

*Hazard/Risk Assessment*DEVELOPMENT OF THE SPRAY DRIFT TASK FORCE DATABASE FOR  
AERIAL APPLICATIONS

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**Abstract**—This article is part of a series describing the development of the Spray Drift Task Force (SDTF) database and its application to agricultural chemical exposure risk assessment modeling. The series describes the development of a large generic database (assuming that active ingredient rate is not a factor affecting physical drift) and its use in estimating spray movement immediately following application by aerial methods. The components of the database are described. In agreement with field trials in the open literature, the database shows that the major variables affecting off-target spray deposition are droplet size, spray release position (boom height and length), and wind speed and direction. In addition, secondary parameters that can affect these variables and drift are also discussed.

**Keywords**—Drift      Aerial spraying      Pesticide application      Physical properties      Droplet size

## INTRODUCTION

The Spray Drift Task Force (SDTF) is a joint development project of 40 agricultural chemical companies that was formed in 1990. The U.S. Environmental Protection Agency (U.S. EPA) Office of Pesticide Programs (OPP) required agricultural chemical manufacturers to provide droplet-size spectrum measurements and field-drift evaluations when adverse effects to nontarget organisms were possible (CFR 40.168.202.1 and 202.2). Submission of spray drift data for individual product registrations were, however, both expensive for the manufacturers and of limited value in evaluation of potential exposure of organisms off-site over the wide range of application variables. The primary goal of the SDTF studies was the provision to OPP of a comprehensive database on the off-site drift of crop protection chemicals during agricultural-spray applications. This database was developed to improve the data for regulatory decision-making and provide a basis for the evaluation of risk mitigation strategies. Although over 40 separate field-trial studies of crop-protection chemical drift were identified in the open literature [1], these studies do not form a systematic dataset for analysis of off-site drift. In addition, these open-literature studies were not collected using Good Laboratory Practice Standards, 40 CFR Part 160 in the Federal Register, as required for regulatory data submissions. A few registrant companies had run very limited range aerial drift and atomization studies.

The fundamental premise of the cooperative SDTF effort was that off-site drift is primarily a function of application techniques, environmental conditions, and the physical prop-

erties of a tank mix and that, after the formation of the spray droplets, is independent of the specific active ingredient. As such, spray drift for different tank mixes applied using the same application equipment can be presumed to be generically related to physical solution properties and not the chemistry of the active ingredient. Therefore, a comprehensive database of off-site drift and deposition phenomena could be developed independent of specific active ingredients. This generic approach rests on three general assumptions. The first is that degradation and volatilization of the active ingredient analyte during the spray and deposition timeframe is negligible. Near-field drift and deposition occur within a short time frame (<30 min). Loss of the active ingredient either through degradation or volatilization must be much slower than this to assure efficacy of the compound within the field. The second assumption is that the physical properties should be measured in the tank mix and tracer levels would correlate to full active-ingredient rates. It should also be noted that adjuvants were not tested completely in the SDTF studies but rather only a subset of tank mixes. The third assumption (U.S. EPA policy/science) is that the risk to nontarget organisms can be evaluated as a two-stage process where environmental concentrations are used to estimate exposure to the contaminant and then combined with measurements of biological activity to determine risk [2].

In the development of the database, spray drift was viewed as a series of physical processes, i.e., atomization, movement, evaporation, and, finally, deposition of droplets. Laboratory and field experiments were performed to analyze and quantify each of these physical components important in the spray drift process. The SDTF reviewed over 800 published and internal company reports on spray drift. Several prior studies had identified droplet size as the primary application variable controlling drift from low-flight agricultural spraying [3–6]. Droplet size is also one of the most important variables affecting spray

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efficacy, along with placement, timing, coverage, and chemical toxicity [7,8]. Many application parameters including nozzle type, nozzle orientation, pressure, aircraft speed, and tank mix formulation affect droplet size. Development of a database to quantify atomization as a function of these application variables and the physical properties of the tank mix was a central effort in the SDTF studies. Additional laboratory studies were performed to quantify the physical properties of tank mixes used in both atomization and field studies as well as the evaporation rate of droplets.

The overall objective of the SDTF studies as required by the U.S. EPA was quantification of downwind sedimentation deposition for a wide range of label conditions and atomization characteristics. Meteorological variables such as wind speed and direction, atmospheric stability, and relative humidity have a significant impact on off-target movement and deposition [3–5,9,10]. The field studies were designed to quantify the response of drift to meteorological variables, resolve discrepancies in the historical studies on the relative importance of application parameters, and account for the confounding effects of the meteorology on these application variables.

This article summarizes the development of the SDTF database in the areas of aerial field, atomization, and physical property studies, summarizes the major results of the aerial field studies, and presents results on off-target deposition. These studies were used to verify and modify existing drift models, thus providing a tool to evaluate a wider range of application and meteorological scenarios than could be tested. Accompanying articles describe the model development and evaluation [11,12]. While the present article focuses on the SDTF aerial database, information on the SDTF ground rig studies can be found elsewhere [13].

The SDTF field, atomization, and physical property studies involved hundreds of treatments. It is beyond the scope of the present article to present all of the data and findings from those studies; however, additional information is available at the U.S. EPA web site for scientific advisory panel reviews at [www.epa.gov/scipoly/sap](http://www.epa.gov/scipoly/sap) or from the U.S. EPA Office of Pesticide Programs docket.

## MATERIALS AND METHODS

### *Aerial field studies*

An application practices matrix was developed based on a survey of registered labels and knowledge of use patterns in the United States to encompass the range of significant application practices. To determine typical application practices, a survey of about 20% of aerial applicators was conducted by the SDTF and summarized by the National Agricultural Aviation Association [14]. Survey results showed that aerial spray application volume rates range from ultralow volume ( $\leq 0.8$  L/ha) through low ( $>0.8$ – $3.0$  L/ha) and medium ( $>3.0$ – $7.7$  L/ha) to high volume ( $>7.7$ – $38.0$  L/ha) and are made using fixed- and rotary-wing aircraft. Flight speeds range from low-speed helicopters ( $11$ – $33$  m/s) through medium-speed fixed-wing piston aircraft ( $>33$ – $50$  m/s) to high-speed turbine engine fixed-wing aircraft ( $>50$  m/s). Typical applications are made using water as a carrier, with an application volume rate in the medium-volume range. Spray pressures are typically around 2 bar. Most aerial applications are made at a height of 1.5 to 3 m above the canopy, with a swath width of 15 to 18 m. Different nozzle types and operational parameters may be used within each combination of application volume rate and flight speed. Appropriate combinations for testing were selected for

