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Evaluation of a solid stream radial nozzle on fixed-wing aircraft, for penetration of spray within a soybean canopy

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Abstract: Experiments were conducted to evaluate the Accu-Flo multiple orifice nozzle for penetration of spray into a soybean (*Glycine max* L.) canopy by comparing results to those from a popular straight stream nozzle and rotary atomizer. A mixture of water + Induce® adjuvant was applied at three different spray release heights in a random sequence, using an Air Tractor 402-B agricultural aircraft. Sampler stands were placed at twenty-four locations in the field. Water sensitive paper (WSP) cards were clipped onto rigid stands just above the canopy and 30 cm off the ground within the canopy. Weather data were recorded using two different stations on-site. Wind was predominantly from the west and parallel to the direction of the spray runs. The spray delivery systems compared were the Accu-Flo nozzles, (64 needle 0.020 opening), CP®-09 straight stream with 5 degree deflection, and Micronair® AU5000 atomisers (14 mesh screen) at a low volume spray rate of 18.7 l/ha. A total of 54 spray runs were made over three days, and heights were varied at 3.7 m, 4.9 m and 6.1 m. Water sensitive papers were scanned and analysed for coverage per unit card area using an image analysis system. Altitude and [Nozzle X Altitude] interaction were significant effects on coverage at the 0.01 and 0.07 significance levels, respectively, for the top cards. Nozzle type was not a significant effect on coverage for the top cards, but was significant at the 0.01 level for the bottom cards. Altitude alone had no obvious effect on coverage for the bottom cards, although it had an effect for the top cards. The highest percentage area of spray coverage was observed from the Accu-Flo nozzles, especially for the bottom cards. Average spray coverage from the Accu-Flo nozzles was 1.7 times higher than coverage from the CP® nozzles or Micronair® atomisers in the lower portion of the canopy.

Key words: aerial application, hydraulic nozzle, plant disease, rotary atomiser, soybean rust, water sensitive paper

Introduction

Effectiveness of spray penetration into crop canopies from both ground and aerial application is influenced by many factors including spray volume, tank mixture, and nozzle or atomiser configuration. For effective control, it is important that a spray delivery system deliver crop protection material efficiently and deep within the canopy. Numerous experiments with ground spraying systems have sought to evaluate different configurations for spray penetration and control of pests and disease. Although the study described herein addresses spray penetration from aerial platforms, it is instructive to indicate background for both ground and aerial application as similar issues are prevalent.

Gimenes *et al*. (2012) evaluated both flat fan and hollow cone nozzles in ground application of Spinosad insecticide under two air assistance levels, for control of *Spodoptera frugiperda* (J.E. Smith) (fall armyworm). All technologies tested in the study promoted a reduction of plant damage from fall armyworm. The hollow cone nozzle showed greater spray deposit when compared with the flat fan nozzle. The flat fan nozzle combined with air assistance, was more effective for controlling fall armyworm that was at the same V4 growth stage. There are well-documented, deleterious effects of fungal spores on plant health and yield. In an efficacy experiment for control of stem canker (*Leptosphaeria maculans* and *L. biglobosa*) in winter oilseed rape crops, Ratajkiewicz *et al*. (2009) applied azoxystrobin fungicide using three varied treatments: water volumes of 200 and 400 l/ha, two adjuvant types, and two nozzle types (TeeJet® XR11002 and air-assist DB11002). As expected, the azoxystrobin caused a significant decrease in the infection by stem canker, but the addition of adjuvants did not significantly increase fungicide effectiveness. However, past experiments had indicated that adjuvants were effective at low doses to aid in controlling Cercospora leaf spot (Ratajkiewicz *et al*. 2008). Both nozzles used by Ratajkiewicz *et al*. (2009) were effective against stem canker. A low volume application was sufficient for control if plants were under 71 cm in height.

