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LIQUID PROPERTY AND NOZZLE EFFECTS ON FLIGHT TIME OF PULSED JET SPRAY

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Time of flight of spray droplet packets is an important design parameter in intermittent spraying when there is relative motion between the atomizer and the spray target. Flight times were measured for jets of various liquids, pulse durations, and nozzles used in roadside herbicide spraying. Liquids included surfactants to enhance deposit and polymers for stream containment. Nozzle orifice diameter, pulse duration, and liquid properties all had highly significant effects on flight time. Flight time increased as initial jet velocity decreased. Time of flight decreased with increasing surface tension and decreased with addition of polymers. Flight time was highly related to surface tension of the liquid. This implies that jet breakup and subsequent drag on the droplet packets is the predominant effect on flight. A simple parametric equation was developed to predict flight time from known release conditions, fluid properties, and nozzle-to-target configuration.

INTRODUCTION AND PREVIOUS WORK

Roadside vegetation management is costly for highway maintenance departments. Recent work [1] has demonstrated a machine-vision-controlled sprayer to detect plant targets. When the detection system was coupled with an intermittent spray system, target-activated herbicide application was achieved. A weed-activated herbicide application system can significantly reduce herbicide use by applying material exclusively to spray targets. Control of vegetation with herbicides is estimated to be at least 40% more efficient and cost-effective than mechanical control such as mowing and other alternatives [1]. This previous work [1] used an image acquisition system with valve control events that were controlled by travel distance. In some tests, approximately 3% of the spray mixture was used when compared to conventional application methods; this represents significant reduction in chemical use and potential environmental contamination.

With target-detecting sprayers, design of liquid handling and nozzle emission are important since precise timing and accurate spray trajectories are required to maintain registration between the detected target location and the resulting spray deposit. In mobile applications such as roadside spraying, the spray system is mounted on a vehicle that is moving relative to the stationary target. Variability in spray trajectory would cause displacement between the target and the spray impact. Since mobile systems cannot easily have real-time feedback to confirm target deposition, errors would not be detected before loss of weed control. A companion study [2] to the work reported herein is extending previous work [1], to develop a specialized liquid handling system. The system will provide a constant pressure at the inlet of a nozzle control valve to help maintain consistent jet conditions, regardless of the number of nozzles activated on a nozzle manifold and the corresponding flow rate through the liquid supply system.

NOMENCLATURE

D	orifice diameter, mm
L	distance from nozzle to target, m
Re	Reynolds number ($= U\rho D/\mu$)
t	flight time, ms
U	steady-state velocity, m/s
We	Weber number ($= U^2\rho D/\sigma$)
α	fitted curve parameter for Eq. (1)
β	fitted curve parameter for Eq. (1)
γ	fitted curve parameter for Eq. (1)
δ	fitted curve parameter for Eq. (1)
θ	release angle ($\tan^{-1} \theta = \text{height of nozzle/horizontal distance to target}$)
μ	viscosity, Pa s (kg/m s)
ρ	density, kg/m ³
σ	surface tension, N/m

When biological targets, such as weeds, are sprayed with biologically active materials such as herbicides, surfactants are often used to increase the surface area of deposition and to promote leaf uptake of the active ingredients. Additionally, liquid adjuvants such as long-chain polymers are often used to inhibit generation of small droplets that can be easily displaced by the wind.

The effect of drift control agents on volumetric droplet size spectra for simulated aircraft-mounted sprayers in wind tunnel trials has been reported [3]. Results showed that some polymer-based adjuvants significantly changed the droplet size spectra of the sprayed formulations. Comparison of the polymers with propanil (a herbicide) alone showed an increase in volume of large and small droplets in the droplet size distribution, indicating reduced coverage and increased spray drift. However, addition of polymer material to a liquid flowable formulation resulted in decreased volume of small droplets, while polymer addition to emulsifiable concentrate increased the volume of large droplets. Therefore, the performance of polymers for drift reduction is affected by other constituents in the spray mix. Similar results from other studies [4] indicated that polymer formulations did not reduce production of smaller drops even though there was a general upward shift in the entire droplet spectrum, indicating that drift losses can still occur. Additional work [4] indicated that stream lengths were less than those previously considered when using a polyacrylamide additive; the research concluded that the material tested may have contained other agents affecting rheological behavior.

Use of polyethylene oxide polymer can reduce liquid drag in piping systems [5], and can increase the distance of water travel from fire hose nozzles by up to 50% [6]. However, there appears to be a degradation effect over time once the polymer is in solution [5], and research indicates that material injected as a slurry with an appropriate size distribution of polymer particulates will allow a continuous release of the drag-reducing polymer into the flow stream in addition to decreasing power requirements as opposed to an aqueous mixture of polymer in solution.

Cylindrical liquid jets ejected will break up and produce droplets; eventually this production will lead to satellite droplets from the original trajectory stream [7, 8]. Infinite

droplet streams have been shown to influence the immediate surroundings at least 15 diameters away from the original stream axis. The entrained air provides a viscous coupling that reduces effective drag on neighboring droplets [7]. Other research indicated that neighboring droplets affect drag and discussed the effect of subsequent collisions and coalescing of trailing drops [8]. Viscous coupling between spray droplets and ligaments produced from an unstable jet could alter the flight time of the spray mass.

OBJECTIVES

The goals of the work reported herein were to measure spray flight times and develop means for predicting flight times for typical right-of-way herbicide spray configurations and liquids that will be deployed with target-sensing control systems. As a practical design matter, the flight time values are required in order to control system timing so that targets are consistently hit with emitted spray. The specific objectives were

1. To determine flight time for intermittent spray bursts emitted from typical, straight-stream nozzles using a parametric experiment with test factors of nozzle diameter, jet pulse duration, distance of travel, and liquid formulation
2. To quantify the effects of liquid formulation and nozzle geometry on flight times, and develop predictive equations to describe flight times for given configurations and liquids within the range tested in the experiment

