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A Reverse Venturi Atomization Chamber

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Abstract

Spray drift is a significant issue facing aerial applicators. Material not applied to the target is a financial loss for the farmer and a potential liability for the applicator. Off-site drift represents an environmental liabilities habitat, water quality and urban encroachment concerns demand greater attention to larger buffer and/or no-spray zones.

During conventional aerial applications, fluid leaving the nozzle is subjected to air shear resulting in an atomization profile (bell curve) with a portion of very small droplets (driftable fines). Increased airspeeds produce more driftable fines, increasing the potential for undesired off-site movement. Controlling the environment where atomization occurs reduces driftable fines, reducing the potential undesired off-site movement of spray material. Control of the nozzle environment is accomplished using the Reverse Venturi Atomization Chamber (RVA), which has three sections. Air enters the diffuser with a restricted opening, and flows into a larger, settling chamber where air velocities are reduced, the nozzle is located, and where atomization occurs. The atomized spray and air travel together through the third chamber (constrictor) where they are accelerated to the aircraft's air speed. By reducing the air speed where atomization occurs, the atomization profile demonstrated by the RVA system produces fewer fines, resulting in less drift.

The RVA chamber has demonstrated up to 93% and 78% reduction in fines at 100 and 150 mph airspeed, respectively, in wind tunnel testing. Field testing with the RVA system on the aircraft at 150 mph demonstrated a 40% reduction in drift at 50 meters downwind compared to a conventional spray system.

Keywords. Reverse venturi, atomization, spray drift, aircraft, spray management

Introduction

Spray drift is one of the most significant issues facing aerial applicators. Material not applied to the target crop or pest is a financial loss for the farmer and a potential liability for the applicator. Off-site drift also represents an environmental liability, particularly as habitat and water quality concerns demand greater attention with larger buffer and/or no-spray zones.

Current practice delivers liquid material through a nozzle, under pressure, and utilizes air shear for at least a portion of the atomization, creating a range of droplets with those less than 200 microns, known as fines, particularly susceptible to off-site drift. As airspeed increases, so does the effect of air shear on the spray leaving the nozzle, resulting in further shatter/fracture of droplets which produces even more fines and leads to increased off-site drift.

The purpose of this USDA, SBIR Phase II study was to develop a controlled environment where atomization occurs, reducing driftable fine production and reducing off-site movement of spray material. Control of nozzle environment is accomplished using a chamber having three sections, called a Reverse Venturi Atomization Chamber (RVA). Air enters the first section (diffuser), with a restricted opening, and flows into a larger section (settling chamber) where air velocities are reduced, the nozzle is located, and where atomization occurs. The atomized spray and air then travel through the third section (constrictor) where they are accelerated to match the aircraft's air speed. By reducing the air speed where atomization occurs, there is less air shear on the atomized spray droplets resulting in an atomization profile with fewer fines and, ultimately, less driftable material.

To date, using the prototype RVA, water as the test medium, and a selection of commercially available nozzles, we have demonstrated up to a 93% reduction in fines at 100 mph and 78% reduction in fines at 150 mph airspeed in wind tunnel testing. Actual drift testing with the RVA on the test aircraft at 150 mph in the field had a 40% reduction in drift at 50 meters down wind compared to a conventional spray system.

Background and Rational

The majority of agricultural materials are applied as a liquid solution utilizing traditional design nozzles, either hydraulic pressure, fan, cone dispersion, or rotary screen types (Akesson and Yates, 1989), and either aircraft (fixed-wing or helicopter) or ground-based methods. In either scenario, the nozzle-atomizer unit must perform two functions. First, it must discharge the solution at a controlled and metered rate to provide appropriate coverage and accurate dosage for the material being applied and the crop/pest being treated/targeted. Second, the nozzle-atomizer must break the solution into appropriately sized droplets for dispersal onto the target. Most nozzle-atomizers in use on agricultural sprayers produce a range of drop sizes approximating a Gaussian or bell curve distribution range, which may be somewhat skewed towards smaller drops.

Although aerial applications have been in practice for many years, in most situations, aerial applicators have used "off-the-shelf" nozzles, originally designed for ground applications, rather than aircraft. Newer, more advanced nozzles are more convenient in actual use and can be easily adjusted for the desired needs of a particular application. Applicators have been creative in combining nozzles, nozzle orientation and spray pressures, and diligent in their attention to environmental conditions, to obtain satisfactory application patterns for the many materials now applied by air. After nozzle selection, orientation and pressure, there has been minimal attention given to the matter of reducing the percentage of fines. What is needed is a system that is relatively easy to use that addresses fines and, hence, off-site drift.

Work by Akesson and Yates, 1974, has determined the critical air velocity (the speed at which droplets break up) and corresponding drop sizes at which this occurs. This work explored a variety of nozzles and atomizers, using water, in the wind tunnel at the University of California, Davis. The results of these investigations follow and mph values have been included as convenient points of reference. As can be seen in Table 1, at common aircraft speeds of over 100 mph, drops ~380μ are subject to being broken up into smaller droplets and, subsequently, there is an increased percentage (or strong likelihood) of driftable fines.

Table 1. Critical air velocities

Critical Velocity, (km/h / mph)	**Drop Size (microns, μ)**
80.5 / ~ 50 mph	1500
105 / ~ 65 mph	900
137 / ~ 85 mph	535
161 / ~ 100 mph	385
241 / ~ 210 mph	170

In response to the problem of nozzle selection, I.W. Kirk (2000) and (2001) has produced a computer program/spread sheet for helicopter and airplane applicators that will predict spray quality under various operational conditions. This program is an invaluable tool to aerial applicators. Data from both programs further supports our hypothesis.

Using Kirk's program/spread sheet we can compare the percent of fines produced by a CP drift reduction high volume flat fan nozzle under the same conditions at two air speeds. The nozzle utilized the same orifice, was operated at 40 psi and oriented at 0° to the airstream. The key criteria for our evaluation was the percentage of droplets <200μ. At 50 mph, the percentage was 2.15% and at 100 mph, the percentage increased to 9.67%. This is a four-fold increase in driftable fines. The effect of increased airspeed, which increases air shear and results in the formation of more fines <200μ, clearly increases the potential for off-site movement or spray drift.

Droplets formed at slower air speeds (and emanating from a nozzle at 0° to the airstream) experience less wind shear and, subsequently, produce less driftable fines. When combined with appropriate orifices and fluid pressures, these slower air speeds are a primary reason why material applied by helicopter has less potential for drift. Depending on the nozzle and application scenario, sometimes a combination of higher fluid pressure and a smaller orifice will accelerate the fluid closer to actual air speed, reducing the wind shear effect on the droplets, and provide the desired size droplet. How can we utilize this information and apply this concept to high-speed, fixed-wing aircraft applications?

