Journal of ASTM International, Vol. 6, No. 4
Paper ID JAI102122
Available online at www.astm.org

W. Clint Hoffmann,[1] *Bradley K. Fritz,*[1] *and Y. Lan*[1]

Evaluation of a Proposed Drift Reduction Technology High-Speed Wind Tunnel Testing Protocol

ABSTRACT: The U.S. Environmental Protection Agency (EPA) has initiated the development of protocols for for measuring spray drift reduction technologies (DRTs) related to the application of agricultural protection chemicals. The DRT Program is an EPA-led initiative program to "achieve improved environmental and human health protection through drift reduction by accelerating the acceptance and use of improved and cost-effective application technologies." The first step in implementing the DRT program is to develop a set of protocols, standard operating procedures, and data quality assurance steps so that the results from any trials or research conducted are scientifically valid and repeatable. A protocol for measuring spray droplet spectra via laser diffraction equipment in a high speed wind tunnel (air velocities >160 kph (100 mph)) was tested. Following the proposed protocol, five reference nozzles were evaluated with spray solutions of deionized water, water + 9 % isopropanol, and water + 0.25 % of a nonionic surfactant. Each of the nozzle and spray solution combinations were evaluated in 160, 193, and 225 kph (100, 120, and 140 mph) airstreams, as well as under static (0 kph) conditions. The results of these atomization studies showed that there were significant differences in droplet spectra between the spray solutions and from the different air velocities. Based on the time to complete the tests, the author suggest using a ±5 % standard deviation values as criteria for accepting atomization tests results.

KEYWORDS: spray classification, atomization, DRT, aerial application

Introduction

Drift continues to be one of the major concerns of the spray application industry. The need for the development of a testing program for measuring drift reduction technologies (DRTs) was recognized by the EPA in 2004 [1]. Drift reduction technologies can be spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers (adjuvants), landscape modifications, or any combinations thereof. The DRT Program is an EPA-led initiative program to "achieve improved environmental and human health protection through drift reduction by accelerating the acceptance and use of improved and cost-effective application technologies." [2] The first step in implementing the DRT program is to develop a set of protocols, standard operating procedures, and data quality assurance steps so that the results from any trials or research conducted are scientifically valid and repeatable. Data quality and protection must also be maintained throughout the study [3,4]. These protocols are being developed in compliance with American, European, and International standards [5]; however, most of these standards are focused on drift deposition and not droplet size measurement near the nozzle.

The work in this article will report on the initial implementation of the DRT program by developing the necessary protocols and conducting DRT evaluations under high-speed conditions (i.e., >100 km/h (~60 mph)), which are relevant to the aerial application of crop production and protection materials. The development of these protocols relies on both established Professional Standards, such as ASTM "Standard Methods for Testing Hydraulic Spray Nozzles Used in Agriculture" (E361-01) [6], ASAE Standard "Spray Nozzle Classification by Droplet Spectra" (S572) [7], ASAE Standard "Procedure for Measuring Drift Deposits from Ground, Orchard and Aerial Sprayers" (S561.1) [8], and peer- and EPA-reviewed protocols developed by the authors, who are working with an EPA consulting firm to develop the protocol presented in this paper.

The measure of performance for the DRT for high-speed wind tunnels will be derived from droplet size distribution measurements. These values will be used by EPA to model deposition from 0 m to 60 m (0–200 ft) downwind. The basic experimental design will be used to measure the droplet size spectrum

Manuscript received September 18, 2008; accepted for publication February 13, 2009; published online March 2009.
[1] Agricultural Engineer, USDA-ARS, 2771 F&B Road, College Station, TX 77845.

Report Documentation Page						Form Approved OMB No. 0704-0188
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE **SEP 2008**		2. REPORT TYPE			3. DATES COVERED **00-00-2008 to 00-00-2008**	
4. TITLE AND SUBTITLE **Evaluation of a Proposed Drift Reduction Technology High-Speed Wind Tunnel Testing Protocol**					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **United States Department of Agriculture (USDA),Agricultural Research Service (ARS),2771 F&B Road,College Station,TX,77845**					8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT **see report**						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**		

TABLE 1—*Flat fan nozzles used in the spray atomization tests.*

Nozzle Spray Angle, (deg)	Nozzle Orifice	Classification Category	Operating Pressure, kPa (psi)
110	01	Very Fine/Fine	450 (65)
110	03	Fine/Medium	300 (43)
110	06	Medium/Coarse	200 (29)
80	08	Coarse/Very Coarse	250 (36)
65	10	Very Coarse/Extra Course	200 (29)

under targeted test conditions with the DRT operating at specified spray pressure, air speed, and the "ambient" conditions. The measured droplet size spectrum of the DRT system and the reference nozzle, along with the established test condition bounds, will be used to predict deposition downwind of an aeriall-applied swath using a spray drift model such as AGDISP [9,10]. The proposed use of these data will be to compare predicted downwind deposition values from the candidate test systems to the predicted values from the reference spray system.