Asian Soybean Rust (ASR) is a serious problem. The effects of ASR have been seen in the United States (U.S.) since 2004 (NCSRP 2009). Most outbreaks have been concentrated in the southern coastal regions, with ASR detected in 184 counties of nine Southern States in the U.S. (IPMPipe 2013). In 2012, ASR was reported in thirteen U.S. states representing 385 counties. Aerial application can be used to combat plant disease if nozzle or atomiser setups efficiently deliver

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fungicide to the lower levels of the crop canopy. Studies have attempted to define the optimal application volume/adjuvant combinations for improving within-canopy spray deposition (Wolf 2004). Other studies have presented information and guidelines for ASR control (McCracken 2005; Gardisser 2007), and have tested atomiser/adjuvant combinations for their effectiveness specifically in rust control using bioassay (Antuniassi 2006). A comparison of two rotary atomiser systems and an electrostatic application aerial system, for their ability to control ASR using curative flutriafol fungicide applied at two rates: 10 and 20 l/ha was conducted by Antuniassi (2006). The highest percentage of rust killed was obtained using a mixture of fungicide, oil, and emulsifier applied with either the Micronair® rotary atomiser at the 10 l/ha rate or the Stol® rotary atomiser at the 20 l/ha rate. Soybean yields were comparable for all treatments, with the highest yield from the use of the Stol® rotary atomiser at the highest rate (20 l/ha). Bayer *et al*. (2012) used water sensitive cards within a field of irrigated lowland rice. They compared within-canopy deposition of fungicide using a conventional hydraulic nozzle, electrostatic nozzle, and rotary atomizer with different volumes of solution. Results generally indicated that rotary atomisers provided superior penetration within the bottom third of the canopy. Conventional hydraulic nozzles operated at the highest spray rate showed the lowest droplet density in the bottom third, although droplet density was highest in the top third of the canopy.

The Accu-Flo nozzle (Bishop Equipment Co., Hatfield PA, USA) applies droplets uniformly through several needles in a radial pattern. Droplets are applied in a wedge pattern by the TVB (Waldrum Specialties, Southhampton, PA, USA) which uses a similar principle. The Accu-Flo nozzle and the TVB differ from the conventional nozzle that shatters the droplet. In an experiment on a spray application of water and using spray sampling, Minogue (2004) indicated a very low percentage of droplets (0.2%) smaller than 153 μm diameter (and prone to drift) from the Accu-Flo nozzles. This was about one-fifth the percentage of small droplets from conventional straight stream nozzles spraying water from a helicopter. Thus, the favourability of Accu-Flo nozzles for drift management can be seen.

To the author's knowledge, no published research data exist on the evaluation of the Accu-Flo nozzle for fixed-wing applications, although Draper *et al*. (2002) documented a preliminary study comparing the Accu-Flo, CP®, and Lund nozzles. The authors observed a more uniform droplet pattern from the Accu-Flo with less off-target movement than the CP or Lund nozzles. No data were presented, however, and the study was intended as a precursor to further investigation.

In addition to drift potential, the degree by which a nozzle facilitates the penetration of spray into the canopy is important for the mitigation of pests and disease. It would also be useful to determine if favourable droplet characteristics of these radial nozzles used on rotary-winged aircraft might also translate to fixed-wing, low volume aerial application. The study described herein, was designed to evaluate spray penetration characteristics of the Accu-Flo nozzle mounted on fixed-wing aircraft for application of water + adjuvant (Induce® in this case) at a mix rate of 2.5 ml/l of water to a soybean field. Water sensitive paper (WSP) cards were placed at the top and 30 cm off the ground, within a soybean canopy. The active ingredient (AI) was not added to the water + adjuvant mixture, as prior results have shown little appreciable influence on droplet size by the addition of AI (Thomson and Lyn 2011). Penetration results from the Accu-Flo were compared to those from a popular fixed nozzle and rotary atomiser.

Materials and Methods

Roundup-Ready® Soybeans (*Glycine max* L., maturity group 5) were planted in twin rows on 101 cm (40 inch) centers on a research field of the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Crop Production Systems Research Unit (CPSRU), Stoneville, MS, USA. Water was applied at three different targeted, spray-release heights of 3.7, 4.9, and 6.1 m (12, 16, and 20 ft) in a random sequence using an Air Tractor 402-B agricultural aircraft. The aircraft was traveling at a ground speed of 65 m/s. Plants were at the beginning of the R6 growth stage, still indicating complete cover although beginning to senesce. Twelve rigid spray sampling stands were placed in one row north and one row south of the east-west centerline. Water sensitive paper cards were clipped onto horizontal trays just above the canopy and 30 cm off the ground on trays within the canopy, for a total of 24 cards per run (Figs. 1 and 2).