Based on the information discussed above the rationale for this proposal is that an atomization chamber can be utilized to minimize the wind shear effect on the spray droplets, reducing driftable fines.

To address the problem of off-site drift by agricultural materials, a Reverse Venturi Atomization (RVA) chamber has been constructed (see complete discussion and Figure 1, below) with the goal of reducing fines. The chamber has three sections: 1) a constricted opening known as a diffuser, that is widely rectangular and opens into, 2) a larger chamber, known as a settling chamber, that houses a spray nozzle directed aft towards, 3) a constricted exit, the annulus. As air enters the RVA chamber, it decelerates in airspeed as it reaches the center of the RVA

chamber, due to the proportions of the chamber. At the center of the chamber, droplets are formed with a nozzle at 0° deflection from the airstream, minimizing air shear. The droplets then continue through the chamber, which constricts toward the exit, accelerating the droplets to or close to the original, external air speed. The droplets then enter the airstream as they were formed and with less fracture or shattering due to abrupt changes in air speed.

Nozzle selection

The primary criteria for nozzle selection was that the spray pattern from the nozzle would not strike the chamber walls (top, bottom or sides) when air was flowing through the test chamber. Due to the shape and exit of the chamber, we determined that only narrow angle flat fan nozzles would perform appropriately in the test chamber in the wind tunnel.

There were nine nozzles considered for use in the RVA chamber, see Table 2, and selected to be evaluated in ARENA Pesticide Management's wind tunnel using the SYMPTEC HELOS-VARIO/KF laser diffraction sensor and computer software for particle size analysis. All nozzles were evaluated at 0° to the free air stream at 50, 100 and 150 mph with pressures of 20 and 50 psi. Only two of the nine produced a very thin and narrow spray pattern that did not impact the inside walls of the test chamber, see Table 3.

Table 2. Nozzles considered

Spraying Systems 1505	CP04 40 degrees
Spraying Systems 2550	CP06 40 degrees
Spraying Systems 5015	CP12 40 degrees
Spraying Systems 4010	
Spraying Systems 4015	
Spraying Systems 5015	

Table 3. Atomization results from the wind tunnel

Nozzle model	Air Velocity (mph)	Liquid pressure (psi)	Dv 0.1	Dv 0.5	Dv 0.9	% of volume <200µ
H1/8VV-1505	50	20	606	967	1361	0.10
	50	50	418	722	1011	0.79
	100	20	349	661	973	2.35
	100	50	370	640	943	1.25
	150	20	164	361	594	15.12
	150	50	193	398	645	10.91
H1/8VV-2505	50	20	466	745	1057	0.48
	50	50	314	553	837	2.41
	100	20	234	486	752	6.87
	100	50	256	465	709	4.79
	150	20	130	301	489	22.89
	150	50	158	335	543	16.90

Chamber Design

Control of the nozzle environment is critical and is accomplished using a chamber having three sections, called a Reverse Venturi Atomization Chamber (RVA). Ram air enters a restricted opening into the first section (diffuser), and slows down as it flows into a larger area (calming/settling) where air velocities are reduced (compared to the outside air), where the nozzle is located, and where atomization occurs. Releasing the spray stream in the area of reduced air velocity is the key to reducing fines. The lower air velocity reduces shatter of the spray stream. The atomized spray and air then travel together through the third section (constrictor) where they are accelerated to match the aircraft's air speed. By reducing the air speed were atomization occurs, fewer driftable fines are produced, resulting in less drift, Figure 1.

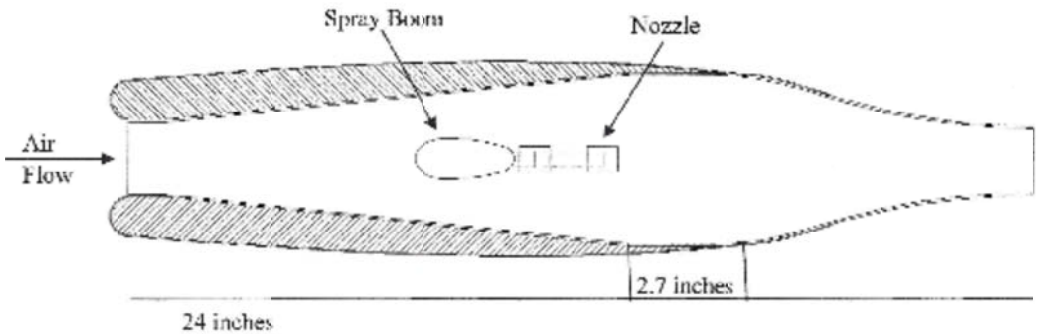

Figure 1. RVA Chamber

In order to evaluate the airflow through and performance of the spray droplets within the chambers when operated in the wind tunnel, W. Peschel, consulting aerodynamic engineer, constructed a Pressure Survey Rake (PSR). This instrument has a series of impact and static orifices that take simultaneous pressure readings at various locations in the tunnel and chamber to provide a snap shot of air velocities at a given time and place. In wind tunnel tests with the RVA chamber at 148 mph, the air speed in the settling/calming section, the slowest section of the chamber, was 49.5 mph and the exit velocity was 141 mph. This gave us a recovery ratio of 0.34 and 0.90 respectively, which are very good values. While the PSR was particularly helpful in evaluating air velocities in the chamber and, hence, locating the spray boom and nozzles, this information was also used in calculating the amount of drag the chamber produced and amount of additional in-flight horse power) the RVA system might require once installed on the aircraft, Table 4.

The RVA Chamber was fitted with a spray boom and nozzle that could be located independent of each other inside the chamber. This modification allowed us to determine the optimal location of the spray boom and nozzle in relation to one other in the chamber. We were able to reduce the driftable fine fraction by 93% at 100 mph using a spray pressure of 20 psi, and 78% at 150 mph with spray pressure of 50 psi, when the spray boom was 12.75 inches from the exit and the nozzle was 10.0 inches from the exit. It is important to understand the importance of spray pressure in relation to air speed. As air speed increases, increasing spray pressure helps reduce the driftable fine fraction, up to a point, because the spray fluid is released into the airstream at a speed closer to that of the airstream. Excessive pressure, however, can be detrimental.

Table 4. Atomization profile of Spraying Systems 2505 nozzle with spray boom at various locations in RVA Chamber.