The specific objectives of these tests are:

- To describe a protocol for testing drift reduction technologies (i.e., nozzles) in a high-speed wind tunnel;
- To evaluate a set of reference nozzles and determine the effects of airspeed, nozzle orientation, and spray solution on droplet spectra;
- To evaluate the described protocol.

Materials and Methods

Framework of Proposed High-Speed Wind Tunnel Testing Protocol

The DRTs tested under this protocol were evaluated using a high-speed wind tunnel [11], where the measure of performance was derived from droplet size distribution measurements made using laser diffraction instrumentation. Droplet size spectra were measured with the DRT operating at targeted test conditions, which include a specified spray pressure, air speed, ambient (temperature and relative humidity) conditions, and other operational conditions that may be unique to a specific DRT. Droplet size measurements were collected with a Sympatec HELOS laser diffraction system (Sympatec Inc., Lawrenceville, NJ). For each set of test conditions, a minimum of three replications were conducted. The full spray volume was traversed for each replication, with each traverse requiring 20–30 s for completion. The primary operator of the laser diffraction instrumentation control software input all test parameter information into the software's database system, which tags each test replication with the appropriate identification data. Collected droplet size distribution data were processed and analyzed to insure that Data Quality Indicator Goals (DQIGs), as specified in the protocol, were met. These DQIGs include guidelines on acceptable variances in spray flow rate (± 0.04 L/min), spray pressure (± 3.4 kPa), spray material and air temperature (measured within $0.1°C$), air speed (between 20 m/s and 80 m/s (50–180 mph) measured ± 2.2 m/s (5 mph)), and acceptable standards deviation on the droplet size measurements. The exact procedures used in these tests are further elucidated in the projects Standard Operating Procedure USDA-4.4: "Determining Cross-Section Average Drop-Size Distributions of Sprays." Many of the procedures follow those established by the Spray Drift Task Force [12].

Nozzles Used in Spray Atomization Tests

To test the proposed protocol, five nozzles (Table 1) were selected for testing the effects of airspeed, nozzle orientation, and spray solution on the spray droplet spectra. These nozzles establish the boundaries between spray classification categories per ASAE Standard "Spray Nozzle Classification by Droplet Spectra." All of the nozzles used were flat fan type nozzles produced by Spraying Systems, Inc. (Wheaton, IL). It has been shown that there are no significant differences between flat nozzles with the same nozzle angle and orifice from different manufacturers [13].

TABLE 2—*Spray solutions used in tests and their physical properties.*

Spray Solutions	Dynamic Surface Tension, mN/m @ 20 ms	Viscosity, cP @ 20°C
Deionized Water	72.2	1.0
0.25 % v/v 90 % NIS in Deionized water	52.5	1.1
9 % Isopropanol in Deionized water	46.7	1.5

Spray Solutions

Each of the nozzles were evaluated using three spray solutions (Table 2); deionized water, a deionized water solution containing 0.25 % volume/volume (v/v) of a 90 % nonionic surfactant (NIS) (R-11, Wilbur-Ellis Company, San Antonio, TX), and a deionized water solution with isopropanol at 9 % v/v. The dynamic surface tension and viscosity of each solution was measured. Dynamic surface tension was measured with a SensaDyne Surface Tensiometer 6000 (Chem-Dyne Research Corp., Mesa, AZ) using the maximum bubble pressure method. The gas flow rate settings were varied until surface age values were found less than and greater than 0.02 s. Then, a table of percent flow rate settings was built in 5 % increments to include the previous settings. This table was calibrated using 200 proof ethanol and pure water. The probes were lowered into the sample and the dynamic surface tension, bubble rate, bubble age, and temperature were measured at each setting in the table. The dynamic surface tension at 20 ms was linearly interpolated from the results. The tests were replicated three times. Viscosity was measured with a Brookfield Synchro-Lectric Viscometer (Model LVT, Brookfield Engineering, Middleboro, MA) using a UL adapter 0.1–100 cps range. The spindle was inserted into the sample. The motor was started and run until the dial reading stabilized and the reading was recorded.

Droplet Size Measurements

A Sympatec HELOS laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) was used to measure the droplet size of the spray material in the dispersion tunnel and presented to the cage and screen samples. The HELOS system utilizes a 623 nm He-Ne laser and was fitted with a lens (denoted by manufacturer as R7) with a dynamic size range of 0.5 μm to 3500 μm which is divided across 32 sizing bins. The laser system has two components, the emitter and the receiver, which were positioned across from each other and outside of the wind tunnel. The laser was horizontally positioned so that the beam was in the center of the wind tunnel outlet. The authors have found that in practice with the high-speed wind tunnel tests, the last two channels (i.e., sizing bins) of the HELOS system are turned off or not factored into the droplet size measurement results. These two channels represent the largest droplet size and tend to pick up some "noise" or random signals. With these two channels turned off, the dynamic range of the instrument is from 0.5 μm to 2460 μm. These channels are not turned off if any droplets are measured within two sizing bins of the smallest turned off channel. For these studies, this criteria meant that no droplets greater than 1740 μm were measured during any of the atomization tests.