the SDTF studies. The aerial survey showed that nozzles were usually oriented  $45^\circ$  backward on booms positioned below and/or behind the trailing edge. Surfactants and/or drift control adjuvants are often used for tank mixing. Swath displacement, offset, or adjustment is nearly always used by aerial applicators to compensate for using finer sprays or spraying under conditions of higher wind speeds. This practice involves offsetting the application by different swath proportions to allow for the wind carrying the droplets downwind. Applications typically cease when conditions favor high drift levels (exact conditions will vary depending on proximity to sensitive areas and other drift mitigation practices, but often 10 mph represents an upper wind speed), especially when close to sensitive or occupied areas. Although the SDTF aerial application studies were developed based on typical application practices for the early 1990s and reasonable worst case meteorological conditions, it should be noted that aerial application is a dynamic industry and application practices change based on available technology, information, and regulations. In particular, new nozzles and global positioning satellite systems are becoming more common place. However, the SDTF database covered a wide range of conditions providing resources for the development of the AgDRIFT® model (Spray Drift Task Force, Stewart Agricultural Research Services, Macon, MO, USA), which can predict drift for a wider range of conditions than actually tested.

### *Test site locations*

Test sites were selected in the high plains of Texas, near Plainview, and in the Rio Grande Valley of south Texas, near Raymondville, USA. These two sites provided a wide range of temperature, relative humidity, and wind speeds. Each test site comprised an area large enough to allow several test areas usable regardless of wind direction. At the Plainview site, applications were made to a level field of mowed grass (height = 10–15 cm). The absence of a crop provided a reasonable worst case scenario for drift (because there was no vegetation to intercept droplets) and also allowed a comparison among all treatments without the confounding effects of a crop canopy. At Raymondville, the applications were made over rough, disked, bare ground or grain sorghum stubble mowed to a height of 25 cm. Two of the variable treatments at Raymondville were applied to a cotton canopy in the green boll stage (height = 104 cm).

### *Covariate approach*

Off-target deposition is a function of application scenario (treatment) and meteorological effects. Since meteorological variables continually change, the ideal experimental design is to apply all treatments simultaneously. However, this is not practical. The SDTF used a covariate approach that provided a reasonable solution to this by always applying two treatments almost simultaneously. One treatment, referred to as the standard treatment, always involved the same application scenario (i.e., the test substance and application parameters remained constant), while the second treatment, referred to as the variable treatment, included a change of those variables being studied. Diazinon (Aventis Crop Protection, Raleigh, NC, USA) was used for all the standard treatments, and malathion (Platte Chemical Company, Greeley, CO, USA) was used for all the variable treatments. A covariate analysis was performed using the standard treatment as the covariate for facilitating comparisons among treatments without the confounding ef-

Table 1. Summary statistics of spray period wind speeds during Spray Drift Task Force field trials

Study	No. of trials	Mean (m/s)	Median (m/s)	Minimum (m/s)	Maximum (m/s)
Plainview 1992	74	3.70	3.62	1.57	6.92
Plainview 1993	48	4.76	4.85	2.27	7.72
Raymondville 1993	60	4.86	5.05	1.34	6.56
Overall	182	4.36	4.54	1.34	7.72

fects of meteorology. The covariate analysis approach is detailed in many statistical texts [15,16]. Data from the standard treatments provided a means for quantifying the effects of meteorological variables on drift through a multiple regression analysis of all meteorological variables (temperature, relative humidity, wind, etc.) and off-target deposition.

#### Meteorological monitoring

Meteorological data were collected at four heights on a tower near the spray area and were used to extract the mean wind speed and aerodynamic roughness length by fitting the wind speed measurements to a logarithmic profile as

$$U = U_r \frac{\ln(z/z_0)}{\ln(z_r/z_0)}$$

where the reference height,  $z_r$ , is assumed to be 2 m (its value is arbitrarily chosen and does not affect the vertical dependence) and the reference wind speed at that height,  $U_r$ , and aerodynamic roughness length,  $z_0$ , were recovered from a least squares analysis of the wind speed recorded during the run.

Meteorological variables affect spray drift, mainly through the evaporation and transport of droplets following emission from a sprayer. The wind speed, wind direction, and air temperature were measured at heights of 0.3, 1.8, 3.05, and 9.1 m above the ground throughout the study. Richardson number, a dimensionless measure of atmospheric stability, was calculated using

$$\text{Ri} = \frac{\frac{g}{T} \left( \frac{dT}{dz} \right)}{\left( \frac{dU}{dz} \right)^2}$$

where Ri = Richardson number,  $g$  = acceleration due to gravity in  $\text{m/s}^2$ ,  $T$  = mean temperature in layer  $dz$  in  $^\circ\text{C}$ ,  $dT/dz$  = temperature gradient in layer  $dz$  in  $^\circ\text{C/m}$ , and  $dU/dz$  = horizontal wind velocity gradient in layer  $dz$  in  $\text{s}^{-1}$ .

Richardson numbers were calculated for the layer between 0.3 and 9 m (layer  $dz$ ). The values showed that the atmospheric conditions were neutral or unstable for nearly all of the trials (Richardson number near or  $<0$ ).

Relative humidity and barometric pressure were recorded

at a height of 1.8 m above the ground. The upwind fetch was unobstructed and properly represented the area of the drift and deposition. Tables 1 and 2 show summary statistics for wind speed, temperature, and relative humidity for each set of studies.

#### Sprayer setup and use

A Cessna Ag Husky® (Cessna Aircraft Company, Wichita, KS, USA) piston engine-powered aircraft flying at 47 to 52 m/s was used for all applications of the standard treatment and most of the variable treatments. This aircraft had been modified to allow application of two tank mixes through separate sets of spray tanks, pumps, booms, and nozzles. The two booms were never used simultaneously in order to avoid any potential interference between the sprays. Applications were also made using an Air Tractor 502 (Air Tractor Corporation, Olney, TX, USA) turbine engine-powered fixed-wing aircraft and a Wasp (Bell Textron, Houston, TX, USA) rotary-wing aircraft (helicopter). These two aircraft represented typical relatively high (66–71 m/s) fixed-wing and low-speed (22–29 m/s) rotary applications, respectively.

Setting the width of the application area required careful consideration of the carrying capacity of the spray equipment relative to the size and time required to spray the area. A relatively large application area was needed to accurately simulate a full field application. However, it takes longer to spray larger areas, increasing the potential variability in meteorological conditions between the variable and standard applications.

