma→fetus | 0.5 | . . . | (*13*) |

[a] In general, the O.R. from diet to plasma, muscle, and bone is about equal although small differences do exist (*2*).