Droplet size measurements included volume median diameters ($D_{V0.5}$) [14], and $D_{V0.1}$ and $D_{V0.9}$. $D_{V0.5}$ is the droplet diameter (μm) where 50 % of the spray volume or mass is contained in droplet of lesser diameter. $D_{V0.1}$ and $D_{V0.9}$ values, which describe the proportion of the spray volume (10 % and 90 %, respectively) contained in droplets of the specified size or less. The percent volume less than 200 μm, which is an indicator of the "driftable" portion of a spray, was also computed along with the Relative Span (RS) (Eq 1), which is a dimensionless measure of the spread of the droplet sizes in the spray:

$$\mathrm{RS} = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \tag{1}$$

All measurements were conducted at the USDA-ARS wind tunnel site in College Station (Fig. 1). Three replications were conducted for each combination of air speed, spray nozzle, spray solution, and nozzle orientation. In order to meet the DQIGs, the measured volume median diameter ($D_{V0.5}$), and the $D_{V0.1}$ and $D_{V0.9}$ (the droplet diameter bounding the upper and lower 10 % fractions of the spray) should vary by less than ±3 %. A replication comprised of traversing the entire spray plume through the Sympatec HELOS

FIG. 1—*Sympatec system positioned on both side of the high-speed tunnel with the tunnel outlet on the right side of the picture.*

laser beam nozzle at a distance of 61 cm (24 in) from the laser beam of the droplet measurement system. Tests were performed within the guidelines provided by ASTM Standard E1260-05: "Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Nonimaging Light-Scattering Instruments" [15].

Results

Over 400 replications comprising 105 combinations of nozzle type, nozzle angle, spray formulation, and airspeed were conducted. The effects of spray solution and nozzle orientations at airspeeds of 96–225 km/h (60–140 mph) are presented in the following section. The droplet spectra from the five nozzles in still air (0 km/h) for the three spray solutions (Tables 2–4) are presented as a reference, since this is the droplet classification data reported by nozzle manufacturers. These data are applicable to ground application but not to the high-speed conditions related to aerial applications conditions.

Spray Solution Effects on Droplet Spectra

The spray droplet spectra were affected by spray solution (Fig. 2). For each of the sprays nozzles, the largest droplet spectra were measured with the deionized water solution (Table 3) followed by the water +0.025 % v/v 90 % NIS solution (Table 4). The water +9 % isopropanol solution resulted in the smallest droplet spectra (Table 5). This trend is consistent with the decrease in dynamic surface tension between the three solutions, which follows the same descending order (Table 2).

Airspeed Effects on Droplet Spectra

At airspeeds other than 0 km/h, the droplet spectra generally decreased within each nozzle classification category as the airspeed increased. One of the more interesting trends in the data is the compression in the range of droplet sizes as the airspeed increased. For example, the differences between the Very Coarse/Extra Coarse (VC/XC) and Very Fine/Fine (VF/F) $D_{V0.5}$'s for the deionized water solution at 96 km/h (60 mph) was 452 μm but only 164 μm at 225 km/h (140 mph) (Table 3). These same differences were 342 μm and 123 μm at 96 km/h and 225 km/h, respectively, for the NIS solution (Table 4) and 331 μm and 113 μm at 96 km/h and 225 km/h, respectively, for the isopropanol solution (Table 5). For the water and NIS spray solution, the boundaries between the Fine/Medium (F/M) and Medium/Coarse (M/C) are indistinguishable in a 193 km/h (120 mph) airstream (Fig. 3).