Four parallel swaths (flight-line passes), the maximum number that could be applied by the modified Cessna Ag Husky® aircraft without reloading, were used in the aerial studies, for an overall spray block width of 50 m. The on-target application rates were verified using 1,000  $\text{cm}^2$  horizontal alpha-cellulose strips on the ground perpendicular to the line of flight. The alpha-cellulose strips spanned 20% of the total swath width (where swath width is the width of the spray deposition from flight passes), producing samples that covered in-swath variation.

The application scenarios (treatments) are summarized in Table 3. The treatments included different sprayer setups (nozzle types, nozzle angles, spray pressures, and tank mixes) for investigating effects on off-target spray movements. The nozzle types (supplied by Spraying Systems, Wheaton, IL, USA) and mean  $D_{v0.5}$  and %vol  $< 141 \mu\text{m}$  values included flat fan nozzles 8002 (with  $D_{v0.5} = 160$ ; %vol  $< 141 \mu\text{m} = 45.1\%$ ) and 8003 ( $D_{v0.5} = 178$ – $332 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} = 6.4$ – $40.4\%$ ); disc-core (swirl) nozzles D4-45 ( $D_{v0.5} = 107$ – $173 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} = 33.8$ – $69.9\%$ ), D6-46 ( $D_{v0.5} = 178$ – $359 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} = 15.0$ – $33.8\%$ ), and D8-46 ( $D_{v0.5} = 340 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} = 6.0\%$ ); solid stream (jet) nozzles D6 ( $D_{v0.5} > 811 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} < 0.2\%$ ) and D8 ( $D_{v0.5} = 413$ – $546 \mu\text{m}$ ; %vol  $< 141 \mu\text{m} = 2.1$ – $6.5\%$ ), where  $D_{v0.5}$  is the

Table 2. Summary statistics for temperature and relative humidity during field trials

Study	No. of trials	Mean ( $^\circ\text{C}/\%$ )	Median ( $^\circ\text{C}/\%$ )	Minimum ( $^\circ\text{C}/\%$ )	Maximum ( $^\circ\text{C}/\%$ )
Plainview 1992	74	27.0/63.2	26.4/62.2	21.1/35.6	32.8/92.6
Plainview 1993	48	13.4/39.9	12.7/35.5	0.2/7.1	29.0/91.4
Raymondville 1993	60	30.7/63.9	31.5/58.6	24.2/43.1	35.1/93.8
Overall	182	24.7/57.3	27.1/57.3	0.2/7.1	35.1/93.8

Table 3. Summary of spray parameters for Spray Drift Task Force aerial field studies

Nozzle type/ angle down (°)	Spray pressure (kPa)	Application volume (L/ha)	Boom height <sup>a</sup>	Boom length <sup>b</sup>	Carrier (water/ soybean oil)	D <sub>v0.5</sub> (μm)	Spray volume < 105 μm (%)	Spray volume < 141 μm (%)
Rotary-wing aircraft (21–25 m/s)								
8003 (45)	200	12	VL	73	Water	332	2.0	6.4
D4-46 (45)	200	25	VL	73	Water	339	2.1	6.2
D4-46 (45)	200	26	MH	73	Water	339	2.1	6.2
D6 (0 back)	200	57	VL	73	Water	811	0.1	0.2
D6 (0 back)	200	56	MH	73	Water	811	0.1	0.2
Piston engine-powered fixed-wing aircraft (47–52 m/s)								
8002 (90)	214	2.8	L	68	Oil	160	35.3	45.1
8002 (90)	214	2.8	H	68	Oil	160	35.3	45.1
D4-45 (45)	214	15	L	68	Water	173	17.6	33.8
D4-45 (45)	214	13	H	68	Water	173	17.6	33.8
D6-46 (45)	214	28	H	68	Water	263	7.8	15.0
D8-46 (0 back)	214	63	L	68	Water	340	2.0	6.0
D8-46 (0 back)	214	65	H	68	Water	340	2.0	6.0
D8 (0 back)	214	70	L	68	Water	546	0.7	2.1
D8 (0 back)	214	67	H	68	Water	546	0.7	2.1
D6-46 (45)	214	30	L	82	Water	263	7.8	15.0
D6-46 (45)	214	29	L	68	Water	263	7.8	15.0
D6-46 (45)	214	30	L	68	Water	178	18.9	33.8
D6-46 (45)	214	30	L	68	Water	318	13.8	20.3
D6-46 (45)	214	33	L	68	Water	256	8.5	15.3
D6-46 (45)	214	35	L	68	Water	325	12.8	19.1
D6-46 (45)	214	30	L	68	Water	235	12.4	20.6
D4-45 (45)	214	16	L	68	Water	173	17.6	33.8
D4-45 (45)	214	16	L	68	Water	173	17.6	33.8
D4-45 (45)	214	14	L	68	Water	173	17.6	33.8
D8 (0 back)	214	74	L	68	Water	546	0.7	2.1
D8 (0 back)	214	69	H	68	Water	546	0.7	2.1
D8 (0 back)	214	73	L	68	Water	546	0.7	2.1
D6-46 (45)	214	30	L	68	Water	263	7.8	15.0
D6-46 (45)	179	32	L	68	Water	359	17.8	31.2
D8 (0 back)	214	74	L	68	Water	546	0.7	2.1
D4-46 (45)	214	14	L	68	Water	173	17.6	33.8
D6-46 (45)	214	30	L	68	Water	263	7.8	15.0
D6-46 (45)	193	30	L	68	Water	200	16.3	26.6
D6-46 (45)	200	30	L	68	Water	241	10.8	18.8
8002 (90)	214	3.2	L	68	Oil	160	35.3	45.1
8003 (30)	200	5.1	L	68	Oil	178	28.6	40.4
Turbine engine-powered fixed-wing aircraft								
D6-46 (45)	214	36	L	68	Water	163	22.6	38.8
D8 (0 back)	214	68	L	68	Water	413	3.2	6.5
D4-45 (45)	214	12	L	68	Water	107	49.2	69.9
D6-46 (45)	214	35	L	68	Water	163	22.6	38.8
D8 (0 back)	214	72	L	68	Water	413	3.2	6.5

<sup>a</sup> VL = very low (1.6–1.8 m); L = low (2.2–2.9 m); MH = medium high (4.0–5.4 m); H = high (6.9–9.3 m).

<sup>b</sup> Percent of wing semispan.

volume median droplet diameter, i.e., the diameter within the droplet size spectrum at which half of the droplets by volume are contained in larger droplets, and %vol < 141 μm is the percentage of the spray volume contained in droplets with diameter below 141 μm (considered by many to be close to the droplet sizes more likely to drift under unfavorable conditions [7]).