EXPERIMENTAL DESIGN AND METHODS

The parametric experiment was conducted as a factorial design with the test factors of: liquid formulation, nozzle diameter, jet pulse duration, travel distance, and combinations of nozzle height and horizontal distance to target. Six test fluids were used; fluid properties are shown in Table 1. Municipal water was the solvent for all test fluids. Typical ranges of physical parameters for the municipal water were a temperature range of 19–23°C, pH range of 7.6–8.4, and hardness range of 70–590 (ppm as CaCO_3). Two types of fluid adjuvants, namely, one surfactant and two polymers, were used. As polymers can degrade over long periods of time and due to elevated temperatures, all fluids during the tests were used within 1–2 h of makeup. The surfactant was an organofunctional, nonionic silicone (Silwet-L77, Loveland Industries, Inc., Greeley, CO) added at a rate of 0.125% v/v. The

Table 1 Liquid Properties for Liquid Solutions Used in the Experiment^a

Fluid additive	Density (kg/m^3)	Viscosity (Pa·s)	Surface tension (N/m)
None	998.2	1.00E-03	0.0728
Surfactant 0.125%	997.1	1.02E-03	0.0284
Polyacrylamide 0.01%	999.9	1.36E-03	0.0479
Polyethylene oxide 0.01%	975.9	1.09E-03	0.0568
Surfactant + polyacrylamide	998.5	1.37E-03	0.0264
Surfactant + polyethylene oxide	965.7	1.02E-03	0.0259

^a Solvent was municipal tap water.

polymers were a polyetheylene oxide (Polyox, Amerchol Corp., Edison, NJ) and a polyacrylamide (Target LC, Loveland Industries, Greeley, CO), both added at a rate of 0.01% w/w. Preliminary results for this research showed that a rate of 0.1% w/w polymer caused Rayleigh flow for the spray conditions reported here as opposed to cylindrical spray stream trajectories. This effect has been reported elsewhere [5]. The fluids were selected to test the effects of surfactant and polymers individually and in combination. Liquid properties were measured with a specific-gravity scale (model S-101, Troemner, Inc.) for density, a Ubbelohde tube (model 0C, Cannon Instrument Co.) for viscosity, and a surface tensiometer (Surface Tensiomat model 21, Fisher Scientific) for surface tension. The effects of adjuvants on the fluid properties were as expected. Addition of the surfactant reduced surface tension to the range of 0.028 N/m and had no effect on viscosity; these effects were virtually unaffected by presence of either polymer. Addition of the polyacrylamide polymer (TLC) increased viscosity of the fluid by 37%, regardless of the presence of surfactant. In the absence of surfactant, addition of the polyetheylene oxide (PEO) or polyacrylamide polymer reduced the surface tension to 0.057 and 0.048 N/m, respectively.

The three test nozzles were commercial, straight-stream nozzles (Nos. SS0005, SS0010, and SS0015, Spraying Systems Co., Wheaton, IL) with orifice diameters of 1.55, 2.18, and 2.72 mm, respectively, and flow ratings of 1.89, 3.79, and 5.68 L/min, respectively, at 275 kPa liquid pressure. Each nozzle was installed along with a commercial flow straightener (SS-1/4x1/4, Spraying Systems Co.) immediately upstream of the nozzle. Liquid flow into the nozzle/straightener assembly was controlled by a three-way, electrically actuated, 12-Vdc, 10-W solenoid valve (model 651064, KIP, Inc., Farmington, CT). The normal (spring) position of the valve routed liquid from the inlet to a bypass line. When actuated, the valve diverted flow from the bypass line to the nozzle. When installed on the mobile vehicle, the bypass line returns liquid to the supply tank and the nozzle actuation from a manifold of nozzles has little effect on system pressure [2]. In these experiments the bypass line was closed, since only one nozzle was actuated at any time. Pulse durations were controlled by a square-wave pulse generator consisting of a digital timing circuit and a field-effect transistor driver with diode suppression of inductive flyback from the valve coil. Pulse durations of 30 and 60 ms were used.

Liquid was supplied to the valve inlet at a pressure of 550 kPa, representing the pressure commonly maintained on the mobile spray vehicle liquid system. Since the pressure control system on the mobile vehicle is configured to maintain pressure on a liquid supply manifold rather than the actual pressure at the nozzle inlet, the experiments were conducted in that manner. This design functionally treated the valve/flow straightener/nozzle assembly as a single unit. Since the solenoid valve and the flow straightener constituted a structure creating a pressure drop upstream of the nozzle, the actual pressure at the nozzle inlet was measured with steady-state tests prior to the time-of-flight experiments. As expected, actual inlet pressure at the nozzle decreased as flow capacity of the nozzle, and correspondingly, the flow through the valve, increased. With the 550-kPa valve inlet pressure, the observed pressures at the nozzle inlet were 448, 304, and 207 kPa for the 0005, 0010, and 0015 nozzles, respectively. Pressure drop across the valve was virtually independent of liquid properties. Steady-state flow rates of each liquid from each nozzle were measured by measuring nozzle discharge for a 1-s burst. From the steady-state measurements and nozzle exit area, steady-state velocities were calculated. These results are presented in Table 2, along with corresponding Reynolds and Weber numbers based on the measured liquid properties in Table 1.

Table 2 Steady-State Velocity, Reynolds Number, and Weber Number of the Emitted Jet for Different Orifice Diameters and Liquid Formulations at 550 kPa

Fluid	1.55-mm diameter			2.18-mm diameter			2.72-mm diameter		
	<i>U</i> (m/s)	Re no.	We no.	<i>U</i> (m/s)	Re no.	We no.	<i>U</i> (m/s)	Re no.	We no.
1 Water	21.9	33,884	10,193	17.7	38,517	9,365	14.2	38,554	7,520
2 Surfactant 0.125%	22.5	34,092	27,550	18.0	38,572	25,075	14.4	38,289	19,802
3 Polyacrylamide 0.01%	19.9	22,678	12,813	16.7	26,766	12,691	12.9	25,797	9,449
4 Polyethylene oxide 0.01%	21.7	30,114	12,540	17.3	33,961	11,340	13.8	33,607	8,900
5 Surfactant + polyacrylamide	19.9	22,481	23,216	15.0	23,992	18,800	13.4	26,366	18,198
6 Surfactant + polyethylene oxide	19.9	29,203	22,887	15.0	31,785	19,277	13.0	33,220	16,877

Right-of-way spraying from a moving vehicle is typically done with nozzles mounted on a vertical column and directed outward such that flow from each nozzle sprays a band parallel to the direction of travel. Bands nearest the vehicle are sprayed by nozzles low on the column, while the farthest bands outward from the vehicle are sprayed by the uppermost nozzles on the column. Therefore, the greatest travel distance for spray is for the outward band sprayed by the uppermost nozzle, while the least travel distance corresponds to the nearest band sprayed by the lowest nozzle on the column. For this experiment, extreme and midpoint conditions for vertical nozzle positions and horizontal target distances outward were selected from the actual vehicle configuration for which the system was designed (Table 3). Nozzle heights of 1.54, 1.92, and 2.30 m and horizontal target distances (from the nozzle exit) of 0.50, 1.83, and 3.66 m were used. The experimental design tested five conditions, the combinations of 1.54- and 2.30-m nozzle heights with 0.50- and 3.66-m target distances, and the single, mid-range combination of 1.93-m height and 1.83-m target distance.