Percent fines produced in free air stream (no chamber)					
50 mph		100 mph		150 mph	
20 psi	50 psi	20 psi	50 psi	20 psi	50 psi
0.5	2.4	6.9	4.8	22.9	16.9

Percent fines produced with nozzle in RVA chamber					
Distance from chamber exit (inches)		100 mph		150 mph	
Boom	Nozzle	20 psi	50 psi	20 psi	50 psi
9.75	7.0	1.87	2.75	13.78	11.98
9.75	8.0	0.96	1.97	11.26	9.34
10.75	7.0	1.38	2.30	13.40	11.21
10.75	8.0	0.75	2.04	10.98	8.73
10.75	9.0	0.53	2.07	8.90	6.24
11.75	7.0	1.52	2.13	12.62	10.74
11.75	8.0	0.62	2.04	10.62	7.97
11.75	9.0	0.49	2.02	8.58	5.37
11.75	10.0	0.49	2.23	7.68	4.38
12.75	9.0	0.56	2.14	8.35	5.44
12.75	**10.0**	**0.45**	**2.18**	**7.34**	**4.30**
12.75	11.0	0.48	2.34	7.47	3.65
13.75	9.0	0.61	2.29	8.39	5.85
13.75	10.0	0.53	2.62	7.55	4.32
13.75	11.0	0.52	2.39	7.48	4.37
13.75	12.0	0.55	2.49	7.67	4.22
14.75	9.0	0.47	2.14	8.32	5.40
14.75	10.0	0.51	2.50	7.69	4.12
14.75	11.0	0.55	2.44	7.44	4.20
14.75	12.0	0.50	2.55	7.63	4.66
14.75	13.0	0.55	2.41	7.68	4.78

Obtain Federal Aviation Administration (FAA) approvals

Safety is always a primary concern when working around aircraft. With that in mind, obtaining appropriate approvals by the FAA were critical to this project.

An AirTractor (AT-301), as the test aircraft, was taken out of “Restricted” category (allowing the aircraft to make commercial applications) and placed into "Experimental" category, (allowing the aircraft to be flown in less restrictive regulations not for hire) for testing purposes only. Each time the aircraft’s airworthy certificate was changed from “Restricted” to “Experimental” and

back to “Restricted” it was inspected by a Federal Aviation Administration (FAA) Designated Airworthiness Representative (DAR). There were over 71 test flights conducted. Both the FAA Designated Engineer Representative (DER) of the and FAA representatives inspected the test aircraft and complete RVA system installed and requested additional structural and aerodynamic information. They were provided with that information in a document titled “Analytical Substantiation of Structural Integrity and Stability for the Air Tractor Model AT-301 Fitted with an Arena Pesticide Management Reverse Venturi Atomization Chamber”, which was developed by consulting aeronautical engineer, W. Peschel. FAA form 337 “Major Repair and Alteration” has since been approved and the AirTractor has been returned to the “Restricted” category. This allows the AirTractor with the RVA chamber installed to make commercial applications, furthering the advancement and development of the RVA chamber technology.

Mount the Chamber on the Aircraft

There have been three different chamber configurations mounted on the aircraft to date:

1. RVA Chamber with the rake, Figures 2, 3 and 4. This unit was used to test air velocities for comparison with wind tunnel work.

2. A 4.5-foot section of RVA Chamber on one side of the aircraft, Figure 5, to determine the effects of the chamber mounted under the wing on aircraft performance and flight controls, and static air testing.

3. A 30-foot section of RVA Chamber , the final chamber, which is the final chamber for this study and will be used in swath testing and drift study, Figure 6.

RVA Chamber With Rake

To compare actual flight measurements of RVA chamber velocity profiles with wind tunnel measurements a streamlined manometer board assembly was developed and attached to the left wing of the AT-301 aircraft. These measurements would provide a basis for validating velocity profiles measured in wind tunnel tests using RVA chamber models. Agreement between flight and wind tunnel tests would further substantiate use of wind tunnel data to evaluate potential improvements to the RVA chamber internal aerodynamics. Since the same RVA chamber would be used for both the wind tunnel tests and flight tests, a one-for-one comparison was considered appropriate since Reynolds numbers (a key element in fluid dynamics) would, for all practical purposes, be identical. Details of the installation of the manometer board assembly and of a typical RVA chamber are shown in Figure 2, below.

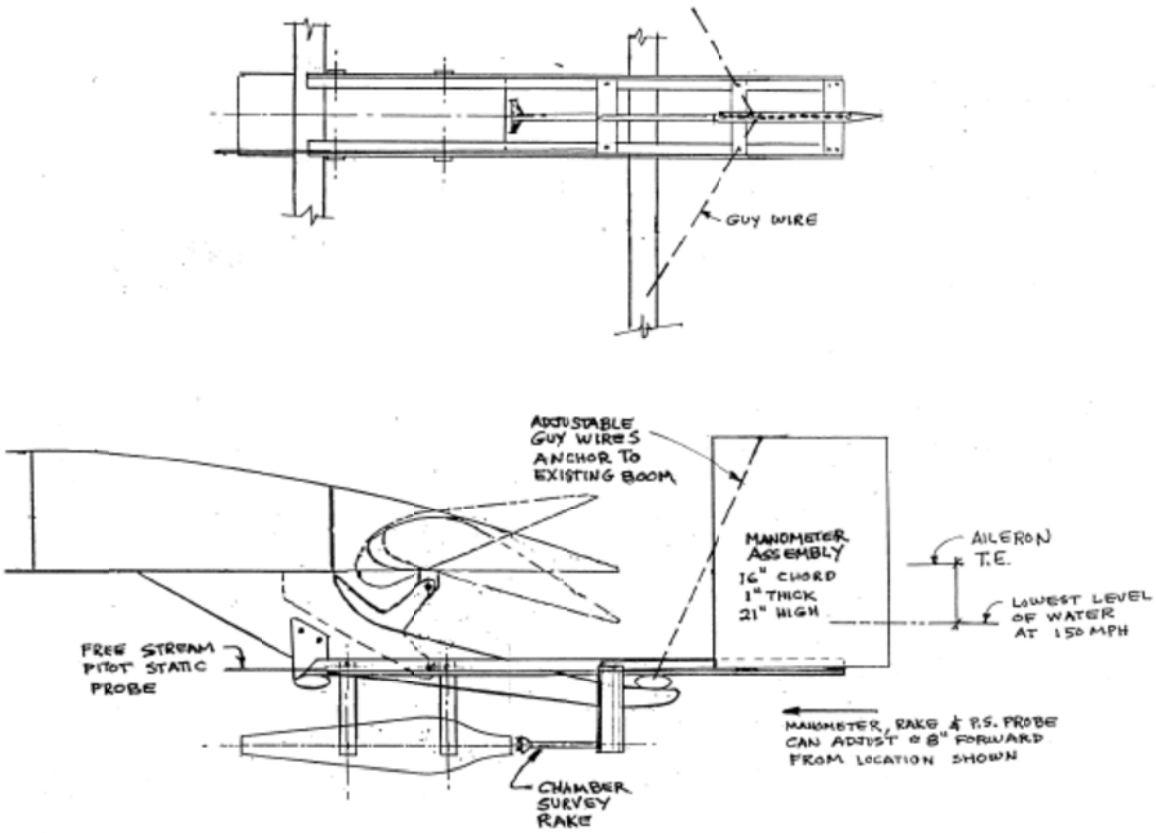

Figure 2. Manometer board assembly and RVA chamber installed under left wing of the AT-301 aircraft

The lower sketch in Figure 2 shows the side view of the installation as viewed from the outboard end of the left wing, and the upper sketch shows the plan view of the installation. Structural support of the manometer board assembly and chamber attachment is provided downstream by the existing streamlined spray boom and upstream by a streamlined boom temporarily installed for these tests only. Guy wires provide torsional stiffness for the manometer assembly.

