# Droplet Size Effect on Spray Deposition Efficiency of Citrus Leaves

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## ABSTRACT

THE objective of this laboratory study was to identify a droplet size range for maximum spray deposition efficiency on citrus leaves. Using a vibrating orifice droplet generator, a wind tunnel and two spray fluids, different sizes of uniform droplets were generated and sprayed towards pairs of targets. The targets, comprising a filter paper and one of four types of leaf surfaces, were held at three distances from the wind tunnel exhaust and were moved at three speeds across the stream of droplets. For each target condition, spraying was replicated 6 times. Assuming that filter paper targets retained 100% of the impacted droplets, percentage of droplets (by weight) retained by leaf targets was used as deposition efficiency criterion. Considering all target conditions, droplet size range of 240 to 340 μm gave the highest deposition efficiency.

## INTRODUCTION

According to Himel (1982), spray application of pesticides is "the most inefficient industrial process in world-wide use." This is because less than 1 to 3% of a pesticide may reach the target pest and contribute toward pest control (Hall, 1985). The rest of the material either drifts away from target area or runs off the plant surface and falls on the ground. Most of the pesticide loss happens during spray droplet transport and impaction on the target (von Rümker and Kelso, 1975); and magnitude of the loss is related to droplet size and size range of released materials (Akesson and Yates, 1981).

Droplet size is a function of spraying equipment (Reichard et al., 1977; Yates et al., 1985); pesticide formulation (Haq et al., 1983; Bouse et al., 1986); and climatic conditions (Göhlich, 1983). Inertial impaction efficiency of droplets depends on the size and velocity of droplets and size, and shape and aerodynamic characteristics of intercepting targets (Golovin and Putnam, 1962; May and Clifford, 1967). However, for a particular droplet size and target size and shape, deposition or retention of sprayed material is dependent on the physicochemical properties of sprays, atmospheric conditions, and surface characteristics of targets (Yates et al., 1974; Herrington et al., 1981; Spillman, 1984; Reichard et al., 1986). Therefore, it is necessary to understand the relationship between droplet size and deposition efficiency for a particular crop so that by applying pesticides at an optimum droplet size, maximum efficiency in spray application can be achieved.

Salyani et al. (1987) developed a methodology to study deposition efficiency of different droplet sizes in the laboratory. Their pilot study on washed citrus leaves indicated a highest deposition efficiency for certain size of droplets. This paper discusses the improvements in the methodology and reports the results of the subsequent tests. The objective of this study was to identify a droplet size range that results in maximum deposition efficiency for spraying citrus.

## EQUIPMENT AND METHODS

### Test Apparatus and Materials

Fig. 1 illustrates the test setup where the instruments are similar to those described by Salyani et al. (1987). The vibrating orifice droplet generator (Thermo-Systems, Inc., Model 3050) could generate several sizes of uniform size droplets. The fan, with flow straighteners, could provide horizontal air transport of droplets towards the deposition targets. One of the two rectangular (5 x 7.5 cm) targets was made of one to three layers of Whatman No. 4 filter paper and the other, of citrus leaves. Both were backed by masking tape to ease handling and minimize water evaporation. They were held at varying distances from the wind tunnel exhaust and moved by the conveyer belt across the stream of droplets. The pressurized fluid tank and 3-way valve provided a closed system for air free filling of the syringes on the pump.

Six orifice sizes and two fluids (water only and water plus 0.1% ORTHO X-77 surfactant) were used to generate different sizes of droplets (Table 1). The calculated values (Dc) were obtained using equation [1], where the values of flow rate (Q) and frequency (F) for each droplet size, correspond to the condition of uniform droplet generation.

$$Dc = [\ (6/\pi)\ (Q/F)\ ]^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

The appropriate flow rate and frequency for each orifice size were determined optically, using a strobelight and a video imaging system. The measured values were obtained by capturing samples of droplets on the surface of a high viscosity silicon oil (DOW CORNING 200

Article was submitted for publication in February, 1988; reviewed and approved for publication by the Power and Machinery Div. of ASAE in October, 1988. Presented as ASAE Paper No. 87-1536.

Florida Agricultural Experiment Station Journal Series No. 8835.