The treatments also included boom lengths of 69 and 82% of the wing span since the spray release position relative to the wing-tip vortices affects droplet movements. Boom length expresses the percentage extent of nozzle positions across the spray boom relative to the length of the aircraft wingspan or helicopter rotor diameter. Spray release height treatments varied from 1.8 to 9.4 m above the ground. The use of oil as a carrier for the ultralow volume applications, the effects of tank mix physical properties, and crop canopy effects on spray movements were also studied.

### Verification of application rates

The on-target application rates were established by careful mixing of the required volumes (see Table 3) of the active ingredient tracers (diazinon, malathion—at 10% of commercial rates), carrier liquid (water or oil), and any adjuvants (surfactants/polymers). The application rate was established through calibration of the spraying system (number of nozzles, flow rate through nozzles, flight speed) and effective swath width. As a check in the field, tank samples were taken prior to and following the application for analysis for tracer concentrations and were frozen until analysis.

### Collectors

The selection of collectors for field studies depends on many issues such as suitability for collecting and extracting the tracers, ease of use, and representativeness for the sur-



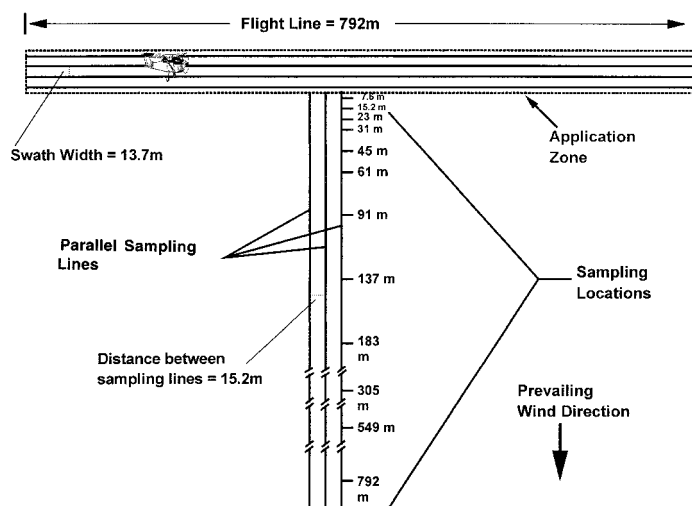


Fig. 1. Layout of test site for aerial field studies showing flight and sampling lines and sample station locations from 8 to 792 m downwind. Although not shown here, a sample station was also located at a distance of 10 m upwind of the spray block. Four swaths were flown on field for each application.

face(s) that are being simulated. Collection efficiency is related to the shape and dimensions of the collector with respect to the drift particle flow field, the local wind speed, and the size and velocity of the droplets in the spray cloud [17,18]. Computer modeling indicates that turbulence intensity may also be important for some conditions [19]. Droplet collection occurs by impaction and sedimentation. Impaction predominates on vertical surfaces, while sedimentation is the main mechanism of collection by fallout onto horizontal surfaces.

The SDTF reviewed the available techniques and selected four types of collectors. Other reviews of field drift sampling techniques exist elsewhere (e.g., [20]). The primary collector used in the development of the database and subsequent models was alpha cellulose (type GR512, Procter & Gamble, Cincinnati, OH, USA), a cotton pulp product thick and stiff enough to facilitate handling under field conditions. The absorbent texture of the alpha-cellulose samplers enabled droplets to be captured while maintaining tracer stability and allowing efficient analytical extraction. Alpha cellulose samplers were fixed horizontally on the ground at all collection sites. Each sampler consisted of a 1,000 cm<sup>2</sup> surface area. There were three of these samplers at each downwind distance, separated by approximately 15 m. The data from these collectors were a measure of deposition primarily by sedimentation, representative of spray collection on ground and aquatic surfaces. Being fibrous in nature, the alpha-cellulose samplers collect some material by impaction, though the primary collection is sedimentation deposition.

#### Sampling layout

All studies were set up with distinct application and off-target drift areas. The American Society of Agricultural Engineers standard procedure for drift studies S-561 [21] suggests that the application length should be at least 0.6 times the length of the collection area. The ratio in the SDTF aerial field studies was 0.8 (application length = 650 m; drift sampling area = 850 m length).

The layout of the field sites is shown in Figure 1. Sampling stations were located at 7.6, 15.2, 23, 31, 45, 61, 91, 137, 183, 305, 549, and 792 m downwind of the edge of the spray block.

Distances were close together immediately downwind from the application area because this area is where most of the differences among treatments would occur and where most of the driftable material would fall and are important in considering buffer zones, a potential regulatory use of the SDTF data. Three collector stations were established 15.2 m apart, at each distance perpendicular to the application area. A single sampling station was also located at a distance of 30 m upwind of the spray block to confirm that drift does not occur in the upwind direction and to check for any background contamination. Since the closest collector to the edge of the field was 7.6 m, meaningful data on deposition closer to the field than this cannot be inferred. The drift sampling lines were set up to be perpendicular to the flight line. Adjustments for deviations from this direction during actual applications, including considerations of effects on the most distant sampling stations, are discussed in the model evaluation article in this series [12]. No account was taken of possible contamination of the samplers by tracer-loaded soil particles that might be blown by the wind, which means that the deposition data might be slightly higher than expected if this did occur for any of the applications under higher wind speed conditions.

#### Sample handling

Following the application of the standard and variable treatments, the drift cloud was allowed to completely pass the furthest sampling stations prior to sample collection (calculated based on droplet release height and wind speed and then doubled to give a maximum of 25 min after application). The samples were then collected, sealed in clear plastic bags, placed on dry ice, and taken to a freezer for storage and shipment. At the analytical laboratory, malathion and diazinon tracer analytes were extracted from the alpha-cellulose collectors and simultaneously analyzed by gas chromatography.

#### Canopies

The SDTF field studies involved applications over bare ground, representing worst case conditions for spray drift. The presence of a canopy would be expected to reduce drift as the droplets are intercepted by vegetation. Studying the effects of crop canopy on drift can be difficult due to the large variety of vegetation types and structures (height, density, orientation, etc). Two treatments involving a cotton canopy were included in the SDTF database only as a means of demonstrating that canopy is a significant factor in drift. The cotton canopy comprised 104-cm-tall plants in 76-cm rows. The plants were at the green boll stage of development and provided a full canopy. Two cotton canopy treatment comparisons were included in the study. One treatment involved a four-swath application starting at the edge of the cotton field (outside treatment). The second treatment involved a four-swath application beginning 59 m (four swaths) in from the edge of the field (inside treatment).