Weather data were recorded using both a Campbell CR21-X data logger (Campbell Scientific, Logan, UT USA) with weather sensors and Kestrel 4500 weather tracker (Nielsen-Kellerman, Boothwyn, PA USA). During the experiment, the air temperature ranged from 30 to 35°C (86 to 95°F); relative humidity ranged from 50 to 71%; wind speed ranged from 0.68 to 2.79 m/s (1.53 to 6.23 mph). Wind direction was from W to NW, essentially parallel to the flight-line.

Spray nozzles and atomisers used were: sixty Accu-Flo nozzles (64 needles per nozzle with 0.020 needle opening), ten Micronair® AU5000 atomisers (using a 14 mesh screen), and fifty-six CP®-09 nozzles (0.062 orifice, 5 degree deflection) (Fig. 3).

The two nozzles and Micronair® atomiser were configured for a low volume spray rate of 18.7 l/ha (2 gal/ac) and a 20 m swath. Nominal system pressures as determined by pressure gauge in the cockpit were: 331 kPa (48 psi) when using the Micronair® atomiser, 195 kPa (24 psi) when using the Accu-Flo nozzle, and 248 kPa (36 psi) when using the CP® nozzle. Height of spray release was determined using a LaserTech ULS laser (Laser Technology, Centennial, CO USA) connected via USB 2.0 interface to a notebook computer mounted in the belly of the aircraft. The laser data acquisition computer, Campbell data logger, and Kestrel 4500 weather tracker were all synchronised in time using an atomic watch.

Fifty-four spray runs were made over three days, and randomised on spray altitude as well as direction of flight. It was not possible to completely randomise the selection of the nozzle set, as this would require changing the spray

Fig. 1. Water sensitive paper cards at top of canopy

Fig. 2. Water sensitive paper cards at bottom of canopy

booms for each run. As it took about ½ hour to change booms and verify nozzle flow and proper operation, this was not practical. A modified plan was implemented by which the booms (nozzles) were changed every six runs, but their sequence was randomised. Direction of flight and spray release height were then randomised within the boom spraying the crop. The time of the field entry for each run was noted to-the- second using an atomic watch.

After each spray run, the cards were carefully removed by their sides from the stands, placed in plastic bags, and then stored in a cooler. In the laboratory, WSP cards were scanned with an image analysis system consisting of a JVC camera and frame grabber. Spray card analysis macros for SigmaScan 5.0 software, obtained the area of each droplet stain within the imaged portion of the card. Total area of all droplets within the viewed portion was then obtained to indicate relative spray coverage at each sampling location. Volume Median Diameter (VMD) and relative span (RS) of droplets among other size parameters, were derived from the droplet data, using spreadsheet macros. Further details of the scanning method and droplet size calculations can be found in Thomson and Lyn (2011). Scanned droplets from WSP were analysed using PROC Mixed in SAS 9.2 (The SAS Institute, Cary NC, USA.)