For each test configuration, the nozzle was positioned at the test height above ground and aimed to strike a target at the test distance horizontally outward at ground level. The target deposition was modeled as a thin, flat stainless steel plate cantilevered on a small floor support. The flex of the plate provided displacement when the spray liquid struck the plate. An accelerometer (model 353B65, PCB Piezotronics, Inc.) was mounted on the cantilevered target plate. An optical passage sensor (model PG-602, Keyence Corp.) was placed at the exit of the nozzle orifice. Response times of both sensors were < 0.5 ms, sufficiently small in relation to the measured flight times. Analog voltage outputs from the optical sensor and accelerometer were monitored on separate channels of an oscilloscope (model TDS 3012B, Tektronix, Inc.). Liquid passage through the optical sensor triggered the oscilloscope sweep of both channels. Activation of the nozzle enabled the optical sensor

Table 3 Nozzle Height, Nozzle Horizontal Distance from Target, Release Angle of Fluid, and Vector Travel Distance of Fluid to Target for Experimental Tests

Position	Height (m)	Horiz. distance (m)	Release angle ^a (deg)	Travel distance (m)
1	1.54	0.50	17.9	1.62
2	1.54	3.66	67.2	3.97
3	1.92	1.83	43.6	2.65
4	2.30	0.50	12.3	2.35
5	2.30	3.66	57.9	4.32

^a Calculated as $90^\circ - \tan^{-1}(\text{nozzle height/horizontal distance to target})$.

signal to be measured on one channel of the oscilloscope as the initial portion of the jet trajectory was ejected from the nozzle orifice. The accelerometer signal from the spray stream impact onto the stainless steel plate was obtained on a separate channel of the oscilloscope. The oscilloscope programming capabilities allowed the time between liquid ejection from the nozzle and spray stream impact onto the stainless steel plate to be measured from the rising edge of signal signatures on the separate channels. A typical example of the oscilloscope output is given in Fig. 1. Each test condition (nozzle-to-target position, pulse time, nozzle diameter, and liquid) was replicated four times.

Photographic images of an exiting cylindrical jet of water are shown in Fig. 2. The initial profile of the exiting stream is observed to have an annulus of laminar flow surrounding the turbulent core, preventing particles in the core from disrupting the jet surface. This type of effect has been described elsewhere [9]. Farther downstream the faster turbulent core breaks through the outer protective laminar annulus [9] and begins to disintegrate as well as produce satellite droplets along the cylindrical jet stream. After several hundred diameters downstream of the nozzle exit, the cylindrical jet has completely disintegrated.

RESULTS AND DISCUSSION

The initial data analysis procedure was a straightforward analysis of variance (ANOVA) that followed the factorial experimental design. Since flight time was obviously dependent

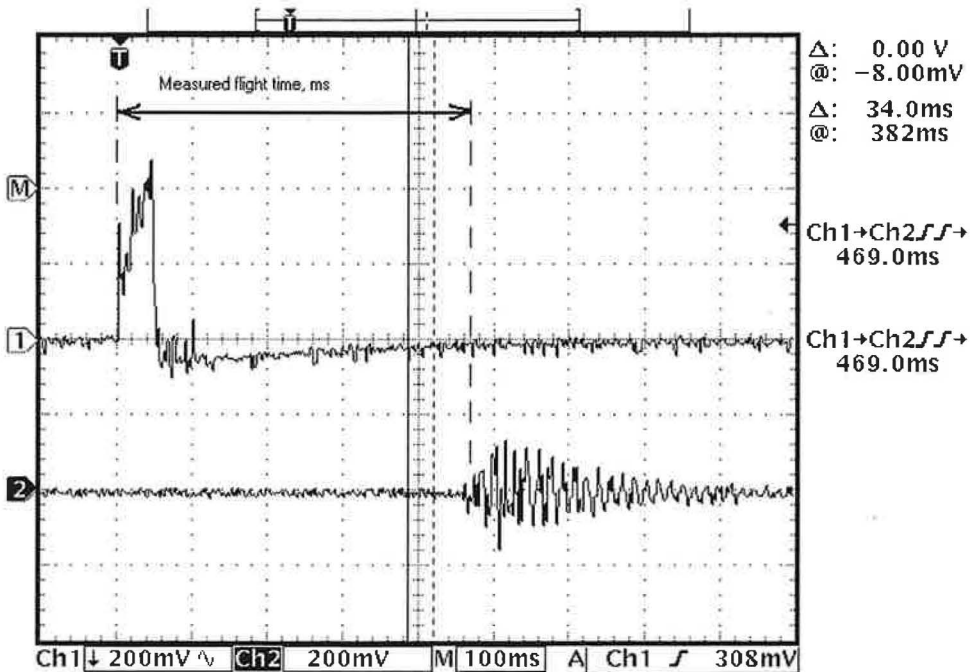


Fig. 1 Typical time of flight generated results from oscilloscope for one replicate of surfactant (0.125%) and polyacrylamide (0.01%) formulation at 550 kPa and 30-ms pulse duration. Signal no. 1 (upper trace) is from the passage detector; signal no. 2 (lower trace) is from the impact plate accelerometer. Time scale is 100 ms/division.