TABLE 3—*Reference nozzle droplet size spectra for deionized water.*

Airspeed, km/h (mph)	Nozzle Category	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD	Relative Span
0 (0)	VF/F	53.5 ± 1.3	105.8 ± 1.2	175.6 ± 0.6	1.2
	F/M	79.5 ± 1.2	180.3 ± 12.7	372.9 ± 46.1	1.6
	M/C	94.7 ± 2.3	214.6 ± 8.8	460.1 ± 36.5	1.7
	C/VC	95.0 ± 10.2	296.5 ± 2.7	517.7 ± 21.0	1.4
	VC/XC	140.4 ± 17.2	422.7 ± 31.7	711.8 ± 58.8	1.4
96 (60)	VF/F	74.0 ± 8.4	159.3 ± 10.4	251.1 ± 7.7	1.3
	F/M	125.7 ± 2.1	241.0 ± 4.8	366.1 ± 11.5	1.0
	M/C	169.3 ± 5.0	342.2 ± 13.1	527.0 ± 42.1	1.0
	C/VC	234.2 ± 4.2	482.2 ± 3.5	784.1 ± 9.0	1.1
	VC/XC	319.6 ± 2.5	612.1 ± 3.1	966.2 ± 1.6	1.1
160 (100)	VF/F	69.9 ± 0.8	143.6 ± 2.0	215.1 ± 3.2	1.0
	F/M	126.9 ± 1.9	251.2 ± 2.7	395.0 ± 3.5	1.1
	M/C	137.8 ± 2.9	297.9 ± 7.3	482.8 ± 24.9	1.2
	C/VC	184.7 ± 3.2	386.2 ± 6.5	640.4 ± 27.7	1.2
	VC/XC	217.0 ± 0.6	456.4 ± 5.2	759.5 ± 36.8	1.2
193 (120)	VF/F	68.5 ± 0.5	149.1 ± 0.9	238.0 ± 4.1	1.1
	F/M	113.0 ± 0.7	233.0 ± 1.2	367.2 ± 4.7	1.1
	M/C	121.6 ± 4.8	266.7 ± 5.6	435.6 ± 13.8	1.2
	C/VC	165.0 ± 6.3	345.2 ± 8.3	560.7 ± 17.0	1.2
	VC/XC	182.0 ± 0.9	390.2 ± 2.0	662.4 ± 18.5	1.2
225 (140)	VF/F	65.5 ± 1.6	143.3 ± 4.1	229.8 ± 14.1	1.2
	F/M	100.2 ± 0.5	212.5 ± 1.3	341.5 ± 6.1	1.1
	M/C	103.7 ± 4.2	228.7 ± 4.9	361.2 ± 10.6	1.1
	C/VC	137.5 ± 2.9	293.2 ± 5.4	471.4 ± 11.1	1.1
	VC/XC	139.8 ± 1.4	307.5 ± 2.3	520.8 ± 13.1	1.2

Nozzle Orientation Effects on Droplet Spectra

As the nozzle orientation changed from straight back (0°) to down and back at a 45° angle, the sprays became finer in high-speed air due to an increase in the shear on the spray droplets [16]. This same trend was measured for all three spray solutions (Tables 6–8) at both 193 km/h and 225 km/h (120 mph and 140 mph). At 225 km/h, the $D_{V0.5}$ decreased by 15.1 % when the orientation of the VF/F nozzle was changed from 0° to 45°. The VC/XC $D_{V0.5}$ decreased by 29.6 % under these same conditions. This roughly twofold increase in the percentage decrease in the $D_{V0.5}$ between the VF/F and VC/XC held for the other two spray solutions.

Discussion

Atomization Results

The effects of the physical properties of the spray solution had a significant effect on the droplet spectra. As the dynamic surface tension of the spray solutions decreased, smaller droplets were created. This supports previous findings [17,18].

The decrease in the range of droplet sizes as the airspeed increased was a result of larger droplets breaking up in the high-speed air. The shatter velocity is a term defined as the velocity at which a spray droplet of a particular size can no longer hold its shape and shatters [16]. For water, the shatter velocity of a 385 μm droplet is 161 km/h [16]. Since the reference nozzles used in this study do not have much separation between them at aerial application speeds, other nozzles [19] may need to be selected that give larger separation in droplet size categories to aid in the selection of nozzles or technologies that reduce spray drift.

TABLE 4—*Reference nozzle droplet size spectra for deionized water + 0.25 % v/v 90 % NIS.*

Airspeed, km/h (mph)	Nozzle Category	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD	Relative Span
0 (0)	VF/F	52.7 ± 1.9	109.1 ± 2.2	184.6 ± 2.8	1.2
	F/M	74.5 ± 1.7	169.0 ± 6.1	375.5 ± 14.3	1.9
	M/C	91.7 ± 2.8	220.5 ± 4.4	483.2 ± 10.1	1.8
	C/VC	82.1 ± 4.7	205.9 ± 17.4	354.8 ± 31.0	1.9
	VC/XC	105.8 ± 13.4	269.1 ± 34.3	477.0 ± 58.7	1.4
96 (60)	VF/F	63.8 ± 0.5	134.3 ± 0.9	228.9 ± 1.9	1.2
	F/M	108.3 ± 0.9	225.1 ± 3.2	353.5 ± 9.9	1.1
	M/C	122.7 ± 1.2	271.0 ± 1.0	460.5 ± 2.2	1.3
	C/VC	198.3 ± 3.2	397.2 ± 1.6	671.5 ± 12.7	1.2
	VC/XC	235.7 ± 4.6	476.9 ± 11.3	808.9 ± 68.3	1.2
160 (100)	VF/F	65.3 ± 0.2	136.0 ± 0.6	219.8 ± 5.3	1.1
	F/M	109.8 ± 0.8	225.4 ± 2.7	356.8 ± 8.9	1.1
	M/C	107.8 ± 2.9	235.2 ± 6.9	381.8 ± 13.4	1.2
	C/VC	145.0 ± 1.4	314.4 ± 2.4	538.9 ± 17.2	1.3
	VC/XC	155.3 ± 1.0	349.9 ± 3.2	593.6 ± 8.7	1.3
193 (120)	VF/F	65.5 ± 0.3	139.2 ± 0.3	226.5 ± 1.7	1.2
	F/M	101.4 ± 1.2	210.6 ± 3.2	332.4 ± 8.8	1.1
	M/C	97.3 ± 1.0	214.7 ± 2.0	347.0 ± 7.0	1.2
	C/VC	127.5 ± 0.3	277.9 ± 1.7	463.5 ± 9.7	1.2
	VC/XC	136.1 ± 2.7	307.9 ± 6.2	528.8 ± 27.8	1.3
225 (140)	VF/F	61.1 ± 1.3	133.1 ± 3.1	216.4 ± 12.1	1.2
	F/M	88.7 ± 1.1	190.2 ± 0.9	305.8 ± 1.6	1.1
	M/C	84.0 ± 0.7	191.9 ± 3.2	316.7 ± 9.2	1.2
	C/VC	104.2 ± 1.1	232.7 ± 2.1	388.4 ± 10.4	1.2
	VC/XC	111.8 ± 1.2	256.3 ± 2.5	444.4 ± 17.0	1.3