During flight, and after setting up a flight velocity test condition, a photo of the manometer board is taken from the cockpit to record the test data. A photo of the manometer board during an actual flight is shown in Figure 3. The straight line drawn on the photo connects separate static pressure readings and is used as a reference during data reduction to account for the flight angle of the aircraft.

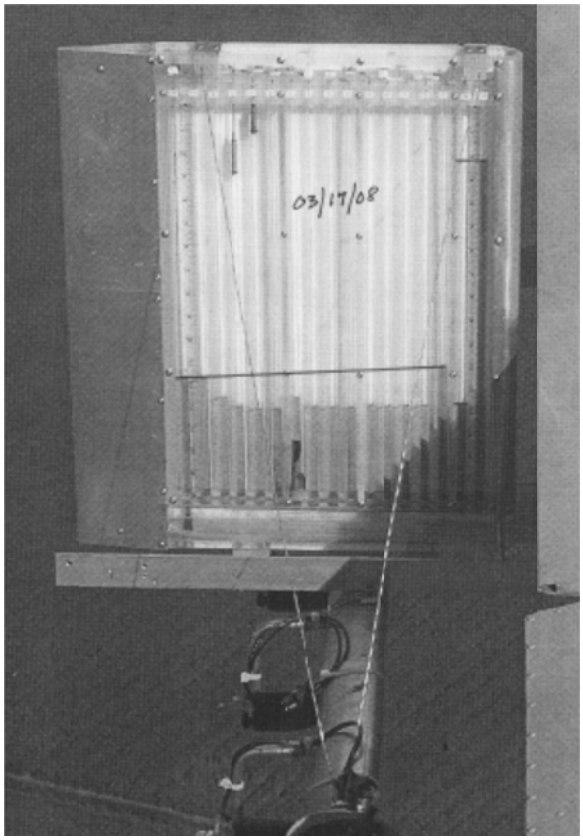

Figure 3. The manometer board during a test flight of RVA Chamber at 150 mph

Flight tests of RVA Chamber were accomplished both with and without internal spray booms installed in the chamber. Comparing the flight test data with wind tunnel data was accomplished by averaging the chamber discharge velocity profiles and dividing these averages by the actual measured inlet air velocity for each test. This non-dimensionalized method was employed to account for the difficulty in establishing exactly the same inlet air velocities in flight conditions as were set up in the wind tunnel, and was accepted as a cost-effective way to avoid repeating tests. Using the non-dimensionalized data to compare flight tests with wind tunnel tests concluded that the measured wind tunnel velocity profiles were acceptable to use as a method for improving the RVA Chamber internal aerodynamics.

Figure 4. Left, photo of manometer board in flight indicating air pressures at various locations in and around RVA Chamber. Right, photo of RVA Chamber mounted 18 inches under wing with rake inside chamber.

Install a 4.5 foot Chamber on the Aircraft

Preliminary results from 15 test flights indicate no adverse effects on flight characteristics or flight controls. For testing purposes and safety, we mounted one 4.5-foot wide section of chamber with spray boom, placing the chamber sections midway between fuselage and wing tip, Figure 5, below. This position would have the most potential impact on the aircraft and flight performance. The test unit was mounted under the wing where half of the left aileron would be impacted by any adverse effects from the chamber making it easy to detect any negative effect on the flight controls, while we would still have half the aileron and the complete aileron on the other side to give aileron authority (control) if there were an adverse effect on the aileron. We then flew the aircraft to test performance. All initial test flights started with a gentle take off and a climb to a safe altitude. After reaching a safe altitude, the test started with slow flying (80 mph) straight forward, then into shallow turns, leading into gentle stalls forward, and then to turning stalls. The next stage of flight testing was at normal flight speeds (130 mph) straight forward and normal turns, leading to more aggressive turns, then power on stalls straight forward, and then turning stalls with and without flaps. The last stage of testing was landing with the use of flaps. Upon landing, we performed a close aircraft inspection of the aircraft, RVA system and attach points looking for any signs of over stress or anything starting to come apart. This was followed with additional flights at higher speeds and under more stressful maneuvers, with flights up to "red line" (176 mph). The last test flights included maneuvers that agricultural pilots encounter in their day-to-day activities. At all times the aircraft with the RVA system on it had very good stall recovery. We also compared static pressure on the bottom side of the wing, where the chamber was mounted, to static pressure on the opposite wing, where there was no chamber, to see if we could measure any effect of the chamber on lift, there was a increase in static pressure between the chamber and wing, indicating a loss of 312 pounds of lift for a 30 foot chamber, Table 5, below. We adjusted the orientation of the chamber to the bottom of the wing by changing the angle of the chamber in relation to the bottom of the wing to look for any changes aircraft performance characteristics. Changing orientation of the chamber did reduce the static pressure but increased the drag, lift gained was lost by additional drag so the chambers were left at 0 degrees to the bottom of the wing. There were no observable effects on flight characteristics. Tuffs of string were taped to the bottom of the wing and aileron above the chamber and a video camera was positioned to observe and determine if there was a smooth laminar flow of air over the bottom of the wing and aileron surface, or if there were disruptions of

air flow. We determined through this testing protocol that there was no adverse flight characteristic effects but that there was a small loss of lift on aircraft performance with the 4.5 foot section of RVA Chamber installed on the aircraft. Actually, as the pilot, I could not tell the unit was on the aircraft. There was one test flight flown by agricultural pilot Tad Dickerson allowing the PI and W. Peschel both to evaluate the system spraying over the runway. He also reported no adverse effects on aircraft performance from the chamber installation and that he could not tell that the system was mounted on the aircraft. This information gave us confidence that mounting a thirty foot section of RVA system would be safe and the next reasonable step in the project.

In the early stages of this study we employed a 2-D computational analysis model (from Flow Analysis Using a PC, H. Ninomiya and K. Onishi, CRC Press, Chapter 6) to determine loss of lift that the chamber would produce on the wing. This analysis determined there would be a loss of 635 pounds of lift.

Table 5. Amount of lift lost with RVA Chamber mounted 18 inches below the wing

Method used to determine loss of lift	**Amount of lift lost**
2-D model loss of lift (calculated)	635 lbs
Static Tube loss of lift (actual measurement)	312 lbs

Figure 5. Different views of RVA Chamber mounted 18 inches under wing of test aircraft. Note that the standard spray boom was left on the aircraft.