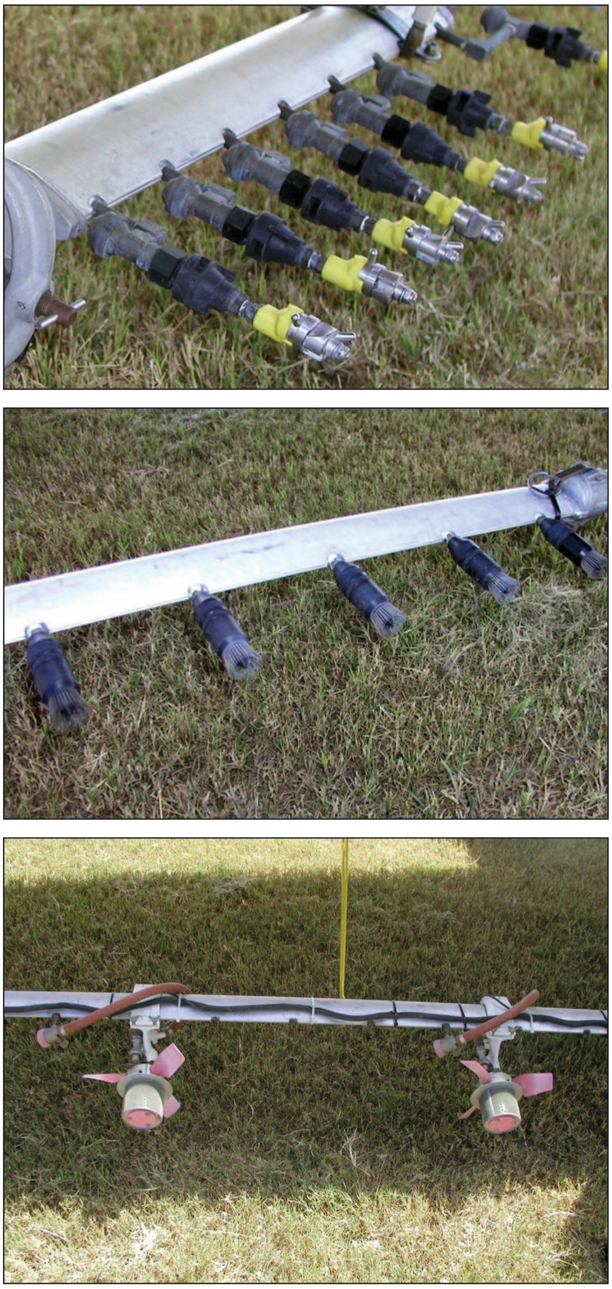

Fig. 3. CP®-09 and Accu-Flo® spray nozzles; Micronair® AU5000 rotary atomiser on spray booms

Results

Droplet characteristics

Droplet sizes deposited on cards and averaged over all runs are illustrated in table 1. The RS is a function of three droplet size parameters. One parameter, the $D_{v0.1}$, indicates a percentage of small droplets. A larger $D_{v0.1}$ indicates fewer driftable fines, and it usually follows that a significantly lower RS (at an equivalent VMD) indicates fewer fines, unless the droplet spectrum is highly skewed. Smaller droplets are favourable for efficacy and spray coverage within a crop canopy, but a high percentage of fines exacerbates drift. With regard to spray coverage, this could be looked at in an alternate way. For an equivalent number of 'fines', the nozzle with the significantly lower RS would permit delivery of smaller drop-

Table 1. Summary droplet data for the top water sensitive paper (WSP)

Nozzle/ atomiser	Coverage* [%]	$SD_{coverage}$*	Target VMD [µm]	VMD* [µm]	SD_{VMD} [µm]	$D_{v0.9}$* [µm]	$D_{v0.1}$* [µm]	RS*	SD_{RS}
Accu-Flo®	1.21	0.21	350	339	52	582	143	1.28	0.47
CP®-09	1.03	0.11	350	344	68	625	164	1.33	0.45
Micronair®	0.89	0.19	280	209	20	305	137	0.80	0.32

*average; SD – standard deviation
VMD – Volume Median Diameter ($D_{v0.5}$), where half of the volume of spray contains droplets smaller than the VMD; $D_{v0.9}$ indicates that 90% of the volume of spray is in droplets smaller (or 10% larger) than this value; $Dv_{0.1}$ indicates that 10% of the volume of spray is in droplets smaller than this value; RS – relative span of droplet sizes indicated by $(D_{v0.9} - D_{v0.1})/D_{v0.5}$

lets, which is advantageous for spray coverage. Data in table 1 demonstrate the latter point well. The $D_{v0.1}$ for the Accu-Flo and Micronair® are equivalent, but VMD of the Micronair® is much lower, indicating a bias towards more small droplets favourable for efficacy.

It should be noted that WSP can only be used to estimate the range of droplets exiting the nozzle. More accurate characterisations of droplet size can be accomplished by other means such as laser diffraction (Fritz *et al*. 2012). However, WSP placed at the top of the canopy gives a good assessment of droplet size ranges at canopy height after turbulence. Ambient effects have also been accounted for, and thus, WSP can serve as a point of comparison between nozzle types in the field.