Time Requirements of Testing Protocol

One of the main considerations when developing a new protocol or conducting any research project is the cost and time associated completing the study objectives. The work presented in this paper required three people. One person operated the wind tunnel and traversed the nozzle. Another person operated the Sympatec HELOS system, while the third person was mixing the spray solutions and getting the nozzles ready when it was time to switch them between tests. With the three people working in concert, each thrice replicated spray treatment took approximately 10 min when everything was working properly. It took approximately one week for all of the 135 treatments to be completed.

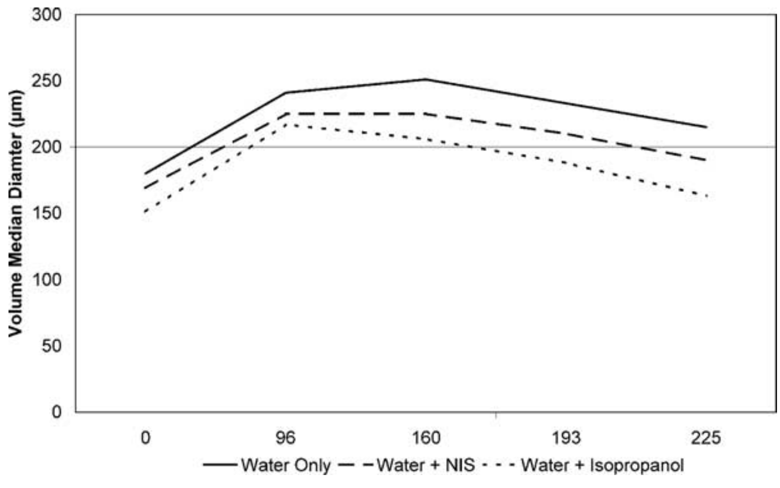

FIG. 2—*Effect of spray solutions on the volume median diameter for the F/M nozzle by airspeed.*

TABLE 5—*Reference nozzle droplet size spectra for deionized water + 9 % isopropanol.*

Airspeed, km/h (mph)	Nozzle Category	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD	Relative Span
0 (0)	VF/F	49.6 ± 0.4	111.0 ± 0.5	197.0 ± 2.8	1.3
	F/M	64.3 ± 3.0	151.0 ± 3.8	308.2 ± 11.8	1.6
	M/C	80.5 ± 1.5	193.0 ± 1.9	378.1 ± 5.2	1.5
	C/VC	66.0 ± 13.3	182.9 ± 16.4	318.7 ± 31.2	1.4
	VC/XC	116.5 ± 12.4	348.9 ± 11.0	631.4 ± 26.4	1.5
96 (60)	VF/F	54.6 ± 0.6	126.0 ± 1.7	218.7 ± 3.4	1.3
	F/M	102.3 ± 0.7	217.4 ± 1.9	354.0 ± 6.1	1.2
	M/C	130.2 ± 1.3	278.8 ± 1.2	424.9 ± 2.1	1.1
	C/VC	182.4 ± 5.5	392.4 ± 16.6	643.9 ± 60.4	1.2
	VC/XC	209.9 ± 3.3	457.2 ± 2.6	795.5 ± 20.2	1.3
160 (100)	VF/F	56.4 ± 0.7	131.2 ± 2.2	213.7 ± 2.2	1.2
	F/M	95.0 ± 1.2	206.1 ± 3.9	340.0 ± 15.2	1.2
	M/C	104.0 ± 2.2	240.9 ± 5.1	399.1 ± 17.3	1.2
	C/VC	138.9 ± 1.0	321.6 ± 4.3	542.6 ± 16.9	1.3
	VC/XC	150.1 ± 2.2	351.7 ± 4.0	585.8 ± 11.5	1.2
193 (120)	VF/F	53.0 ± 0.3	127.4 ± 0.8	216.7 ± 4.2	1.3
	F/M	82.5 ± 1.3	187.8 ± 2.8	317.5 ± 14.9	1.3
	M/C	84.7 ± 1.6	203.7 ± 4.6	337.7 ± 12.4	1.2
	C/VC	111.6 ± 0.7	268.6 ± 1.1	464.7 ± 6.0	1.3
	VC/XC	125.4 ± 1.2	307.2 ± 4.6	578.2 ± 29.4	1.5
225 (140)	VF/F	48.4 ± 0.3	119.1 ± 1.0	207.3 ± 4.2	1.3
	F/M	67.6 ± 0.3	163.0 ± 0.8	284.1 ± 2.1	1.3
	M/C	66.7 ± 1.1	168.5 ± 0.8	297.2 ± 6.1	1.4
	C/VC	86.6 ± 0.7	214.1 ± 1.4	385.5 ± 10.6	1.4
	VC/XC	91.7 ± 0.6	231.9 ± 2.9	431.5 ± 20.4	1.5