Install RVA Chamber, One 30-foot Section, on the Aircraft

The RVA Chamber was constructed in 5-foot sections and mounted to brackets that attached to the existing spray boom mounting points on the wing of the aircraft. The spray booms in each 5-foot section were connected to the next chamber with a hose connection. For safety, we mounted the two center chambers first and secured them for flight. This gave use a 10-foot section of chamber closest to the center of the aircraft. This orientation would have the least impact on the performance of the aircraft and provide the greatest degree of safety for the first tests. We then performed the same testing protocol as was done for the 4.5 foot RVA Chamber described above.

Once we were confident that the aircraft was performing well, we installed an additional chamber on each wing and repeated the test flights. Again, all was well, so we installed a third chamber on each wing, for a total of three on each side, and repeated the test flights. Figure 6 shows the final orientation. In all instances the aircraft performed well, safely, and certainly within normal performance criteria. At all times the aircraft had very good stall recovery, which is critical for safe flight.

Figure 6. Full scale RVA Chamber installed on aircraft, two views. Note the conventional spray boom was maintained for testing.

After we had a complete 30-foot chamber mounted on the aircraft we wanted to verify that air flow over the chamber was the same as with the 4.5 foot section and that there were no changes that could lead to problems later on. Tuffs of string were taped to the top of the

chamber a video camera positioned to determine if there was a smooth laminar flow of air over the chamber and no disruption in air flow. We also did a number of stalls with the tuffs in place and recorded their response with the video camera to see if the boundary layer would stall or break during these maneuvers and it did not, which is very good. We also placed some drops of oil on the top surface of the chamber and then repeated the test flights to see what kind of oil streaking would be generated. We did notice with the oil, and record with the tufts and video, that there was some abnormal air flow (increased turbulence) around the open space between the chambers because of the gap between the chambers. This has been corrected by a redesign of the system by connecting all three chambers on each side together and making them one 15-foot chamber and one continuous spray boom on each side.

The spray system was connected, reservoir tank loaded, and water was sprayed with the RVA system. After test spraying and fixing all the leaks, the spray system was ready for spray testing.

To better accommodate swath testing and the drift studies the aircraft was setup with a dual spray system consisting of the conventional system and RVA system, see Figures 5 and 6. Both systems use the same spray tank, pump and spray valve. Aircraft was equipped with two additional valves aft of the spray valve allowing the pilot to activate the desired spray system. Each system had 60 H1/8VV-2505 TeeJet nozzles spaced six inches apart.

Several other tests were conducted and calculations were performed to evaluate the amount of drag and power loss the RVA system would create. One test performed before this Phase II study used a Turbo AgCat with a typical spreader (used on many agricultural aircraft for the dispensing of dry materials such as seed and fertilizer). The AgCat was flown with the spreader mounted on the aircraft at a noted power setting and airspeed of 115 mph, then the aircraft was landed, the spreader was removed, and aircraft flown at 115 mph while adjusting the amount of power needed maintain 115 mph. It took 48 horse power less to maintain the 115 mph airspeed without the spreader. Based on this information and data collected from the wind tunnel, we were able to develop Table 6 for evaluation of drag and horse power needed for the RVA system compared to a conventional spreader.

The conventional spray system weighs 70 pounds (which is removed when using the spreader or RVA system) the RVA system has a net additional weight of 174 pounds to the aircraft. When comparing two airplanes, one with the RVA system and one with the dry spreader system, the airplane with the RVA system is 44 pounds lighter and is using 36 less Hp to fly at 150 mph. This demonstrates that the RVA system can be used with no additional cost in fuel and speed when compared to dry type applications (seed and fertilizers) when considering weight and drag. The drag from the conventional spray boom was negligible and was not considered.

Table 6. Comparisons of weight and horse power (Hp) needed for RVA system vs dry spreader

	Weight in lbs	**Drag in lbs**	**Loss Hp**
Chamber 115 mph	244	156	48
Chamber 150 mph	244	265	106
Spreader 115 mph	218	205	63
Spreader 150 mph	218	349	144

Perform Swath Testing

Comparisons of the spray pattern of both the RVA system and a conventional spray system were conducted by flying over a collection line perpendicular to the flight path directly into the

prevailing wind with the spray turned "on". Swath testing and analysis was accomplished with the assistance and collaboration with Richard Stoltz**,** Operation S.A.F.E. Analyst, California Agricultural Aircraft Association. CAAA provided the Digital Field Fluorometer, and Drop Scan System.

A Rhodamine dye and water solution was placed in the aircraft spray tank while two different types of samples were collected for each system, see Figure 7, below. The Digital Field Fluorometer, WRK system was used to determine the deposition of the spray pattern. For the first type of samples, one hundred feet of test string was fed from a reel across the collection line to a take up reel. After each pass over the collection line, an electric take-up reel collected the 100 foot sample of line into a covered reel. After three passes, the take-up reel was fed into the Digital Field Fluorometer where the string was analyzed for each pass, the passes are averaged, and the average was analyzed for the coefficient of variation (C.V.) of a particular swath width. The results are the summary of three treatments or test passes, see Figure 9, below. A C.V. of 20% or less is strived for in herbicide applications. A 25% C.V. is considered adequate for insecticide and fungicide applications.

For the second set of samples, on the third pass over the collection line, Syngenta® water sensitive paper (WSP) were place along the collection line in close proximity to the string. The placement protocol calls for one card in the center of the spray swath with additional cards placed at five-foot intervals to the left and right of the center of the swath. This placement usually covers twenty feet on either side of the center of the swath. The cards were then retrieved after the third pass and analyzed on a flat bed scanner. The cards were analyzed for volume median diameter (VMD), diameter volume 0.1 (Dv 0.1), diameter volume 0.9 (Dv 0.9) and the percent of spray volume below 200 microns (μ), see Table 7.