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**Acknowledgment:** Technical assistance of Mr. Joseph W. Serdynski throughout the study and preparation of this paper and statistical consultation of Dr. Ramon C. Littell are gratefully appreciated.

  

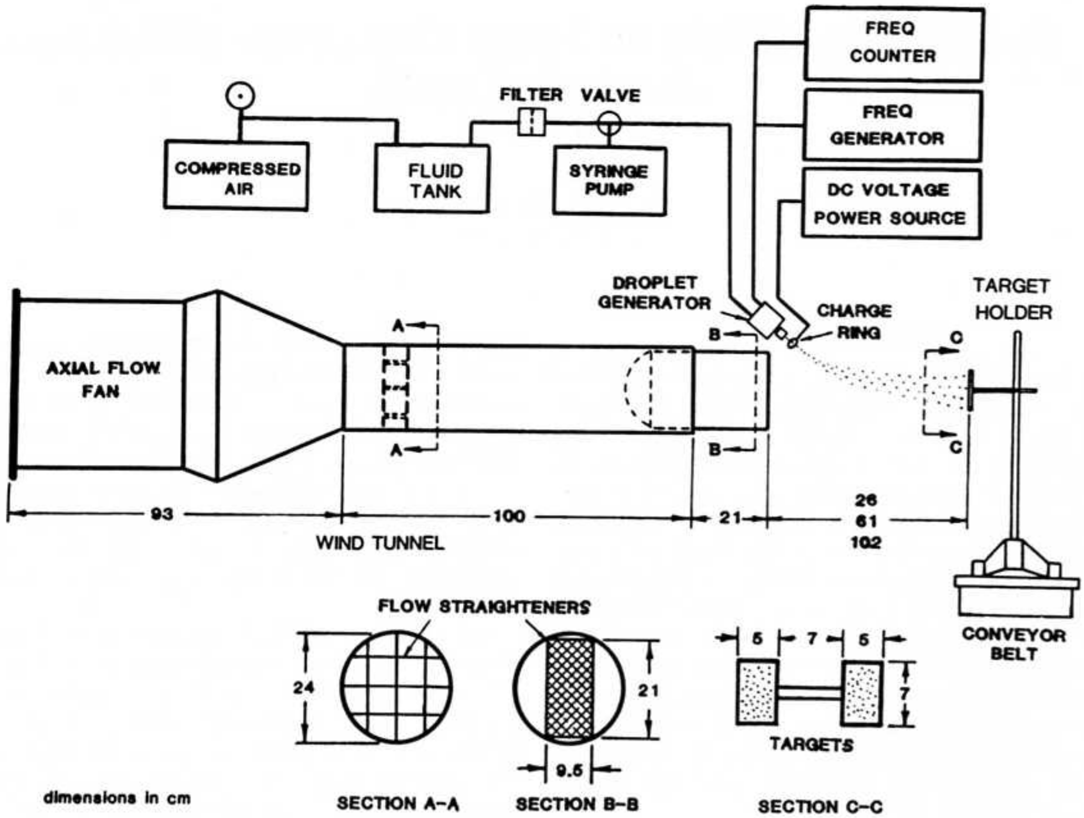


**Fig. 1—Schematic view of the test setup.**

Fluid) and measuring droplet diameters under a microscope. The measured droplet sizes (D1, D2, and D3), in Table 1, refer to sampling distances of 26, 61, and 102 cm and each value represents the average of 10 measurements and three replications. Surface tension for the two fluids, measured with the CAHN Scanning Wettability Analyzer, were 72.4 and 30.8 dynes/cm, respectively.

Target conditions involved three target distances (26, 61, and 102 cm), three target speeds (8.9, 26.8, and 44.7 cm/s), and 4 citrus leaf surfaces (new top, new bottom, old top, and old bottom). Different target distances were used to obtain changes in air and droplet velocities (Fig. 2). The distances and air velocities, representing different droplet velocities, were within the range observed in actual grove spraying. Different target speeds were used to provide various amount of droplet deposits. The target speed of 44.7 cm/s (1 mph) is comparable to spraying speed of citrus in actual field applications. Leaf samples were taken from different age