Variance in Droplet Spectra Data

An important part of the proposed protocol is the level of variance between replications that one deems acceptable for a valid data set. At the outset of this work, a level of ±3 % in the standard deviation was thought to be the targeted value. Based on the results in Tables 3–5, 48 % of the means for $D_{V0.1}$, $D_{V0.5}$, or $D_{V0.9}$ did not meet these criteria; however, this number drops to 23 % if a ±5 % in the standard

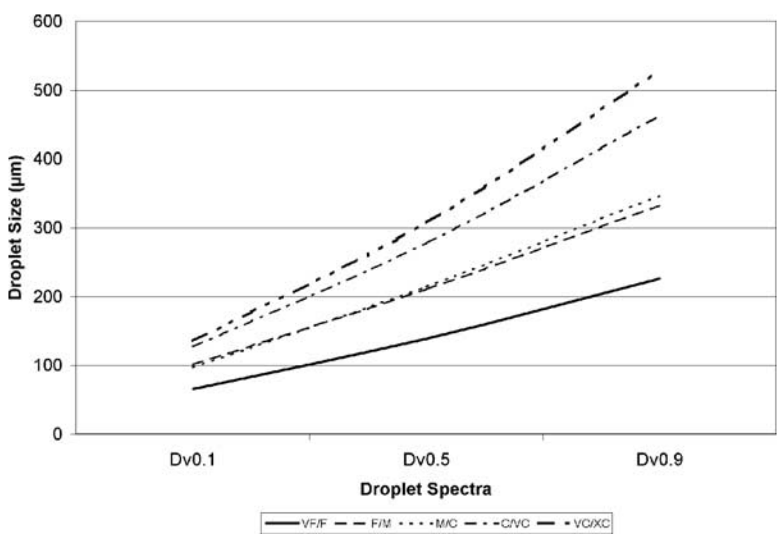

FIG. 3—*Spray classification category boundaries in a 193 km/h airstream for a deionized water plus 0.25 % v/v of a 90 % nonionic surfactant solution.*

TABLE 6—*Effects of nozzle orientation on droplet size spectra for deionized water.*

Airspeed, km/h (mph)	Nozzle Category	Nozzle Orientation, (deg)	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD
193 (120)	VF/F	0	68.5 ± 0.5	149.1 ± 0.9	238.0 ± 4.1
		45	58.5 ± 1.8	130.5 ± 4.6	212.5 ± 10.4
	F/M	0	113.0 ± 0.7	233.0 ± 1.2	367.2 ± 4.7
		45	83.0 ± 0.1	190.6 ± 0.1	295.3 ± 1.8
	M/C	0	121.6 ± 4.8	266.7 ± 5.6	435.6 ± 13.8
		45	87.9 ± 0.4	218.7 ± 1.5	351.4 ± 5.0
	C/VC	0	165.6 ± 5.8	346.9 ± 7.5	569.3 ± 14.8
		45	103.7 ± 1.1	257.9 ± 1.2	423.1 ± 6.2
	VC/XC	0	182.0 ± 0.9	390.2 ± 2.0	662.4 ± 18.5
		45	107.0 ± 0.8	275.9 ± 0.3	464.8 ± 6.3
225 (140)	VF/F	0	65.5 ± 1.6	143.3 ± 4.1	229.8 ± 14.1
		45	53.0 ± 0.8	121.6 ± 1.6	206.2 ± 6.2
	F/M	0	100.2 ± 0.5	212.5 ± 1.3	341.5 ± 6.1
		45	69.7 ± 0.2	163.8 ± 1.0	258.2 ± 7.2
	M/C	0	103.7 ± 4.2	228.7 ± 4.9	361.2 ± 10.6
		45	70.1 ± 1.4	176.5 ± 3.4	289.0 ± 6.9
	C/VC	0	137.5 ± 2.9	293.2 ± 5.4	471.4 ± 11.1
		45	83.7 ± 0.3	207.4 ± 0.2	341.8 ± 2.1
	VC/XC	0	139.8 ± 1.4	307.5 ± 2.3	520.8 ± 13.1
		45	84.7 ± 0.9	216.2 ± 2.3	355.4 ± 5.4