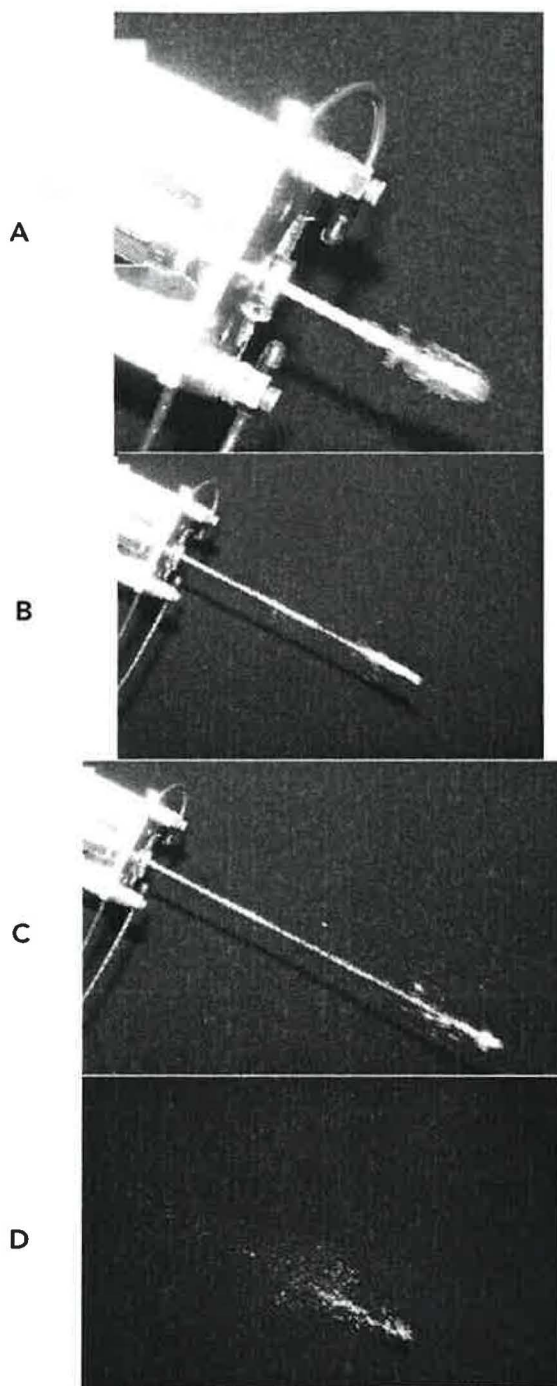


Fig. 2 Sequential images of water exiting nozzle, where (A) shows an annulus of laminar flow surrounding the turbulent core, (B) shows effects after the turbulent core breaks through the outer laminar layer, (C) shows the beginning of fluid front disintegration, and (D) shows complete disintegration several hundred nozzle diameters downstream of the nozzle exit.

on travel distance, the ANOVA was conducted for each of the five nozzle-to-target configurations. The analysis found that nozzle diameter, fluid, and pulse time (only at the greatest distance) were all significant ($\alpha < 0.05$) factors on flight time. The results are shown in Table 4. At each position, the effect of nozzle and fluid was highly significant. The effect of pulse time was relatively minor, as were interactions between pulse time and nozzles or fluid. Since position, nozzle diameter, and test fluid had significant effects on flight time, a tabular presentation of the flight times and standard deviations for each distinct condition are shown in Table 5. Mean flight times ranged from 75 ms at the shortest travel distance to 475 ms at the longest travel distance. These times, in relation to the 10-Hz current operation rate of the target-sensing sprayer, are substantial and confirm that spray flight time and the associated influences of liquid formulation and nozzle geometry are significant process control variables.

The results also indicated that fluid effects are more significant with the larger nozzle orifice diameters and as the total travel distance increased. The general trend was that the solutions with lower surface tension, i.e., the surfactant solution, the surfactant + polyacrylimide, and the surfactant + polyethylene oxide, produced longer flight times. However, when compared to solution of surfactant alone, addition of the polyacrylimide and polyethylene oxide polymers to the surfactant solution reduced the flight times.

The observed results provided the expected flight times for the tested configurations, while the analysis of variance was useful in quantifying the relative influence of the experimental factors on flight time. However, of greater utility for system design is the ability to predict flight times for various configurations, liquids, and nozzles. Accurate flight-time predictions would facilitate system improvements and reduce tuning and software configuration effort. Additionally, real-time, adaptive control algorithms could use on-board computation of flight times in adapting the system operations to changes in ground speed, nozzle orientations, and target locations.

The observed test data were used to develop predictive equations for flight time. A number of candidate forms of predictive equations were evaluated. The most useful form found was

$$t = \alpha U^\beta [\tan(\theta)]^\gamma L^\delta \quad (1)$$

where

t = flight time, ms

U = nozzle exit velocity (steady-state velocity), m/s

θ = release angle, degrees

L = travel distance from nozzle to target, m

$\alpha, \beta, \gamma, \delta$ = fitted curve parameters.

Conceptually, this product string formulation was logical, as it allowed the U term to account for the release conditions, reduced to only the initial velocity, while the trigonometric function $\tan(\theta)$ and L terms accounted for the nozzle-to-target geometry. In an

Table 4 Results from Analysis of Variance for Flight Time as Affected by the Factors of Nozzle, Fluid, Pulse Time, and All Interactions^a

Test factor	Position 1		Position 2		Position 3		Position 4		Position 5	
	<i>F</i>	<i>p</i> > <i>F</i>	<i>F</i>	<i>p</i> > <i>F</i>	<i>F</i>	<i>p</i> > <i>F</i>	<i>F</i>	<i>p</i> > <i>F</i>	<i>F</i>	<i>p</i> > <i>F</i>
Nozzle	1259.4	<0.001	107.0	<0.001	1147.7	<0.001	1762.3	<0.001	43.3	<0.001
Fluid	8.43	0.004	38.6	<0.001	22.2	<0.001	21.1	<0.001	54.8	<0.001
Pulse time	0.12	0.728	0.25	0.617	1.39	0.240	0.02	0.894	5.02	0.027
Nozzle × fluid	6.85	0.010	1.98	0.167	11.3	0.001	32.4	<0.001	0.80	0.373
Nozzle × pulse	3.55	0.062	0.03	0.874	0.33	0.570	0.05	0.819	0.06	0.809
Fluid × pulse	1.05	0.308	0.01	0.968	1.44	0.232	4.19	0.043	1.56	0.213
Nozzle × fluid × pulse	4.04	0.047	0.02	0.892	0.03	0.857	0.02	0.879	0.14	0.707

^a Each parametric condition was replicated four times.