TABLE 1. DROPLET SIZES GENERATED BY VARIOUS ORIFICE SIZES

| Orif. size, μm | Fluid‡ | Flow Q, mL/min | Freq. F, kHz | Dc, μm | Droplet size* D1 $\bar{D}_{10}$/sd†, μm | D2 $\bar{D}_{10}$/sd, μm | D3 $\bar{D}_{10}$/sd, μm | Dm $\bar{D}_{10}$/sd, μm |
|---|---|---|---|---|---|---|---|---|
| 103 | W1 | 2.10 | 9.380 | 192 | 179/8 | 175/5 | 175/5 | 177/6 |
| 153 | W1 | 5.80 | 12.530 | 245 | 275/20 | 262/17 | 270/16 | 269/17 |
| 203 | W1 | 8.10 | 7.009 | 333 | 338/25 | 337/25 | 321/10 | 332/20 |
| 254 | W1 | 11.55 | 4.145 | 446 | 449/26 | 435/13 | 427/14 | 437/17 |
| 356 | W1 | 16.03 | 1.916 | 643 | 611/22 | 602/23 | 591/27 | 601/24 |
| 432 | W1 | 22.30 | 1.870 | 724 | 719/31 | 727/30 | 715/21 | 720/27 |
| 103 | W2 | 2.10 | 9.372 | 192 | — | 160/14 | — | 160/14 |
| 153 | W2 | 5.60 | 12.534 | 242 | — | 241/13 | — | 241/13 |
| 203 | W2 | 7.80 | 7.015 | 328 | — | 313/14 | — | 313/14 |
| 254 | W2 | 11.45 | 4.148 | 445 | — | 428/20 | — | 428/20 |
| 356 | W2 | 15.88 | 1.913 | 642 | — | 556/21 | — | 556/21 |
| 432 | W2 | 22.20 | 1.872 | 723 | — | 682/35 | — | 682/35 |

*Droplet sizes Dc, D1, D2, D3, and Dm refer to calculated, measured for sampling distances of 26, 61, and 102 cm, and measured average (rounded), respectively.
†$\bar{D}_{10}$/sd = length mean diameter/standard deviation.
‡W1 = water only (surface tension: 72.4 dynes/cm); W2 = water plus 0.1% surfactant (Surface tension: 30.8 dynes/cm.

grapefruit trees. New leaves were summer flush (less than 3 months old) and old ones were more than 1 year old. All the leaves were in field condition. For each target condition, spraying was replicated six times.

### Experimental Procedure

Each run involved several weighings of the target pairs (with ZIP-LOC plastic bags) on a 0.1 mg resolution analytical balance (SARTORIUS Model R300S). Assuming that the droplet flow was uniform and filter paper targets retained 100% of the impacted droplets, deposition efficiency could be calculated as the percent of droplets (by weight) retained on the leaf targets, i.e.

$$Ed = 100[WL/WF]$$

$$= 100[(WL2 - WL1)/(WF2 - WF1)] \quad \ldots\ldots\ldots [2]$$

where

Ed = deposition efficiency, %
WL = deposit on the leaf target, mg
WL1 = tare weight of leaf target plus bag, mg
WL2 = weight of the sprayed leaf target plus bag, mg
WF = deposit on the filter paper target, mg
WF1 = tare weight of filter paper target plus bag, mg
WF2 = weight of the sprayed filter paper plus bag, mg

To obtain the above weights, targets had to be handled with speed and care. When droplet flow was stabilized first the filter target was weighed (WF1) and mounted on one of the two positions on the target holder so that for one half of the replications the filter targets and for the other half the leaf targets were in leading position (Fig. 1). Then a leaf target was loaded on the balance. As soon as fluctuations of the readout stopped and then started to come down (due to evaporation from leaf surface) a stopwatch was started and readout recorded (WL11). Thirty seconds later another readout (WL12) was taken, the target was removed from the balance, and mounted on the target holder. The fan was turned on, the target holder was placed on the moving conveyor belt, and when the targets moved into the stream of droplets the stopwatch was stopped. As soon as the targets passed by the droplet stream, the fan was turned off, the targets were removed from the target holder, placed in their bags and sealed to prevent evaporation, and weighed to obtain the weights WF2 and WL2. The leading target was always bagged first. The tare weight of the leaf target (WL1) was calculated as follows:

$$WL1 = WL11 - T[2(WL11 - WL12)] \quad \ldots\ldots\ldots\ldots [3]$$

where

T = recorded time, min
2(WL11 − WL12) = leaf moisture evaporation for one minute

The recorded time for all but few replications was around 1.25 min. The ranges of ambient temperature and relative humidity during the tests were 21 to 23.5°C and 45 to 60%, respectively.