#### Atomization studies

The measurement of droplet size spectra under field conditions introduces many sources of variability and uncertainty compared with the controllable and easily monitored environment of a wind tunnel. Field assessments of droplet size typically involve collection of a sample of the spray cloud and subsequent measurement of the droplet sizes [22,23]. Such techniques are intrusive and may not sample the smallest droplets efficiently. Furthermore, the droplets are measured after

evaporative and other effects may have caused them to change in size following emission through the nozzle. Some success has been found measuring droplet size on aircraft sprayers using optical array probes [24]. However, such measurements are relatively difficult, expensive, and time consuming compared with using a wind tunnel to simulate the sprayer. Highly accurate laser-based instruments are used to measure droplet size in wind tunnels. Wind tunnels have been successfully used for several decades at research facilities around the world to make such measurements. Previous studies have shown good agreement between droplet size spectra data measured in wind tunnels and on fixed-wing aircraft (e.g., [24]).

It was assumed that generic phenomena such as droplet size effects on drift from aerial applications can be covered for a wider range of nozzles than were tested in the field. At the initiation of the SDTF studies, disc-core nozzles were most common. However, during the course of the SDTF studies, a deflector nozzle (CP nozzle, CP Products, Mesa, AZ, USA) was introduced to the market and quickly became widely used. Therefore, the SDTF conducted droplet size measurements for this nozzle type to provide a more complete database. By knowing the droplet size spectrum for any aerial nozzle, drift potential can be predicted from the existing database and models. In cases where other factors influence drift, e.g., with applications using electrostatic or wing-tip modification systems, additional tests may be needed to demonstrate drift potential.

An underlying objective of the SDTF atomization studies was to evaluate a wide range of droplet size spectra through the use of a range of typical commercial practices. Within each aircraft speed, the different spray volumes and droplet size spectra were achieved by changing nozzle type, orifice size, and/or orientation. The nozzle types, application volume rates, and summary droplet size spectra statistics are shown in Table 3.

### Equipment

The SDTF atomization studies were conducted using wind tunnels at New Mexico State University (Las Cruces, NM, USA) and at SpraySearch, Werribee, Australia. The SDTF atomization studies measured droplet size spectra of simulated aerial sprays using Malvern (Malvern Instruments, Malvern, Worcestershire, UK) and Sympatec (Princeton, NJ, USA) laser diffraction particle size analyzers in wind tunnels. Details of the measurement procedures are described elsewhere [25]. Representative sampling for the nonuniform sprays was achieved using a continuous scan technique or multiple measurements at different heights within the spray plume [26].

The wind tunnel studies included airstream velocities representing those encountered in applications with helicopters (18–36 m/s) and fixed-wing piston engine- (36–54 m/s), and turbine engine- (54–72 m/s) powered aircraft. The major nozzle types used for commercial applications and tested in the wind tunnel studies include simplex swirl (disc-core), jet (solid stream), hollow and full cone, flat fan, deflector, rotary cage, rotary drum, spinning disc, air shear, and preorifice twin fluid (including air inclusion and air induction). Several different designs and sizes were tested for many of these nozzle types. The measured droplet size spectra were used to develop models for predicting droplet size and drift for aerial spray applications. The study findings were too numerous to be comprehensively reported here, so only major findings are discussed.

### Physical property studies

For database and modeling developments, the SDTF also measured droplet size spectra for combinations of application variables and liquid physical properties encompassing a wide range of possible aerial spray applications. These data, in conjunction with the model, yield drift data for a much wider range than those of typical or normal agricultural tank mixes.

The physical properties of agricultural tank mixes can affect drift mainly through their effect on the initial droplet size spectra emitted from the sprayer and through subsequent decreases in droplet size from evaporation. The SDTF developed a database on physical properties for the tank mixes that were sprayed in the field and atomization studies. Atomization was shown to be related to several physical property parameters that can be measured using various techniques. These included the dynamic surface tension at surface lifetime ages representative of the atomization process for typical hydraulic agricultural nozzles (e.g., 20 ms) and shear and extensional viscosity. Dynamic surface tension was measured using a maximum bubble pressure technique [27]; shear and extensional viscosity were measured using a Rheometrics RFX instrument [28] (this instrument is no longer being manufactured). Shear viscosity was assessed at shear rates up to 10,000/s, with low and high shear viscosity being represented by shear rates of 1 and 8,000/s, respectively. Extensional viscosity was represented by the maximum inertia-corrected value measured at strain rates up to 20,000/s. The ratio of extensional to shear viscosity, referred to as effective Trouton ratio, was an appropriate way to represent viscous forces for modeling atomization/physical property relationships [29].

Evaporation rates were measured using a video-imaging technique that assessed the rate of change of droplet mass over time for different conditions (e.g., temperature and relative humidity, formulations, and droplet diameters [30,31]).

## SUMMARY OF RESULTS

### Aerial field studies

*Calculation of application rate.* Ideally, the tank mix samples would agree with the application volume rate established from the tank mix preparation. However, there was a discrepancy between these two values. For malathion, the mean pre- and postapplication tank mix samples were 85 to 106% of the target concentrations from the mixing recipes. For diazinon, the mean was 91 to 108%. Although there were differences in tank sample concentrations between studies and treatments, there was no significant difference between tracer concentration rates for the pre- and postapplication samples within a given treatment. This supports the concept that there was no degradation of the tracers during application. The difference between the target recipe and tank sample tracer application rates could be due to several factors.

Since the tank mixes included emulsifiable concentrate formulations, the active ingredient was held in suspension and subject to a somewhat heterogeneous mixture. Study protocols specified that the tank mixture must be continually agitated. However, it is possible that the small sample volumes (10 ml) relative to the total tank mix (110 L) may not have been totally representative of the entire tank mix. Prior to analysis, the samples were serially diluted, which can magnify (or compound) small deviations. Finally, the exact amount of active ingredient withdrawn is subject to variation from the type of pipette used. During the initial phases of testing, the SDTF

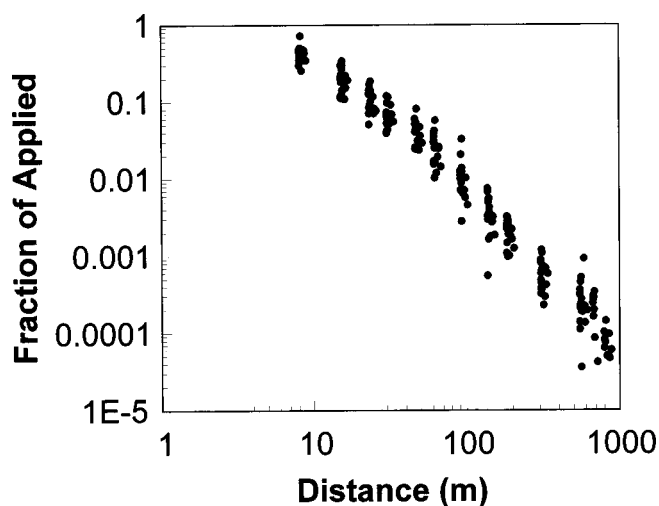


Fig. 2. Deposition with distance from edge of spray block. Example for standard applications with wind speeds of 9 to 11 m/s.

determined that pipettes or syringes with small inlet orifice diameters could produce a bias toward the withdrawal (sampling) of aqueous solution.