Table 5 Mean Flight Times (in ms, with standard deviations in parentheses) by Position, Nozzle Orifice Diameter, and Fluid^a

Fluid	Position 1 1.54 m × 0.50 m			Position 2 1.54 m × 3.66 m			Position 3 1.92 m × 1.83 m			Position 4 2.30 m × 0.50 m			Position 5 2.30 m × 3.66 m		
	1.55	2.18	2.72	1.55	2.18	2.72	1.55	2.18	2.72	1.55	2.18	2.72	1.55	2.18	2.72
	(orifice diam., mm)			(orifice diam., mm)			(orifice diam., mm)			(orifice diam., mm)			(orifice diam., mm)		
1	76.7 (2.2)	87.7 (20.5)	107.7 (4.4)	260.7 (8.4)	278.7 (8.0)	327 (9.0)	147.3 (3.3)	165.7 (5.4)	188 (3.5)	106.8 (2.6)	130.7 (3.6)	152.6 (2.0)	322.1 (30.2)	311.7 (7.5)	359.7 (7.7)
2	76.8 (2.8)	93.8 (6.6)	112.1 (4.9)	338.7 (11.4)	330.8 (13.1)	413.9 (11.4)	152.2 (4.9)	172.6 (3.8)	201 (6.4)	127.6 (3.6)	134.5 (5.3)	156.6 (3.5)	396 (16.0)	400.4 (11.1)	464.7 (54.5)
3	80.6 (3.6)	94.1 (3.1)	112.5 (4.1)	257.2 (8.4)	273.1 (3.5)	323.7 (14.7)	144.6 (5.4)	159.8 (2.5)	191.3 (5.0)	109.5 (2.9)	129.1 (1.9)	157.4 (1.6)	319.5 (10.5)	326 (7.6)	374.2 (17.0)
4	74.2 (1.0)	87.3 (2.2)	108.3 (6.1)	253.8 (7.2)	287.6 (3.9)	332.8 (8.9)	140.2 (5.4)	171.1 (7.9)	192.6 (2.67)	108.4 (2.1)	131.9 (1.4)	159.8 (2.3)	314 (10.2)	339.8 (10.8)	361.2 (8.7)
5	76.7 (2.6)	98.1 (1.9)	119.1 (2.3)	328.4 (9.1)	357.5 (6.7)	416.1 (13.4)	152.2 (4.4)	170.2 (4.5)	204.4 (8.4)	114 (3.7)	138 (2.7)	167.5 (5.0)	394.6 (14.2)	433.5 (15.1)	462.6 (10.0)
6	76.4 (3.4)	93.7 (5.7)	113.4 (7.1)	327.8 (11.3)	334 (11.7)	428.3 (12.0)	147.6 (5.5)	180.6 (6.7)	205.3 (8.3)	110.5 (2.6)	136.9 (4.0)	167.2 (4.2)	405 (11.6)	422.4 (16.2)	476.8 (16.2)
$F_{1,47}$	0.8	5.06	7.45	7.54	19.42	17.91	0.02	12.64	18.44	1.04	14.05	108	12.96	34.31	14.51
$p > F$	0.47	0.03	0.01	0.01	0.001	0.001	0.88	0.01	0.001	0.31	0.001	0.001	0.001	0.001	0.001

^a F and p values shown in bottom row are for fluid effects blocked within position and nozzle orifice diameter.

ideal system with no gravity or drag effects, curve parameters would be $\alpha = 1$, $\beta = -1$, $\gamma = 0$, and $\delta = 1$. Equation (1) was useful in that all tested nozzles could be pooled, since only the initial velocity was needed. Additionally, this would allow a priori system design in that nozzle exit velocity can be predicted from the volumetric flow rate and the orifice diameter.

Equation (1) was fitted to the observed data for each liquid after data for 30- and 60-ms pulse times and the three test nozzles were pooled. Individual equations were fitted for each test liquid, since the equation did not have any terms accounting for formulation effects. It was hypothesized that the resulting least-squares parameter estimates would reveal the effects of fluid properties. Resulting parameter estimates are shown in Table 6. Each fitted equation was based on 120 observations and had 119 corrected total degrees of freedom and 4 regression degrees of freedom. F values are shown for each curve; in all cases the $p > F$ was < 0.001 .

The fitted equations closely predicted the flight times of jet pulses from the tested nozzles and fluids and the test configurations (Figs. 3 and 4). Inspection of the results in Table 6 revealed that the flight times were generally proportional to the inverse square root of initial jet velocity; estimates of the β parameter ranged from -0.4530 to -0.5281 . The δ value indicates sensitivity of flight time to increasing flight distance; a strong inverse relationship was observed when surface tension was considered. Data for water, with the highest surface tension (0.0728 N/m), produced a δ estimate of 1.329 . The polyethylene oxide and polyacrylamide solutions without surfactant and with surface tensions of 0.0568 and 0.0479 N/m, respectively, had δ estimates of 1.379 and 1.395 , respectively. The test fluids with surfactants, with surface tensions of 0.0284 , 0.0264 , and 0.0259 N/m, had δ estimates of 1.654 , 1.673 , and 1.720 , respectively.

The general trends were intuitively consistent with expected results. As initial velocity increases, flight time decreases, although this relationship is nonlinear because of drag effects. As surface tension decreases, the jet was more likely to disintegrate, especially

Table 6 Least-Squares Parameter Estimates with Standard Errors for Spray Flight Times as Predicted by Eq. (1) for the Six Test Fluids

Fluid	α (s.e.)	β (s.e.)	γ (s.e.)	δ (s.e.)	$F_{4,119}$
1	169.1 (17.62)	-0.4541 (0.0326)	-0.0233 (0.0124)	1.329 (0.0387)	7,630
2	135.4 (17.87)	-0.453 (0.0399)	-0.0142 (0.0169)	1.6538 (0.0532)	4,833
3	180.6 (16.64)	-0.5167 (0.0294)	0.0023 (0.0113)	1.3947 (0.0358)	9,015
4	185.4 (14.64)	-0.506 (0.0246)	-0.0086 (0.0097)	1.3789 (0.0306)	12,391
5	155.4 (17.19)	-0.5259 (0.0356)	-0.0123 (0.0132)	1.673 (0.0417)	7,922
6	146.8 (18.88)	-0.5281 (0.0409)	-0.0024 (0.0162)	1.7195 (0.0516)	5,272