Statistical analysis

Results from SAS model runs are summarised in tables 2 and 3. The models indicated Nozzle*Day as a random effect. Weather variables wind speed, wind direction, relative humidity, and air temperature were not significant effects on spray coverage for either top or bottom cards, so they were dropped out of the final model to increase statistical precision. Results indicated that altitude was a significant effect at the 0.01 level for the top cards (p = = 0.0090) with lower altitude runs producing higher coverage. Least squares means for the Accu-Flo nozzle indicated 1.35% coverage at the 3.7 m spray release height, 1.27% coverage at the 4.9 m height, and 1.07% coverage at 6.1 m height. [Nozzle X Altitude] interaction was significant at the 0.10 level (p = 0.0657). Nozzle type was not a significant effect on spray coverage for the top cards (p = 0.4174) but was significant at the 0.01 level for the bottom cards (p = 0.0081). There was no [Nozzle X Altitude] interaction effect for the bottom cards (p = 0.6781). The latter is an interesting finding, as this indicates evidence of penetration differences between nozzles/atomisers, but the differences were not influenced by spray release height. Consistent with these findings, altitude alone had no significant effect on coverage for the bottom cards (p = 0.5048), although there was a significant effect for the top cards, as previously indicated.

The highest percentage area of coverage for the bottom cards within the canopy was observed from the Accu-Flo nozzles (Fig. 4). The average value was about 1.7 times higher than coverage for the CP® nozzles or Micronair® atomisers. The average percent coverage was 0.77 for the Accu-Flo, 0.46 for the CP®-09, and 0.44 for the Micronair®. The Accu-Flo was significantly different than the others at the 0.01 level using Fisher's Least Significant Difference (LSD) test for pair-wise comparisons. The average number of droplets within the scanned area of the cards was 92 for the Accu-Flo, 60 for the CP®, and 138 for the Micronair®.

Table 2. Statistical analysis results – top water sensitive paper (WSP)

Effect	Numerator df	Denominator df	F Value	*Pr > F
Day	2	1	0.62	0.6680
Alt	2	6	11.41	0.0090
Nozzle	2	1	2.37	0.4174
Nozzle*Alt	4	6	3.96	0.0657

*probability of significance level

Table 3. Statistical analysis results – bottom water sensitive paper (WSP)

Effect	Numerator df	Denominator df	F Value	*Pr > F
Day	2	7	5.68	0.0343
Alt	2	7	0.75	0.5048
Nozzle	2	7	10.37	0.0081
Nozzle*Alt	4	7	0.59	0.6781

*probability of significance level

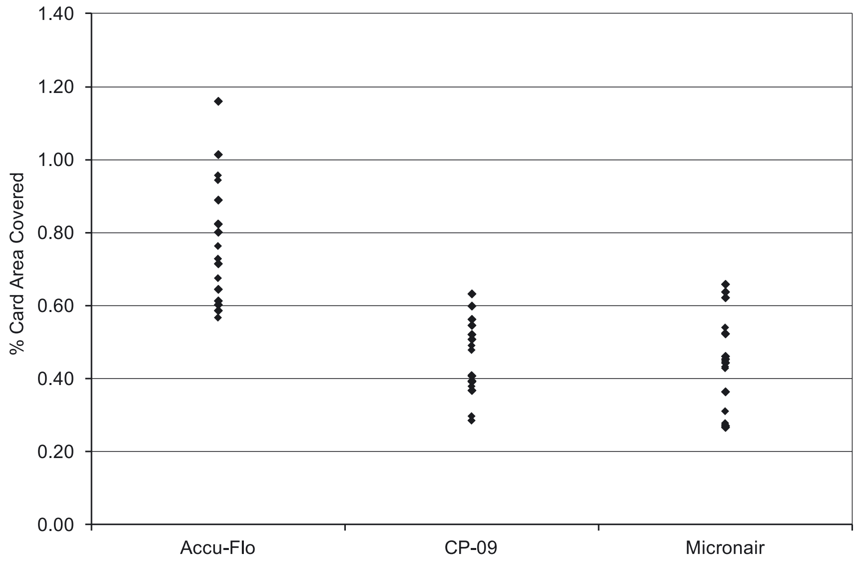

Fig. 4. Spray coverage on water sensitive paper (WSP) cards at bottom of the canopy for the Accu-Flo® and CP®-09 nozzles and Micronair® atomiser. Each point represents an average of twelve cards