## RESULTS AND DISCUSSION

All data presented herein pertain to the single rectangular targets held at 90 deg to the stream of droplets (Fig. 1). The effects of target size, shape, and orientation on the deposition efficiency were not studied in these tests.

### Filter and Leaf Targets

Among the range of materials tested, Whatman No. 4 filter paper was found to be the most suitable for capturing and retaining droplets. Other tested materials were cardboard, packaging foam, sandpaper, plastic cloth, chemical wiper cloth, and air conditioning filter. Three layers of the filter paper were found to be adequate for retaining all of the impinged droplets. The maximum amount corresponding to the largest droplet size and the lowest conveyor belt speed. All droplets that impacted on the filter paper targets were adsorbed immediately and no runoff was observed from any of the targets. Therefore, the assumption that filter paper targets retained 100% of the impacted droplets was considered to be reasonable.

Leaf targets, having the same size and shape as filter paper targets, received the same amount of droplets. However, due to their surface characteristics, did not retain all of the impinged droplets; some rebounded or ran off the target surface. Both targets had minimum percentage of deposits (compared to targeted amount) when sprayed with the smallest droplet size. This probably was due to the fact that some small droplets tend to pass around a target rather than depositing on its surface; however, that effect could not have a bearing on the deposition efficiency since it was a relative measure.

For all leaf surfaces evaporation rate (measured up to 6 min) was constant and very repeatable. Therefore, a time period of 30 sec was found to be enough to establish evaporation rate for each leaf target.

### Droplet Size Data

Unlike droplet size data reported earlier (Salyani et al., 1987), measured values of droplet size were closer to that of calculated values and also were more uniform (Table 1). This is believed to be due to the modification of the fluid pump system which resulted in more uniform and stable fluid discharge for all orifice sizes, and also due to improvements in droplet sampling and measurement techniques.

Droplet sizes, sampled at various target distances, were significantly different at 5% level (Table 1). On average, droplet size slightly decreased as the distance increased. Water plus 0.1% surfactant produced smaller droplets than those obtained with water only. This may have been due to reduced surface tension of the fluid, i.e., 30.8 versus 72.4 dynes/cm, respectively.

### Target Distance Effect

Target distance was used as a variable to represent relative changes in spray droplet velocity near the targets. The actual velocity of the droplets was not measured in this test; however, it could be assumed that droplet velocity increases as entraining air velocity increases. Air velocity profiles measured at three target distances were significantly different (Fig. 2). The