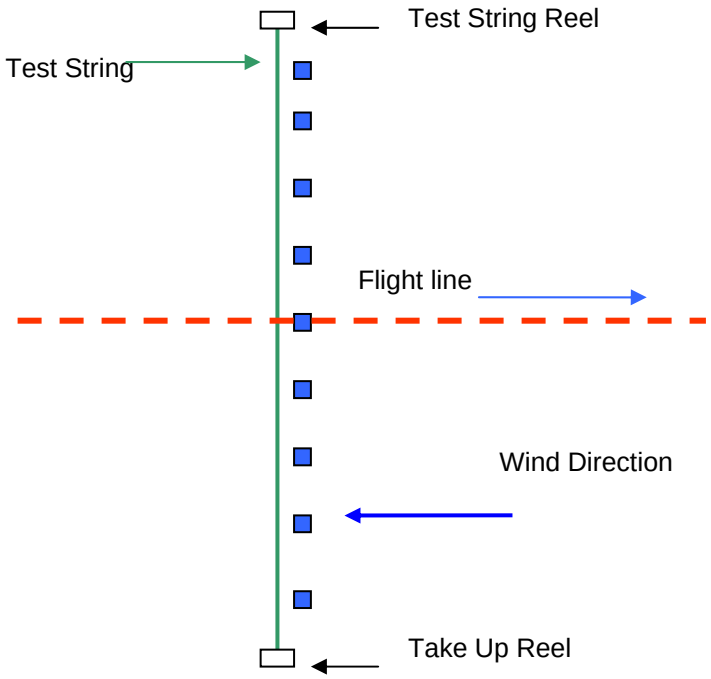

Figure 7. Diagram of swath testing

Analysis was made for both "Back-To-Back" and "Racetrack" spray patterns. Both are used in agricultural aviation. A "Back-To-Back" pattern results in sequential passes that are side by side, one pass one way and the other the opposite, and the pilot accomplishes this by making a 180 degree turn at the end of each pass back into the field on the next pass. A “Racetrack" pattern is the result of wider, sequential ovals and wider turns, with an un-sprayed space of several swath widths left open between the back and forth passes. Each spray pass then shifts one swath width to the right, for example, until the ovals eventually cover the entire area. The "Racetrack" pattern allows the sprayed material to settle before an additional pass is made, which can be beneficial in some applications. Different strategies are appropriate for different situations, or are preferred by individual pilots, so both pattern styles were tested, see Figure 8, below for a comparison of the two patterns.

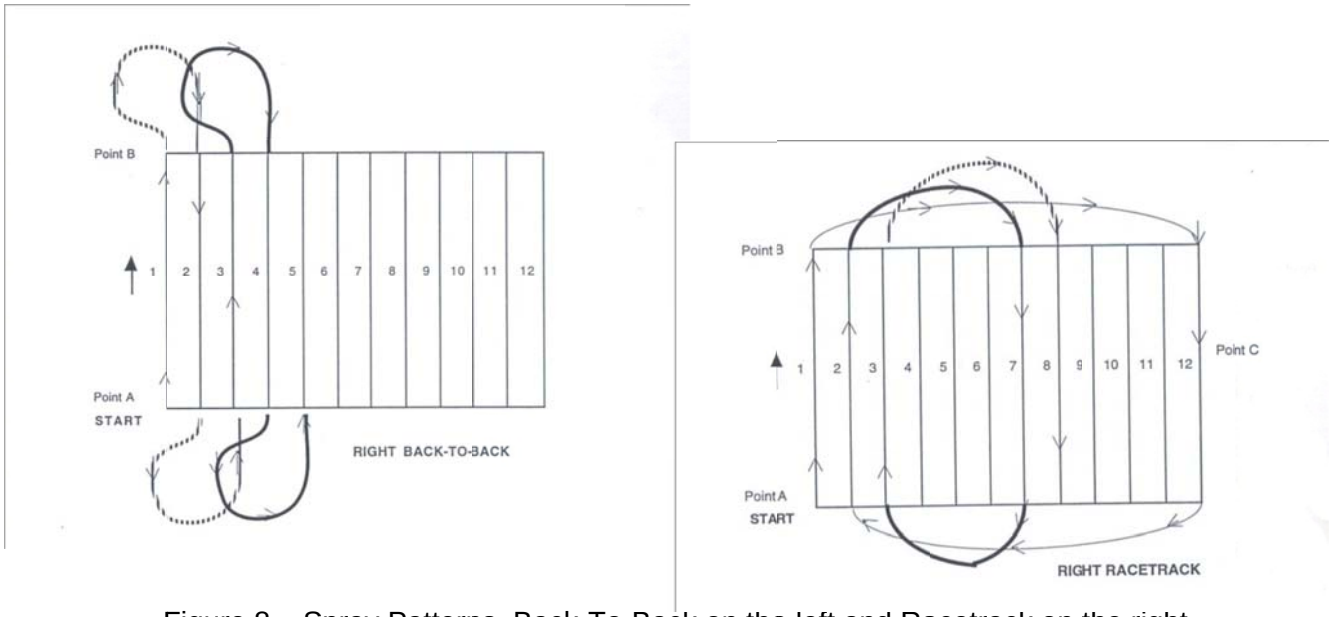

Figure 8. Spray Patterns, Back-To-Back on the left and Racetrack on the right.

RVA spray system performance

The patterns below (Figure 9) demonstrate the spray pattern achieved when multiple passes are placed side by side, with normal overlap, and you take a sample of the overall spray pattern. These graphs demonstrate that the RVA system has a comparable spray pattern to conventional methods. The C.V. values for the conventional method was 11 for Back-To-Back and 19 for Racetrack, while the RVA system achieved 13 for Back-To-Back and 13 for Racetrack, both providing acceptable spray patterns with the RVA system performing slightly better.

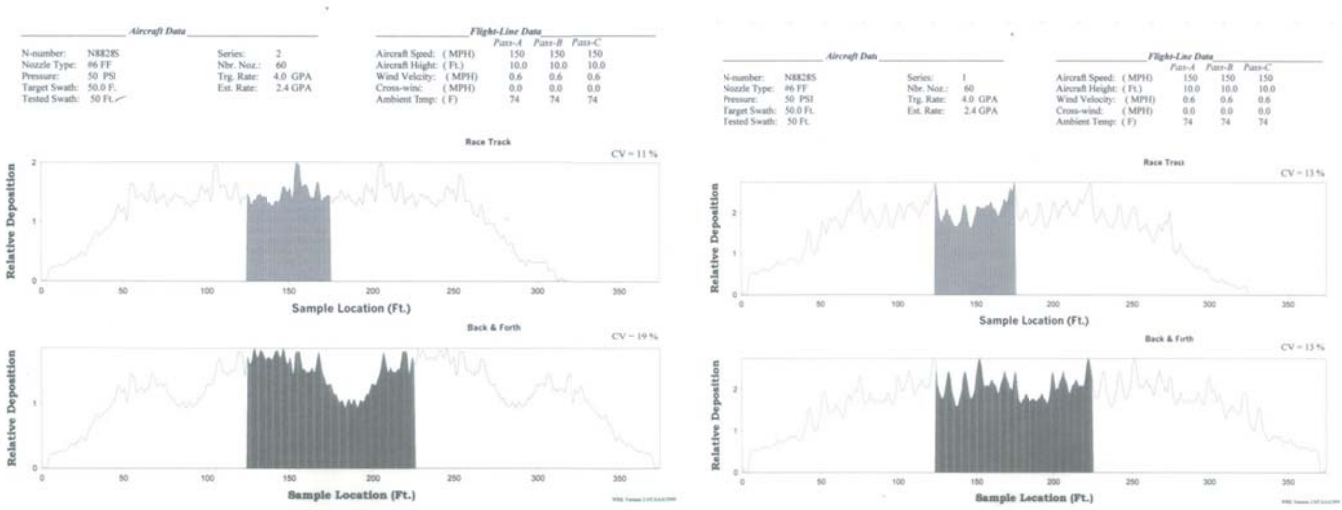

Figure 9. The left panel represents the pattern produced by conventional spray equipment and right panel represents the pattern achieved with the RVA chamber spray system. These data demonstrate that the RVA system is generating larger droplets across the board and produces fewer driftable fines, 3.7% compared to 5.0% for conventional, Table 7, below.