Discussion

The Accu-Flo nozzles performed well in this experiment; better than the standard CP®-09 nozzles set at a 5 degree down-angle for canopy penetration. However, the Micronair® propeller-driven atomisers were expected to perform better than they did for coverage within the canopy. Under the conditions of the experiment, the Micronair® indicated a lower VMD (208 µm) than our target value of 280 µm, which was set to balance deposition efficacy with drift potential. Thus, some of the finer droplets may have drifted or evaporated before reaching the bottom cards. There was still room for adjustment of the Micronair® to reduce propeller/spray cage speed. The median droplet size also seemed to have been under-estimated by the Micronair® setup charts. Using the charts, an increase of propeller blade angle by 10 to 15 degrees for the rotary driver should slow the propeller, and thus, increase median droplet size by approximately 50 µm. Since the droplets showed good size uniformity or small RS (Table 1), % fines would probably be small and spray coverage should improve.

The smallest restrictors (size 3/32) had to be used with the Accu-Flo nozzles in order to obtain adequate pressure for smooth operation at low volume. However, observation of log files from the aircraft's guidance system showed occasional irregularities in flow, even at the seemingly acceptable operating pressure (165 kPa or 24 psi). The Accu-Flo nozzles used their own check valves for improved aerodynamics, and these valves open above 124 kPa (18 psi). It is possible that some "chatter" around the operating point took place when pressure became intermittently low, although neither our pilot nor workers on the ground noticed anything unusual. Even so, performance of the Accu-Flo nozzles was excellent for spray coverage. Higher flow rates might provide smoother operation for the Accu-Flo nozzles with their check valves, and also improve the droplet spectrum, as RS was only comparable with the CP®-09 positioned 5 degrees downward. It is easy to select the CP®-09 nozzle and settings for desired droplet size. A down-angle of 30 degrees might have improved RS for that nozzle. The best droplet size uniformity was noted for CP® -11 TT flat fan nozzles in a previous experiment using a downward deflection of 30 degrees (Huang and Thomson 2011).

Our observations using fixed-winged aircraft were consistent with the wind tunnel studies conducted by the USDA, ARS, Area-Wide Pest Management Research Unit (APMRU), College Station, TX for the Accu-Flo at air speeds customary for rotary-winged aircraft. The indication was that a combination of high airspeeds and low pressures would result in an increased number of fine droplets due to the lower exit velocity of the fluid, resulting in a greater differential velocity with the airstream (Fritz 2013). This could help explain the high (undesirable) value for RS in our field experiment. The data also indicated that if pressures are not sufficient to insure full, continuous flow through all the tubes, the resulting intermittent flow can also result in finer sprays. However, the Accu-Flo nozzles gave a good result for canopy penetration even though pressure was at the low end of its acceptable operating range. Table 1 also indicates higher percent coverage for the Accu-Flo over the CP® for the top cards at canopy level. It is not immediately clear why this was the case as the aircraft and flow control were set up the same way, and spray characteristics were comparable. Lower operating pressures and the fact that coverage was more variable for the Accu-Flo could have contributed to differences. Standard deviation of percent coverage for the Accu-Flo was double that of the CP® (Table 1).

Data were analysed using target altitudes, not actual altitudes. This is because the laser stopped logging due to data overflow in the early runs due to the acquisition rate being set too high. We used a highly experienced pilot for the runs, however, and based on results, we felt confident about integrity of altitude data. Percent coverage followed expected trends (more material deposited at lower altitudes) consistently throughout the experiment. For this study, we decided to place WSP on rigid stands instead of clipping them on leaves, to remove inherent variability present in the latter method. Results from WSP placed in this manner, therefore, may be different than results from WSP placed on leaves or results directly from leaf samples.

The Accu-Flo nozzles are advertised to give a narrow droplet spectrum. The use of drop tubes are recommended for their operation with fixed-wing aircraft to demonstrate their potential (Bergey 2006). We used a drop-boom arrangement instead, and aerodynamics behind the nozzle would be different with this arrangement. It is also critical that the Accu-Flo nozzles be set exactly parallel to air flow in flight, and we tried to assure this with our experimental setup. In summary, the Accu-Flo nozzle was highly efficient and performed well for penetration of spray within the canopy. This nozzle would be a good one to consider for fixed-wing aerial spray applications in terms of application efficacy, especially over dense or tall canopies.

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