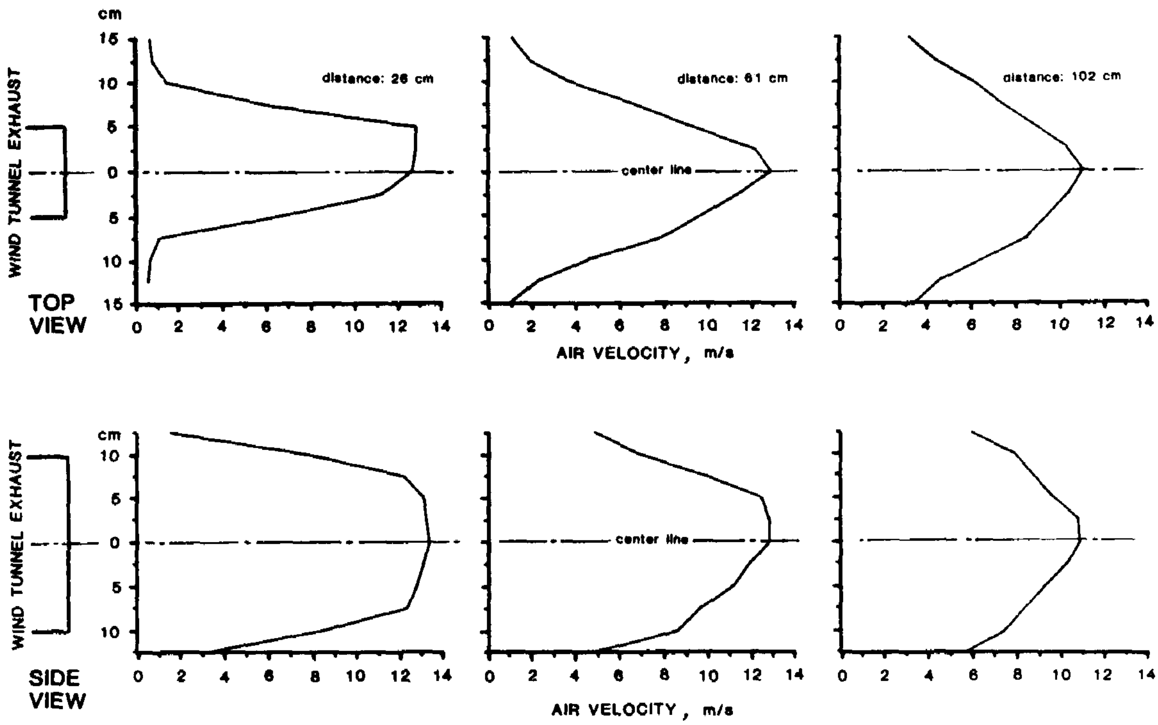


**Fig. 2—Air velocity profiles for different target distances.**

average air and droplet velocities decreased as the distance increased.

Table 2 shows the results of Duncan's Multiple Range Test for different target distances (at a constant target speed of 26.8 cm/s). The smallest droplet size had significantly less deposition efficiency than larger sizes. This may have been due to rebound of droplets from the leaf target surface; but, the effect of droplet size on rebound is not clear in the literature. Reichard et al. (1986), using high-speed photography, have observed that water droplets ranging from 63 to 545 μm tend to rebound from cabbage surface after first impingement. Spillman (1984) has related the rebound to the surface tension of the spray fluid, kinetic energy of droplets, and wettability and roughness of the target surface. He has concluded that droplets smaller than 100 μm in diameter will almost certainly be retained on impact irrespective of other factors.

There was a peak deposition efficiency at each target distance but it did not correspond to the same droplet size. Average deposition efficiency for 26 cm distance (highest droplet velocity) was greater than those for longer distances (with lower droplet velocities).

### Target Speed Effect

Target speed was used as a variable to reflect the effect of spray quantity on deposition efficiency. For this series of tests, the target distance was kept at 61 cm. Target speed had a significant effect on deposition efficiency (Table 3). As speed increased (spray quantity decreased) deposition efficiency also increased. Low speed gave enough time for larger droplets to build up enough liquid to run off the target; and the amount of runoff increased with droplet size.

For all speeds, droplet size effect on deposition

TABLE 2. DEPOSITION EFFICIENCY AT DIFFERENT TARGET DISTANCES*

| 26 cm | | 61 cm | | 102 cm | |
|---|---|---|---|---|---|
| D1†, μm | Ed‡, % | D2, μm | Ed, % | D3, μm | Ed, % |
| 179.3 | 76.7b | 174.8 | 74.7d | 175.3 | 68.2d |
| 274.5 | 93.7a | 262.4 | 91.6a | 270.0 | 81.0c |
| 338.0 | 96.4a | 336.5 | 86.3b | 321.3 | 86.5abc |
| 449.2 | 93.8a | 435.3 | 82.3c | 427.2 | 83.4bc |
| 610.8 | 91.9a | 602.3 | 87.2b | 590.5 | 97.1a |
| 718.8 | 90.6a | 726.6 | 84.9bc | 715.4 | 93.6ab |
| Avg. | 92.5 | Avg. | 84.5 | Avg. | 85.0 |

*At target speed of 26.8 cm/s.
†D1, D2, and D3 are length mean diameters of droplets (Table 1).
‡Ed is deposition efficiency. Means followed by same letter in each column are not significantly different (5% level) using Duncan's Multiple Range Test.