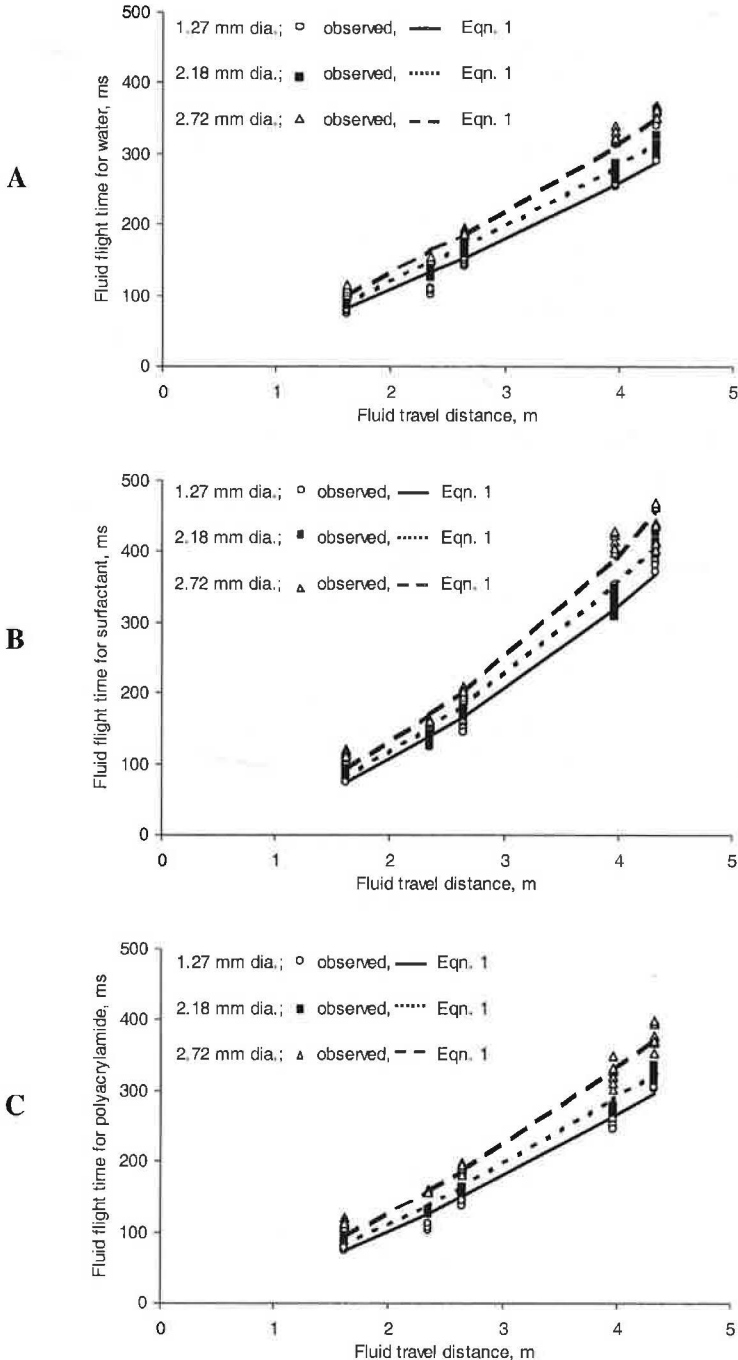


Fig. 3 Observed and predicted flight times using Eq. (1) for water (A), surfactant (B), and polyacrylamide (C) for each nozzle size and spray travel distance.

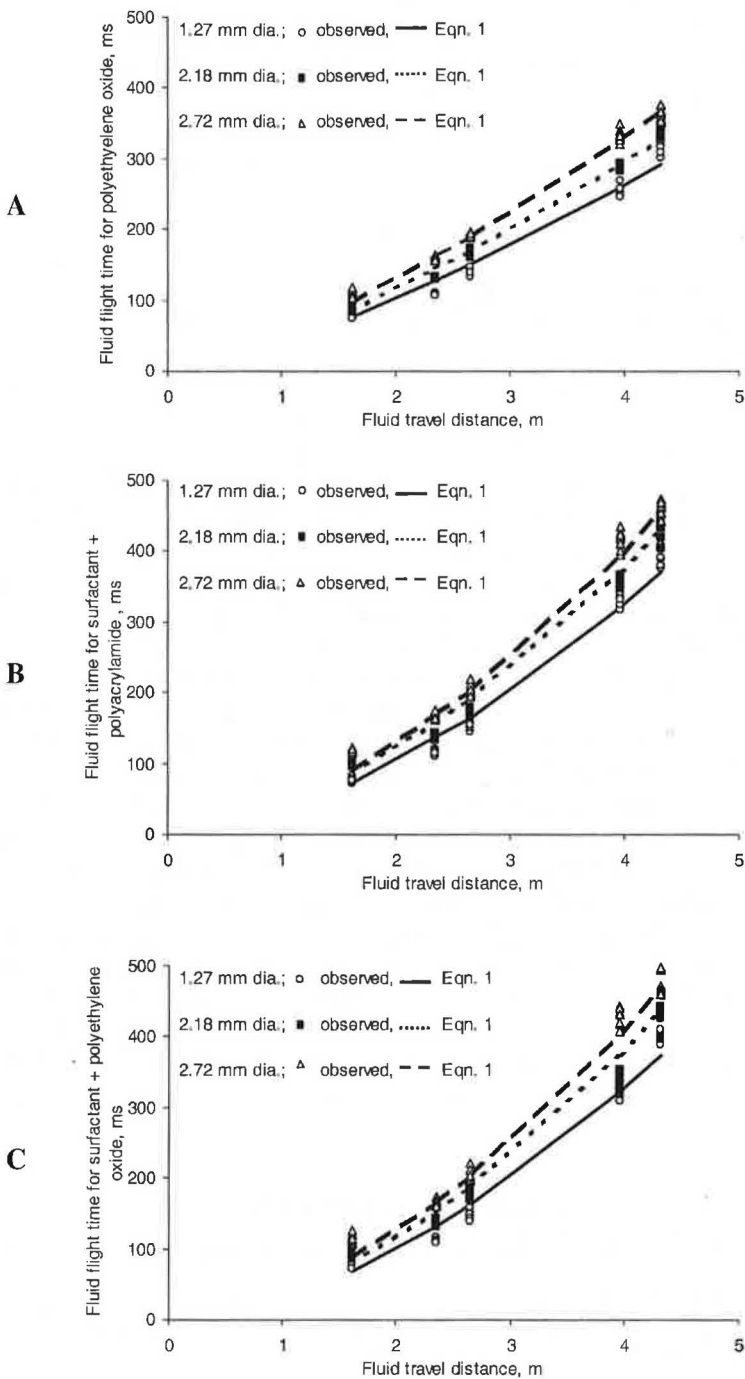


Fig. 4 Observed and predicted flight time using Eq. (1) for polyethylene oxide (A), surfactant + polyacrylamide (B), and surfactant + polyethylene oxide (C) for each nozzle size and spray travel distance.