The actual application rates were based on the measured average flight speed and flow rate, lane separation of 13.7 m as the swath width, and a tank mix concentration based on the field mixing recipe. A data logger was installed on the aircraft to monitor these parameters. Aircraft flight speed was measured using a radar gun.

**Deposition.** This section describes deposition data on horizontal alpha-cellulose collectors. It should be noted that the deposition rates measured for applications with sprays finer than coarse and applications at relatively high wind speeds were higher in the SDTF studies than would be expected in real-world situations because the SDTF data were not adjusted for swath adjustment, which is a common practice in most aerial applications [14]. Swath adjustment can, however, be applied with drift assessments using the AgDRIFT® model.

Overall, the SDTF results were consistent with observations in previous drift studies [1]. Off-target deposition rates were always highest within a relatively short distance of the edge of the application area and decreased rapidly with distance (Fig. 2). This figure is a set of standard case applications in a narrow range of wind speeds (9–11 m/s) and illustrates the declining deposition with distance from the edge of the field (distance = 0 m) as droplets deposit by sedimentation (and, to a much lesser degree for horizontal collectors, impaction) on surfaces. The wide range of deposition values at each measurement distance shown in Figure 2 cannot be directly explained by any of the variables observed during the trials. This level of variability is consistent with variability observed in other field trials.

The selection of tracer, diazinon or malathion, did not have a large effect on deposition rate measurements and so was not a major source of variability, as shown on Figure 3. However, diazinon did generally show lower deposition rates beyond 300 m from the edge of the field. This is probably due to volatile losses of diazinon at far-field distances due to its greater volatility than malathion.

**Flight speed.** Aircraft flight speed is one of the most important variables affecting droplet size. Different aircraft types can operate at different speeds. The SDTF field studies in-

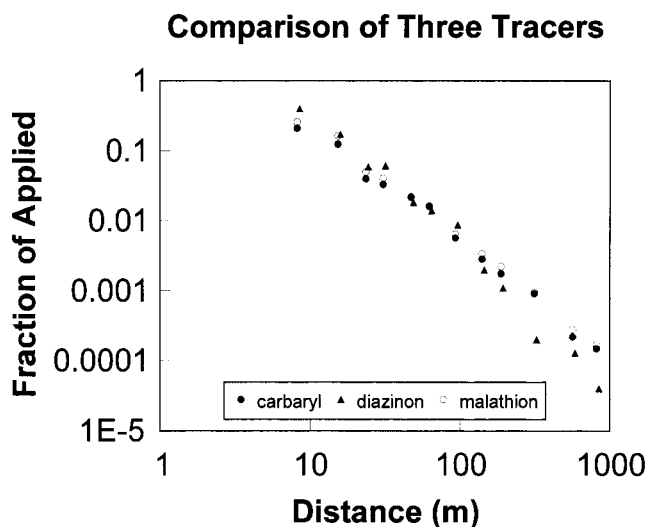


Fig. 3. Spray deposition against downwind distance from edge of spray block for different tracers.

cluded rotary-wing aircraft and piston and turbine engine-powered fixed-wing aircraft. These were operated at increasingly high speeds for the SDTF studies, in the respective order 28, 48, and 68 m/s mean flight speed. The increasing air shear associated with these higher speeds results in finer sprays. This can be partly offset through the selection of different nozzle types and uses such as lower operational pressure that can increase droplet size. Figure 4 shows the off-target deposition that was measured in the field for these three aircraft types. All of these applications were made using D6-46 or D4-46 disc-core nozzles with spray pressure around 200 kPa and a medium-volume application rate. As explained above, the higher speed applications produced higher downwind deposition rates primarily because they produced finer sprays. The sprays showed droplet size spectra using D6-46 nozzles of, for high-speed application,  $D_{v0.5} = 163 \mu\text{m}$  and  $\% \text{vol} < 141 \mu\text{m} = 38.8\%$ ; for medium-speed application,  $D_{v0.5} = 263 \mu\text{m}$  and  $\% \text{vol} < 141 \mu\text{m} = 15.0\%$ ; and for low-speed application,

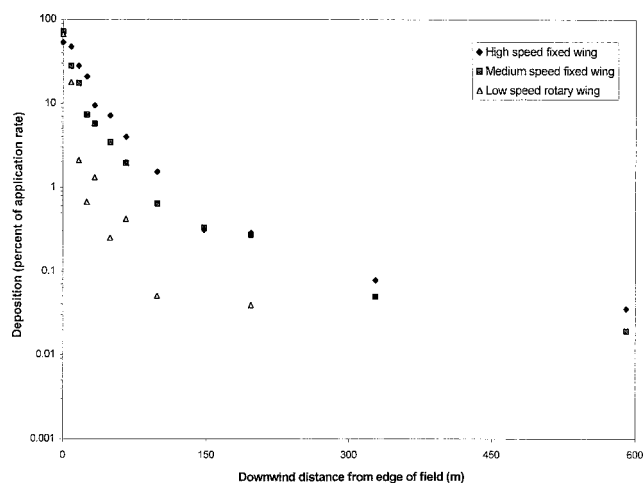


Fig. 4. Mean deposition rates for applications with different aircraft (high-speed fixed-wing producing fine spray, medium-speed fixed-wing producing medium spray, and low-speed rotary-wing producing coarse spray) with medium volume rate. Rotary-wing aircraft data only plotted to 200 m because deposition beyond 200 m was less than the level of quantification.