TABLE 3. DEPOSITION EFFICIENCY FOR DIFFERENT TARGET SPEEDS*

| Droplet size (D2), μm | Deposition efficiency†, % for | | | |
|---|---|---|---|---|
| | 8.9 cm/s | 26.8 cm/s | 44.7 cm/s | Avg. |
| 174.8 | 89.3a | 65.9b | 68.8c | 74.7d |
| 262.4 | 87.8a | 88.3a | 98.7a | 91.6a |
| 336.5 | 81.6b | 88.8a | 88.5b | 86.3b |
| 435.3 | 72.5c | 90.1a | 84.5b | 82.3c |
| 602.3 | 73.7c | 93.3a | 94.6a | 87.2b |
| 726.6 | 70.9c | 87.7a | 96.0a | 84.9bc |
| Avg. | 79.3c | 85.7b | 88.5a | 84.5 |

*At target distance of 61 cm.
†Means followed by same letter in each column (for droplet sizes) and in Avg. row (for velocities) are not significantly different (5% level) using Duncan's Multiple Range Test.

TABLE 4. DEPOSITION EFFICIENCY FOR DIFFERENT LEAF SURFACES

| Leaf surface | Deposition efficiency*, % for | | | |
|---|---|---|---|---|
| | 8.9 cm/s | 26.8 cm/s | 44.7 cm/s | Avg. |
| new top | 78.9ab | 84.3ab | 88.7a | 84.0a |
| new bottom | 81.7a | 87.8a | 87.9a | 85.8a |
| old top | 77.3b | 83.0b | 88.2a | 82.8a |
| old bottom | 79.4ab | 87.6ab | 89.3a | 85.4a |

*Means followed by the same letter in each column are not significantly different (5% level) using Duncan's Multiple Range Test.

efficiency was significant and averaged over all speeds, the 262.4 μm droplet size showed the highest deposition efficiency (Table 3). There was a significant interaction between droplet size and target speed. At the lowest speed, maximum deposition efficiency was achieved with the smallest droplet size and it decreased as droplet size increased. At higher speeds, there was not much runoff and peak efficiencies were obtained with larger droplet sizes.

### Leaf Surface Effect

Table 4 shows the deposition efficiency for different leaf surfaces. New leaves, having less waxy surface, showed slightly better deposition than the old ones. Bottom surfaces, with rougher texture, captured more droplets than the top surfaces. In general, leaf surface did not have a significant effect on deposition efficiency of different droplet sizes; however, when target speed effect was included in the analysis, for speeds of 8.9 cm/s and 26.8 cm/s leaf surface showed a significant effect on deposition efficiency (Table 4).

### Fluid Type Effect

As the generated droplet sizes for the two fluids were different, their respective data were analyzed separately. For both fluids, the effect of droplet size on deposition efficiency was significant (Table 5). For water only, the 269.0 μm droplet showed maximum deposition efficiency, while for water plus surfactant the maximum corresponded to 313.3 μm droplet size. On average, water plus surfactant had better deposition efficiency than water only. The improvement in the efficiency may be attributed to reduction in the surface tension of the fluid which, according to Spillman (1984), results in less rebound from the target surface.

TABLE 5. DEPOSITION EFFICIENCY FOR DIFFERENT FLUIDS

| Water only | | Water with surfactant | |
|---|---|---|---|
| Dm*, μm | Ed†, % | D2*, μm | Ed, % |
| 176.5 | 74.4e | 159.8 | 65.3b |
| 269.0 | 91.0a | 240.8 | 90.1a |
| 331.9 | 88.7ab | 313.3 | 97.8a |
| 437.2 | 83.2d | 427.8 | 91.4a |
| 601.2 | 88.3bc | 555.5 | 90.4a |
| 720.3 | 85.9c | 682.3 | 87.6a |
| Avg. | 85.4 | Avg. | 87.1 |

*Droplet sizes (see Table 1).
†Means followed by same letter are not significantly different (5% level) using Duncan's Multiple Range Test.

## CONCLUSIONS

Generally speaking, droplet size had a significant effect on deposition efficiency; however, it is important to note tha its effect could be influenced by droplet velocity (a function of air velocity), spray quantity (a function of target speed), leaf surface properties, and spray fluid formulation (surface tension). For the range of droplet size tested, the sizes obtained by the smallest orifice were the least efficient. For most target conditions in these tests, a size range of 240 to 340 μm appeared to result in highest deposition efficiencies. This is in agreement with the previous report of about 400 μ (Salyani et al., 1987), and the discrepancy originates from the error in droplet size measurement which was discussed earlier.

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