with increasing flight distance. As the jet disintegrates into smaller ligaments and droplet packets, relative drag increases and reduces the bulk velocity of the jet, resulting in longer flight times.

The results suggested that the six test fluids could possibly be considered as two fluids, viz., a high-surface-tension fluid and a low-surface-tension fluid. For analysis, water, water + polyacrylamide, and water + polyethelyene oxide solutions were pooled as one fluid type, and the water + surfactant, water + surfactant + polyacrylamide, and water + surfactant + polyethelyene oxide solutions were pooled as the other fluid type. Effectively, this partitioning of fluids combined liquids with surface tension values of 0.0259 to 0.0284 N/m into a low-surface-tension group and liquids with surface tensions from 0.0479 to 0.0728 N/m into a high-surface-tension group.

Equation (1) was fitted to the two liquid groups; resulting parameter estimates and standard errors are shown in Table 7. The results show that the δ exponent is significantly greater with the low-surface-tension group, confirming that the reduced surface tension results in greater deceleration of the jet. While the α parameter is greater for the high-surface-tension fluid, the effect of the higher δ predominates the relationship between nozzle-to-target distance and flight time. This can be illustrated by considering the partial derivative of flight time with respect to distance from Eq. (1). Considering a typical configuration with experimental conditions of $U = 17.0$ m/s, $\tan(\theta) = 3.0$, and distance = 3.0 m, the resulting numerical values for $\partial(\text{time})/\partial(\text{distance}) = 89$ and 124 ms/m for the high-surface-tension and the low-surface-tension fluids, respectively.

The utility of Eq. (1) with the least-squares parameter estimates of Table 7 was further investigated by comparing the flight times predicted by the equation with the experimentally observed values for the entire experimental data set. For the high-surface-tension liquids, the average difference between observed and predicted flight times was 0.182 ms (std. dev. = 13.15) and the maximum differences were -33.9 and +72.4 ms. For low-surface-tension liquids, the average difference between observed and predicted flight times was 0.821 ms (std. dev. = 20.38) and the maximum differences were -63.9 and +82.9 ms. Differences between the observed and the predicted flight times for the two liquid types, versus the observed flight times, are shown in Fig. 5.

The fitted equations provide a useful a priori estimate of spray flight time that could be used in process control algorithms where timing of intermittent spray release is critical. Once a nozzle is installed, the nozzle-to-target configuration defined, and the fluid type (high or low surface tension) determined, the flight times can be estimated. All these input conditions are known prior to sprayer operation in roadside spraying. While this experiment did not consider the practical case where the nozzle is in motion and there is

Table 7 Parameter Estimates with Standard Errors for Spray Flight Times as Predicted by Eq. (1) for the Two Groups of Test Fluids

Surface tension (N/m)	α (s.e.)	β (s.e.)	γ (s.e.)	δ (s.e.)	$F_{4,359}$
High surface tension, 0.0479 < σ < 0.0728	170.7 (9.25)	-0.4771 (0.0170)	-0.0095 (0.0067)	1.3684 (0.0211)	25,971
Low surface tension, 0.0259 < σ < 0.0284	129.9 (9.19)	-0.4614 (0.0219)	-0.0095 (0.0092)	1.6838 (0.0292)	16,212