Comparison of Conventional to RVA system in drop size.

Overall, the RVA system generated larger drops than the Conventional system. Also note that the RVA system has a smaller percent of spray less than 200µ (which is in the driftable fraction).

Table 7. Comparison of drop size of RVA and Conventional spray systems in swath testing

SYSTEM	VMD	DV 0.1	DV 0.9	%<200µ	# DROPS <200µ
Conventional	406	238	553	5.0	330
RVA	456	287	647	3.7	232

Perform Drift Studies

The objective of this drift study was to evaluate the reduction in spray drift from the RVA system as compared to the conventional spray system. This test was setup so that the test aircraft would make a pass over the test area with a cross wind of 3-5 mph. As the spray material was released, it would moved down wind with the heavier particles (i.e., larger droplets) falling out first in the swath and smaller particles (i.e., smaller droplets) would fall out farther down wind past the swath area.

The collection media included monofilament line, Mylar, Water Sensitive Paper (WSP), and fluorescent dye as the tracer. The spray solution consisted of water, fluorescent dye (15 g/acre), and 0.25% v/v of a non-ionic surfactant. Targeted spray rate was 3 gal/acre so the aircraft was loaded with 90 gallons of water and 450 g of dye. This same mix was used for both treatments. There were two treatments (conventional and RVA system) with four replications of each. Each replication consisted of one spray pass with the right wing on the downwind side. All passes made were flown at 10 feet above the ground (samplers), 50 psi, and at 150 mph. The AirTractor 301 can achieve 150 mph with a light load, working power and in a shallow dive.

Samplers and Sampling Locations (see Figure 10)

In-Swath Deposition: Directly under the aircraft, samplers were located at 15, 10, 5, and 0 meters upwind from the downwind edge of the spray swath (designated as -15, -10, -5, and 0 meters). At each location, a Mylar card and WSP card (water sensitive) were placed on the ARS sampling stations, which were placed on the ground. The sampling stations are just a simple card holder (Hoffmann, 2007).

Downwind Mylar: At 5, 10, 20, 30, 40, and 50 meters from the spray swath edge, Mylar cards were placed at on the ARS sampling stations which were placed on the ground. Hoffmann, 2007.

Drift Towers: Two drift towers were placed at 10 m and 50 m from the downwind edge of the spray line. At each location, two T-posts were driven in the ground so that the tops were 1.5 meters above the ground. The posts were 10 meters apart and oriented parallel to the flight line. Monofilament line was stretched between these posts using USDA-ARS sampling equipment. After a spray replication, the line was reeled in using ARS equipment and the string placed in labeled zip-top bags (Hoffmann, 2007).

As a spray pass was made over the test course, the spray settled out and fell to the ground being collected on the Mylar and WSP samplers. The largest drops with little tendencies to drift are collected the in swath sample area and smaller droplets will move down wind with the smallest droplets moving the farthest from the swath edge. After sufficient time was allowed for spray material from a test to move down wind past the test plot and dry (approximately 5 minutes), the samples were collected, placed in labeled plastic bags, stored in ice chests out of the sun, and transported for laboratory quantification. The monofilament line and Mylar were later analyzed by pipetting 40 ml of ethanol into each bag and thoroughly washing the monofilament line to allow all the dye to dissolve into solution. The effluent from each bag was poured into a cuvette. The cuvettes were then place into a spectrofluorophotometer (Shimadzu, Model RF5000U, Kyoto, Japan). The fluorometric readings were converted to µg of dye/cm2. The minimum detection level of the dye and sampling technique is 0.00007 µg/cm2. WSP samples were analyzed using the same Drop Scan System as in the swath testing process (Hoffmann, 2007).

The WSP collectors demonstrated the RVA system produced larger drops than the conventional system which reinforces the results from the swath testing, Table 7.

The Mylar collectors in swath (-15, -10, -5, and 0 meters) had similar looking results with the RVA chamber producing slightly more deposition, again larger droplets. Down wind Mylar collectors (5, 10, 20, 30, 40, and 50) indicate the RVA chamber produced less driftable droplets because more droplets are falling out closer to the 0 meters location.

Both systems are producing a range of droplet sizes and these droplets fall out onto the collectors. After the spray pass is made drops move down range (down wind) the larger ones fall out first in swath, or close to it, and the smaller ones fall out further down range. I expected we would observe a greater difference between the two systems, but we did not. There is a small up tic with the conventional system at 50 meters, but the significance of this difference is unclear because we have no data points past that point, see Figure 11, below.