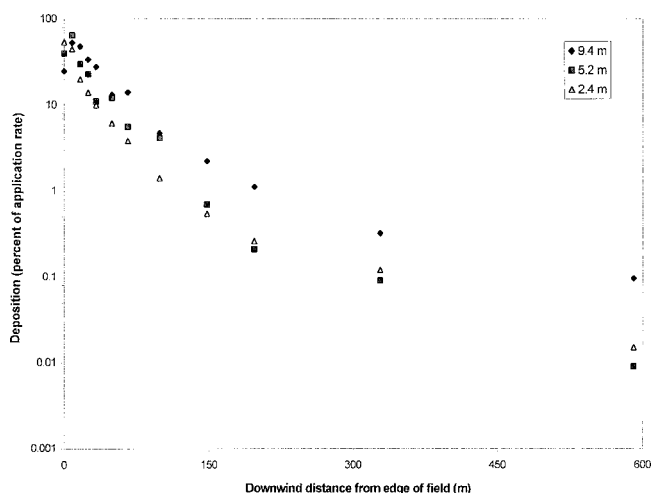


Fig. 5. Deposition rates for different spray release heights (2.4, 5.2, and 9.4 m above ground) with low volume rate, fixed-wing aircraft application.

$D_{v0.5} = 339 \mu\text{m}$  and  $\% \text{vol} < 141 \mu\text{m} = 6.2\%$ . Using the British Crop Protection Council (BCPC) [32] and American Society of Agricultural Engineers S-572 [33] spray classification schemes, these were fine, medium, and coarse sprays, respectively. Data for deposition with the rotary-wing aircraft application at distances beyond 200 m were not plotted because recovery rates were lower than the level of quantification, indicating extremely low deposition rates at these far-field distances.

**Spray release height.** Sprays are applied in the field at release heights that are appropriate for obtaining effective spray coverage in flight swaths while maintaining a safe distance from the ground. For a low application volume rate with the fixed-wing piston engine aircraft, drift potential at distances up to 200 m from the edge of the sprayed field increased with greater spray release height (Fig. 5) due to the greater fall distance and opportunity for wind displacement prior to sedimentation deposition. At distances beyond 200 m, the greatest release height always produced the highest off-target deposition rates. Beyond 200 m, the lowest release height deposition rate was not significantly different from the medium release height.

**Boom length.** The movement of aircraft tends to cause a roll-up of air into trailing vortices from each wing or rotor tip. If droplets become entrained in the vortices, they may be displaced vertically and laterally, often increasing the potential for drift. Boom length can be adjusted relative to the wing semispan to offset this effect. Figure 6 shows the slight decrease in off-target deposition when the boom length was decreased from 84 to 69%. The missing data point for the 84% boom length at a distance close to 600 m reflects the fact that the deposition rate for this location was lower than the level of quantification. The data shown on Figure 6 are for an application of a medium spray at a medium flight speed (piston engine fixed-wing aircraft). Further decreases might be expected for finer sprays and shorter boom lengths than 69%, based on model predictions using AgDRIFT® [34,35], which supports the suggestion that shorter boom length is important in practical drift management with aerial spray applications.

**Wind speed.** Wind speed is an important meteorological variable affecting spray drift potential. Figure 7 shows de-

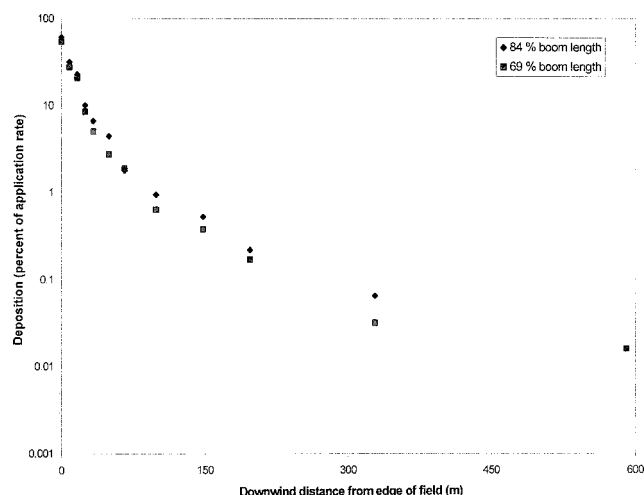


Fig. 6. Deposition rates for different boom length (84 and 69% of wing semispan) with medium volume rate, fixed-wing aircraft application.

position for different wind speeds for the standard application. Off-target deposition increased with higher wind speeds due to droplet transport to greater lateral distances prior to sedimentation deposition. The wind speeds were measured at a height of 3 m above the ground.

**Canopy.** Two cotton canopy treatment comparisons had been included in the drift studies. One treatment involved a four-swath application starting at the edge of the cotton field (outside treatment). The second treatment involved a four-swath application beginning 59 m (four swaths) in from the edge of the field (inside treatment). There was no significant difference in downwind deposition between the no-canopy (bare ground) standard treatment and the outside treatment (see above). However, downwind deposition appeared to be reduced by a canopy when the tracer was applied in the inside treatment scenario in which drift moved across and through four swaths of cotton canopy (Fig. 8). It should be noted that these results do not reflect downwind deposition with swath adjustment (offsetting the aircraft position to compensate for cross wind). If appropriate swath adjustment had been applied, then the canopy may have intercepted a relatively greater

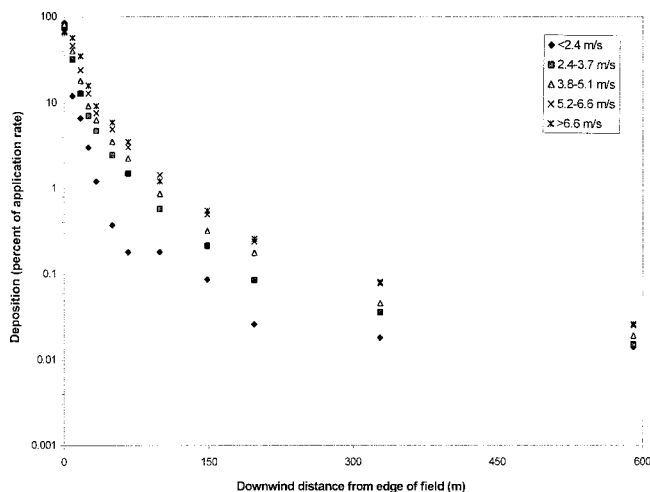


Fig. 7. Deposition rates for different wind speed ranges (wind speed measured at 10 ft. above ground) with standard treatment conditions.