deviation is deemed acceptable. If only the data from the airspeeds from 96 km/h to 225 km/h are subjected to these criteria, the numbers of means that had standard deviations greater than ±3 % and ±5 % were 40 % and 15 %; respectively.

This number is important because it represents the number of spray runs that would need to be repeated. If 40 % of the spray runs had to be repeated, the costs associated with completing DRT

TABLE 7—*Effects of nozzle orientation on droplet size spectra for deionized water + 0.25 % v/v 90 % NIS.*

Airspeed, km/hr (mph)	Nozzle Category	Nozzle Orientation, (deg)	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD
193 (120)	VF/F	0	65.5 ± 0.3	139.2 ± 0.3	226.5 ± 1.7
		45	55.9 ± 0.8	127.5 ± 1.3	207.8 ± 2.9
	F/M	0	101.4 ± 1.2	210.6 ± 3.2	332.4 ± 8.9
		45	77.7 ± 1.2	182.7 ± 2.6	297.0 ± 4.7
	M/C	0	97.3 ± 1.0	214.7 ± 2.0	347.0 ± 7.0
		45	76.0 ± 2.5	189.7 ± 5.5	312.2 ± 11.2
	C/VC	0	127.5 ± 0.3	277.9 ± 1.7	463.5 ± 9.7
		45	95.5 ± 1.8	232.7 ± 5.1	376.2 ± 10.2
	VC/XC	0	136.1 ± 2.7	307.9 ± 6.2	528.8 ± 27.8
		45	96.4 ± 0.8	239.6 ± 1.1	394.2 ± 6.3
225 (140)	VF/F	0	61.1 ± 1.3	133.1 ± 3.1	216.4 ± 12.1
		45	49.9 ± 0.9	115.4 ± 1.5	183.3 ± 4.8
	F/M	0	88.7 ± 1.1	190.2 ± 0.9	305.8 ± 1.6
		45	63.6 ± 1.0	152.8 ± 2.6	244.8 ± 5.5
	M/C	0	84.0 ± 0.7	191.9 ± 3.2	316.7 ± 9.2
		45	60.2 ± 0.7	154.4 ± 1.0	252.6 ± 5.3
	C/VC	0	104.2 ± 1.1	232.7 ± 2.1	388.4 ± 10.4
		45	75.0 ± 0.5	185.0 ± 0.6	297.1 ± 0.8
	VC/XC	0	111.8 ± 1.2	256.3 ± 2.5	444.4 ± 17.0
		45	76.5 ± 0.5	190.5 ± 0.1	314.8 ± 1.7

TABLE 8—*Effects of nozzle orientation on droplet size spectra for deionized water + 9 % isopropanol.*

Airspeed, km/h (mph)	Nozzle Category	Nozzle Orientation, (deg)	$D_{V0.1}$, μm ± SD	$D_{V0.5}$, μm ± SD	$D_{V0.9}$, μm ± SD
193 (120)	VF/F	0	53.0 ± 0.3	127.4 ± 0.8	216.7 ± 4.2
		45	39.2 ± 0.7	104.5 ± 1.7	176.9 ± 4.9
	F/M	0	82.5 ± 1.3	187.8 ± 2.8	317.5 ± 14.9
		45	52.2 ± 0.3	140.5 ± 0.2	233.9 ± 0.8
	M/C	0	84.7 ± 1.6	203.7 ± 4.6	337.7 ± 12.4
		45	55.2 ± 0.7	156.8 ± 2.0	268.5 ± 10.6
	C/VC	0	111.6 ± 0.7	268.6 ± 1.1	464.7 ± 6.0
		45	70.6 ± 6.3	190.1 ± 6.3	325.8 ± 13.7
	VC/XC	0	125.4 ± 1.2	307.2 ± 4.6	578.2 ± 29.4
		45	70.4 ± 1.1	202.9 ± 2.4	351.3 ± 1.6
225 (140)	VF/F	0	48.4 ± 0.3	119.1 ± 1.0	207.3 ± 4.2
		45	34.3 ± 0.4	93.4 ± 1.6	155.1 ± 5.7
	F/M	0	67.6 ± 0.3	163.0 ± 0.8	284.1 ± 2.1
		45	40.1 ± 0.3	111.9 ± 0.3	189.1 ± 3.0
	M/C	0	66.7 ± 1.1	168.5 ± 0.8	297.2 ± 6.1
		45	43.7 ± 1.2	127.1 ± 2.2	221.0 ± 7.2
	C/VC	0	86.6 ± 0.7	214.1 ± 1.4	385.5 ± 10.6
		45	53.5 ± 1.8	150.9 ± 4.7	259.8 ± 13.4
	VC/XC	0	91.7 ± 0.6	231.9 ± 2.9	431.5 ± 20.4
		45	56.1 ± 1.0	160.6 ± 2.1	284.5 ± 2.7