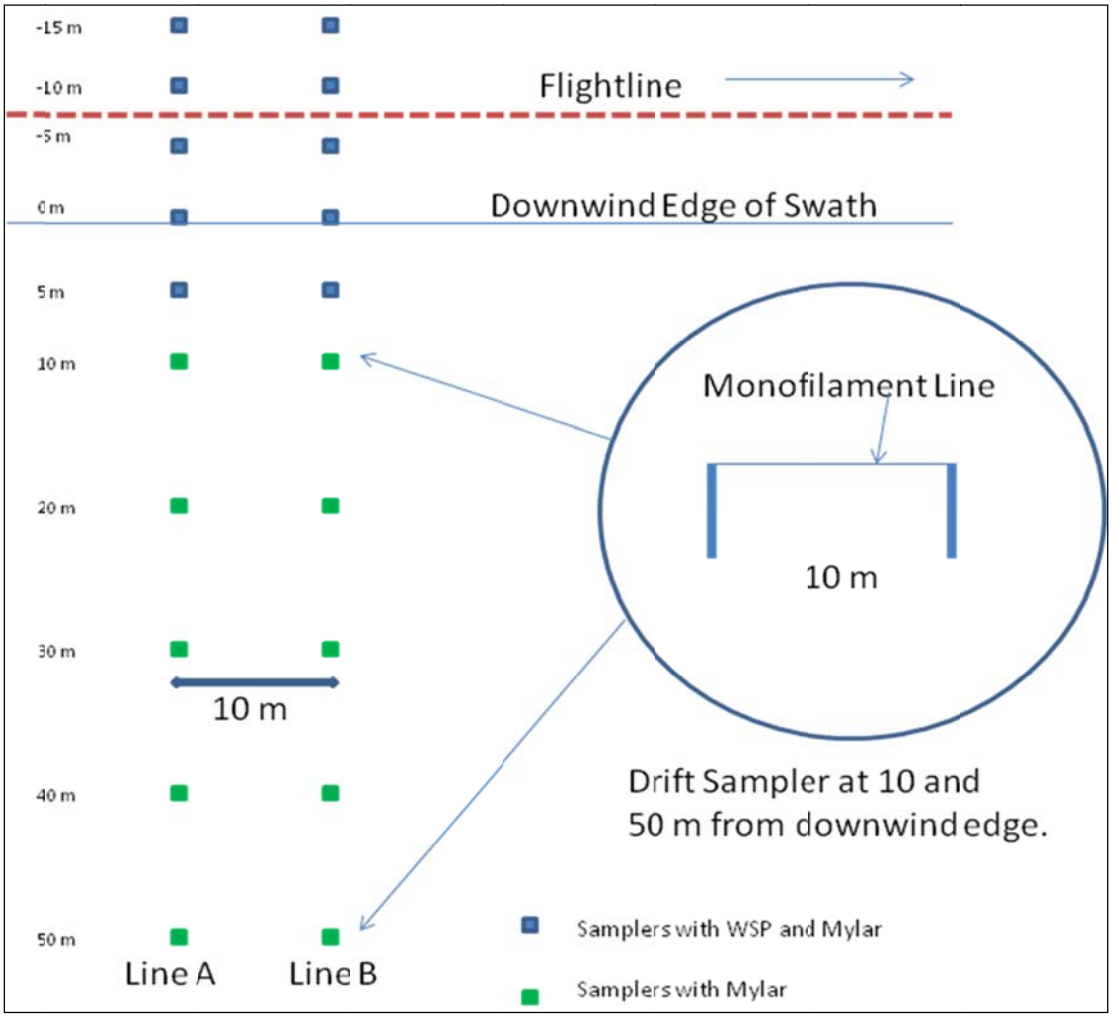

Figure 10. Study layout

As predicted, the monofilament line collectors demonstrated the most significant reduction in drift. The monofilament line is more effective at collecting very small droplets and these droplets are the ones that create the most drift because they remain suspended longer and are carried further away from the application site. The conventional treatments collected 0.073896 µg/cm^2 at 10 meters and 0.009984 µg/cm^2 at 50 meters. The RVA System treatment collected 0.043758 µg/cm^2 and 0.006055 µg/cm^2, respectively, producing a 40.8% reduction in drift at 10 meters and a 39.4% reduction at the 50 meters. This demonstrates that the RVA system is performing as it was intended, reducing driftable droplets, therefore reducing drift or off-site movement.

Table 7. Comparison of drop size produced by Conventional and RVA Spray Systems in swath and down wind on water sensitive cards

SYSTEM	VMD	DV 0.1	DV 0.9
Conventional	389	231	539

RVA	441	300	591

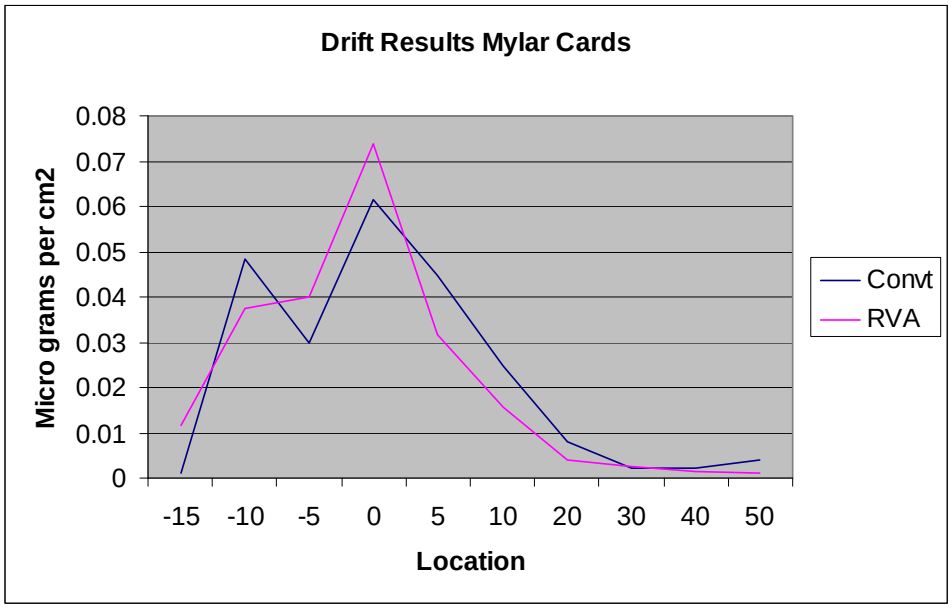

Figure 11. Graph of amount of tracer detected on samplers

Conclusion

We have designed, built and tested the concept of an RVA system to reduce spray drift during aerial application of pesticides. We have built and mounted a 30 foot RVA system on an aircraft and test flown it, determining it to be safe to fly with minimal cost in additional drag, lost lift and added weight. We have demonstrated up to a 93% reduction in fines at 100 mph and 78% reduction in fines at 150 mph airspeed in wind tunnel tests. Actual drift testing in the field with the RVA on a test aircraft at 150 mph using water with dye and non-ionic surfactant (to simulate pesticides tank mix) has demonstrated a 40% reduction in drift at 50 meters down wind compared to a conventional spray system. A complete 30 foot RVA system has been installed on the test aircraft (AT-301), test flown, and met with FAA approval allowing for commercial use of the system. We consider these results to be a successful outcome for this project.

Outcomes/Impacts

US Patent number 7,131,600 issued November 7, 2006

Australian Patent Pending

Canadian Patent Pending

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References

Akesson, N.B., and W.E. Yates. 1989. Pesticide deposit and activity as a function of spray atomizers and liquid formulations. Proceedings, 11th International Congress on Agricultural Engineering (CIGR), Secretariat 22, Clyde Rd., Dublin, Ireland, Vol. 3, pp. 2081-2090.

Akesson, N.B., and W.E. Yates. 1974. The use of aircraft in agriculture. FAO Agriculture Development Manual #94. FAO of the United Nations, Rome, Italy.

Hoffmann, W.C., 2007. AGDISP Sensitivity to Crop Canopy Characterization. Trans. ASAE 50(4): 1117-1122.

Kirk, I.W., 2000. Spray quality for helicopter spray nozzles. NAAA/ASAE Joint Technical Session, Reno, NV, No. AA00-006, ASAE, St. Joseph, MI.

Kirk, I.W., 2001. Droplet spectra classification for fixed-wing aircraft spray nozzles. ASAE International Meeting, Sacramento, CA, No. 01-1082, ASAE, St. Joseph, MI.