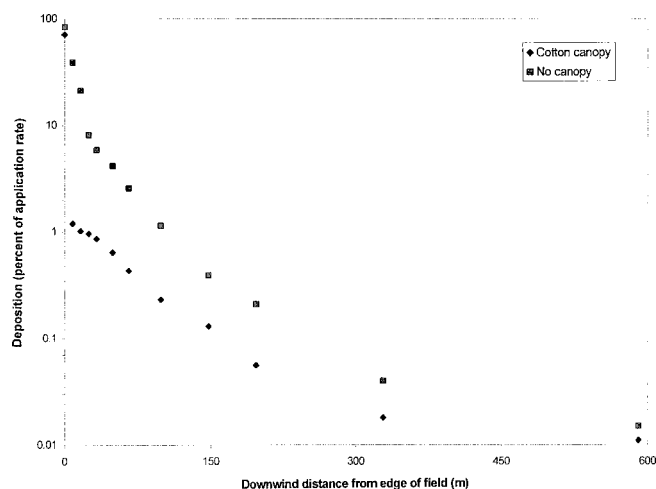


Fig. 8. Deposition rates for application with and without cotton canopy. Same equipment setup with and without canopy—piston engine fixed-wing aircraft,  $D_{v0.5} = 263 \mu\text{m}$  and %vol  $< 141 \mu\text{m} = 15\%$ .

amount than the no-canopy treatment. These results also probably do not represent all canopy types. Different trends might be expected with different canopy types and locations.

With no swath adjustment, the cotton canopy only slightly decreased downwind ground deposition when applied near the downwind edge of the canopy. However, it reduced downwind exposure from airborne droplets. There was a substantial decrease in ground deposition for treatments applied further inside the cotton canopy. The results also indicate that the worst case drift scenario is associated with low-growing vegetation or no vegetation, the standard condition for most of the SDTF applications. It should be noted that these canopy effect treatments were very limited in replication and scope and so only illustrate general trends.

**Atomization.** With a few noted exceptions, the droplet size spectra produced by the hydraulic nozzles generally became coarser with lower airstream velocity, larger orifice diameter (within a nozzle type), lower liquid pressure (except with solid-stream jet nozzles at small angles to airstream), and lower nozzle angle relative to the airstream. Solid-stream nozzles and some nozzles described by the manufacturers as being low drift produced relatively coarse sprays. Examples of the droplet size spectra with the same  $D_{v0.5}$  for different nozzle types within the thousands of atomization data sets are shown on Figure 9. These were data sets that could be closely matched for liquid flow rate. The data show that substantial differences in droplet size spectra occurred with different nozzle types. Solid-stream nozzles generally produced the coarsest sprays (largest droplets), and the full cone nozzles produced relatively fine sprays (small droplets).

The sprays produced by flat fan nozzles became coarser (general increase in droplet size) with narrower spray angle. Spray angle is the angle formed by the spray plume as it leaves the nozzle. Going from 110 to 80, 65, and 40° spray angles, the flat fan nozzles produced coarser sprays. A comparison of flat fan and deflector nozzle tips produced by different manufacturers for similar flow and spray plume angle specifications showed that some sprays were similar while others differed. Differences, where observed, were due to differences in the nozzle designs. The sprays produced by the rotary atomizers became coarser with lower airstream velocity, lower rotation

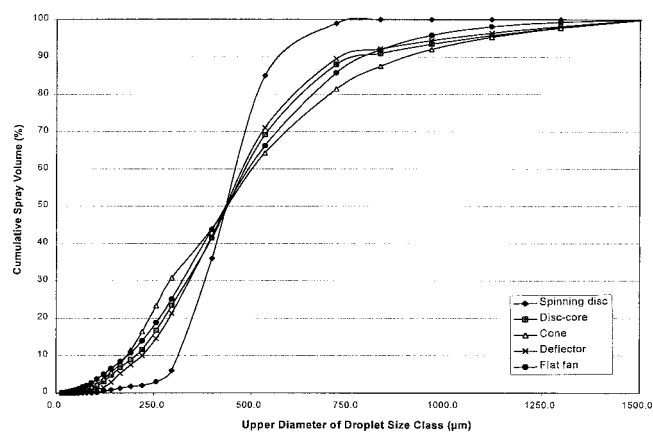


Fig. 9. Examples of cumulative volumetric droplet size spectra with same  $D_{v0.5}$  (volume median diameter) values but different distributions for different nozzle types spraying water.

rate, and higher liquid flow rate. A spinning disc atomizer produced very narrow droplet size spectra (relative span = 0.42–0.48) compared with hydraulic nozzles, which generally produced relative span values  $> 1$ . Relative span is a useful parameter for describing the width of a droplet size spectrum by volume, with a smaller value indicating that the droplets are contained in fewer size classes. It is calculated by  $(D_{v0.9} - D_{v0.1})/D_{v0.5}$ , where  $D_{v0.9}$ ,  $D_{v0.5}$ , and  $D_{v0.1}$  are the respective droplet diameters at which 90, 50, and 10% of the spray volume is contained in droplets with smaller diameter. Most of the trends observed in SDTF studies agreed with those reported in the literature (e.g., rotary atomizer tests [36] and hydraulic nozzle tests [37]).

#### Physical properties studies

Liquid physical properties were not as important as application variables for determining droplet size. The SDTF studies had investigated dynamic surface tension (at very short surface ages) and shear and maximum extensional viscosity. With a few exceptions, sprays tended to become coarser with higher dynamic surface tension, extensional viscosity, and shear viscosity. Droplet size produced by many non-Newtonian test substances containing a polymer was sensitive to agitation rates. The type and rate of agitation can be important for such substances [38]. Droplet size trends for the SDTF sprays have been summarized and confirmed elsewhere [39].

Evaporation was found to occur at a constant rate within a given temperature/relative humidity regime. The only effect of physical properties on droplet evaporation was the final droplet size achieved (i.e., the nonvolatile fraction). More discussion of evaporation effects from the SDTF database is provided elsewhere [30,31,40].

Further information on the SDTF atomization and physical property studies is provided in the following publications. The SDTF atomization study designs and measurement techniques were described earlier [25,39,41]. The results are summarized in several articles [39,42]. The analysis of the data to develop atomization models is explained [29,43,44], and the inclusion of the atomization data and models within the AgDRIFT model is discussed [45].

#### DISCUSSION AND CONCLUSIONS

The SDTF field drift studies and associated atomization and physical property studies showed that spray drift is af-

ected by many variables associated with the application, droplet size spectrum, meteorological conditions, and spray release position. Drift tended to be greater with the application of smaller droplets, greater release heights, greater wind speeds, and greater boom lengths. The findings of the SDTF studies were very extensive. More information on the studies and detailed description of the protocols and techniques are included in other reports [46,47]. The results have been used to develop and validate modeling tools that are described in the two other articles in this series [11,12].

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