evaluation studies would only increase. The authors believe that a 15 % repeat rate would be acceptable and will use ±5 % standard deviation values as criteria for accepting tests results.

Acknowledgments

The authors would like to thank Lee Denham and Charlie Harris for their efforts in collecting and compiling the data. This study was supported in part by a grant from the Deployed War-Fighter Protection (DWFP) Research Program, funded by the U.S. Department of Defense through the Armed Forces Pest Management Board (AFPMB).

References

[1] Sayles, G., Birchfield, N., and Ellenberger, J. "US EPA's Research Proposal for Encouraging the Use of Spray Drift Reduction Technologies," Proc. Int. Conf. on Pesticide Application for Drift Management, pp. 204–209. http://pep.wsu.edu/drift04/proceedings.html

[2] EPA, "Pesticide Spray Drift Reduction Technologies: Verification and Incentives for Use," http://www.epa. gov/etop/forum/problem/progressreports/pest-spray-9-15-06.html

[3] EPA, "Environmental Technology Verification Program, Quality Management Plan," EPA Publication No. EPA/600/R-03/021; Office of Research and Development, U. S. Environmental Protection Agency, washington DC.

[4] Kosusko, M., Bullock, K., Birchfield, N., and Hewitt, A. J., "Development of a Test Plan to Verify Pesticide Drift Reduction Technologies," *ASABE Annual International Meeting*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

[5] Hewitt, A. J., "Developments in International Harmonization of Pesticide Drift Management," *Phytoparasitica*, Vol. 29, 2001, pp. 93–96.

[6] ASTM, Standard E361–01, "Standard Methods for Testing Hydraulic Spray Nozzles Used in Agriculture," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2005.

[7] ASAE, Standard S572, "Spray Nozzle Classification by Droplet Spectra," American Society of Agricultural Engineers, St. Joseph, MI, 1999.

[8] ASAE, Standard S561.1, "Procedure for Measuring Drift Deposits from Ground, Orchard, and Aerial

Sprayers," American Society of Agricultural and Biological Engineers, St. Joseph, MI, 2004.

[9] Hoffmann, W. C., "Field-Collected and AGDISP-Predicted Spray Flux from an Aerial Application," *J. ASTM Int.* Vol. 3, 2006, pp. 156–167.

[10] Bird, S. L., Perry, S. G., Ray, S. L., and Teske, M. E., "Evaluation of the AgDISP Aerial Spray Algorithms in the AgDrift Model," *Envir. Toxicol. Chem.* Vol. 21, 2002, pp. 672–681.

[11] Hoffmann, W. C., Hewitt, A. J., Ross, J. C., Bagley, W. E., Martin, D. E., and Fritz, B. K., "Spray Adjuvant Effects on Droplet Size Spectra Measured by Three Laser-Based Systems," *J. ASTM Int.* Vol. 5, 2008, pp. 1–12.

[12] Hewitt, A. J. and Spray Drift Task Force, 2001, www.agdrift.com/PDF_FILES/Tankmix.pdf

[13] Womac, A. R., Maynard, R. A., and Kirk, I. W., "Measurement Variations in Reference Sprays for Nozzle Classification," *Trans. ASAE* Vol. 42, 1999, pp. 609–616.

[14] ASTM, Standard E1620–97, "Terminology Relating to Liquid Particles and Atomization," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2004.

[15] ASTM, Standard E1260–05, "Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Nonimaging Light-Scattering Instruments," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2005.

[16] Matthews, G. A., *Pesticide Application Methods*, John Wiley & Sons, Inc., New York, 1988, p. 336.

[17] Lan, Y., Fritz, B. K., Hoffmann, W. C., and Huang, Y., "Effect of Adjuvant Physical Properties on Spray Characterization," ASABE Paper No.08–4174, 2008.

[18] Sanderson, R., Hewitt, A. J., Huddleston, E. W., and Ross, J. B., "Relative Drift Potential and Droplet Size Spectra of Aerially Applied Propanil Formulations," *Crop Prot.*, Vol. 16, 1997, pp. 717–721.

[19] Hewitt, A. J., "Droplet Size Spectra Classification Categories in Aerial Application Scenarios," *Crop Prot.*, Vol. 27, 2008, pp. 1284–1288.