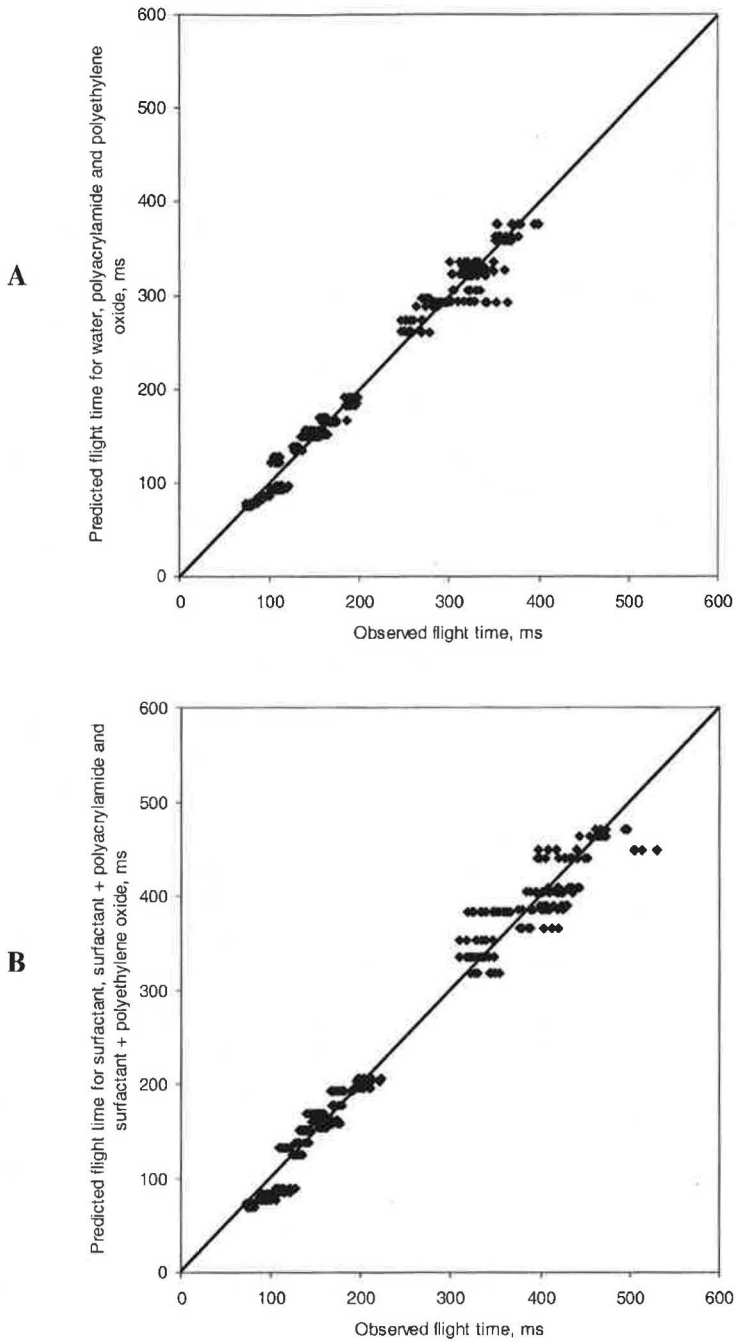


Fig. 5 Observed and predicted flight times for all fluids and conditions: (A) shows results for water, polyacrylamide, and polyethylene oxide; (B) shows results for surfactant, surfactant + polyacrylamide, and surfactant + polyethylene oxide.

aerodynamic drag normal to the jet motion, the results provide a useful initial estimate from which the operating system can be tuned based on observed performance.

CONCLUSIONS

Flight times for pulsed jets from straight-stream nozzles were electronically measured using an optical detector and an impact plate. Jet diameters of 1.5–2.7 mm and jet velocities of 13–22 m/s were created for pulse durations of 30 and 60 ms. Flight distances ranged from 1.6 to 4.3 m. For the nozzle, fluid, and nozzle-to-target geometries tested in this experiment, the flight times ranged from 75 to 475 ms. These times represent substantial periods for designing process control of automated intermittent spraying with relative motion between the nozzle and the target. Flight time was significantly affected by initial jet velocity, relative angle of jet release with respect to gravity, and the surface tension of the liquid. A simple, product-string model was developed to predict flight time from the jet initial velocity, the angle of release, the nozzle-to-target distance, and the liquid surface tension. While the best predictions resulted from fitting an equation for each tested fluid, prediction equations developed for high- versus low-surface-tension fluids were comparably accurate for prediction. The predictive equations were simple enough to be implemented in a real-time process controller where the user need enter only the spray configuration, fluid type, and nozzle characteristics of diameter and volumetric flow rate.

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EXHIBIT D

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PULSED-JET MICROSPRAY APPLICATIONS FOR HIGH SPATIAL RESOLUTION OF DEPOSITION ON BIOLOGICAL TARGETS

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In agricultural spraying, where discrete targets and nontargets are present in a localized region, high spatial resolution of liquid deposition is essential for selective treatment. Microspraying with small jets can provide high resolution in spray dose and position. Pulsed microspray jets were created with various orifice sizes and duration of liquid emission and deposited with various orifice-to-target distances. Formulations included surfactants that increase area covered onto plant surfaces for increased herbicide efficacy, and polymers to inhibit splash during deposition. Kromekote™ cards were used as the deposition target. Image analysis measured deposition area and centimeter-scale splashing, i.e., "microdrift" from the pulsed jets. Liquid properties were measured; Reynolds (Re), Weber (We), and Ohnesorge (Oh) numbers were calculated. Formulations containing polyethylene oxide polymer were more effective at reducing microdrift than polyacrylamide polymer, and silicone surfactant increased spreading compared to an oil-based surfactant.

INTRODUCTION

In agricultural spraying, effective use of spray adjuvants to alter liquid properties can minimize spray drift, worker hazards, and surface-water contamination through irrigation or runoff. Uniform deposition of small, concentrated droplets can provide higher biological efficacy than large, dilute droplets [1–3]. Improved spray technology has increased our ability to dispense dose volumes precisely, on the order of microliters, onto specific target locations. Selective applications within 1 cm are a completely new scale of accuracy and precision in agricultural chemical treatment. Spray applications can aim the initial deposit toward weed surfaces that are only slightly displaced from adjacent crop plants. A precise postemergent treatment system, coupled with an effective adjuvant, may allow nonselective herbicides to be used for weed control. Nonselective herbicides are those that can kill the crop as well as the target weeds. In specialty and organic cropping systems, nonselective, postemergent herbicides may be the only effective option for chemical weed control.

Figure 1 shows a typical scene from a commercial processing tomato field, where a grassy weed grows in close proximity to a tomato plant. These weeds can significantly reduce crop yield, since they are highly competitive with the crop plants for water, light, and nutrients. The position of the weed within the crop row makes mechanical removal difficult. Machine vision inspection systems have been developed to distinguish and locate weeds in scenes similar to that shown in Fig. 1 [4–6]. However, once the weed targets are located, the challenge is to deposit an effective or lethal dose of herbicide solution exclusively on the weed while preventing damage to the adjacent crop plant.

Adjuvants can significantly increase the physical transport of chemical across a leaf surface after initial droplet deposition. The surfactant Silwet-L77 was found to improve

NOMENCLATURE

D	orifice diameter, m
DS_{50}	distance within which 50% of microdrift stains occurred from primary stain center, m
L	nozzle length, m
Oh	Ohnesorge number $[= (We)^{1/2}/Re]$
PS	primary stain area, m^2
PS/V	primary stain area/volume applied, m^{-1}
Re	Reynolds number $[= (U\rho D)/\mu]$
TS	total stain area, m^2
U	steady-state velocity, m/s
V	volume, L
We	Weber number $(= U^2 \rho D)/\sigma$
μ	viscosity, Pa·s
μD	microdrift, m^2
μDf	fraction of microdrift area versus total stain area $(= \mu D/TS)$
ρ	density, kg/m^3
σ	surface tension, N/m

droplet spread by a factor of 100 on Johnsongrass leaves, while other materials have shown improvement by up to a factor of 500 [7]. Deposition analysis of pesticide formulations, spray diluents, and petroleum sprays to estimate deposition area, spray droplet size, and extent of area covered using water-sensitive cards, oil-sensitive paper, and Kromekote cards has been conducted for a number of years [8–10]. These studies used the ratio of deposit

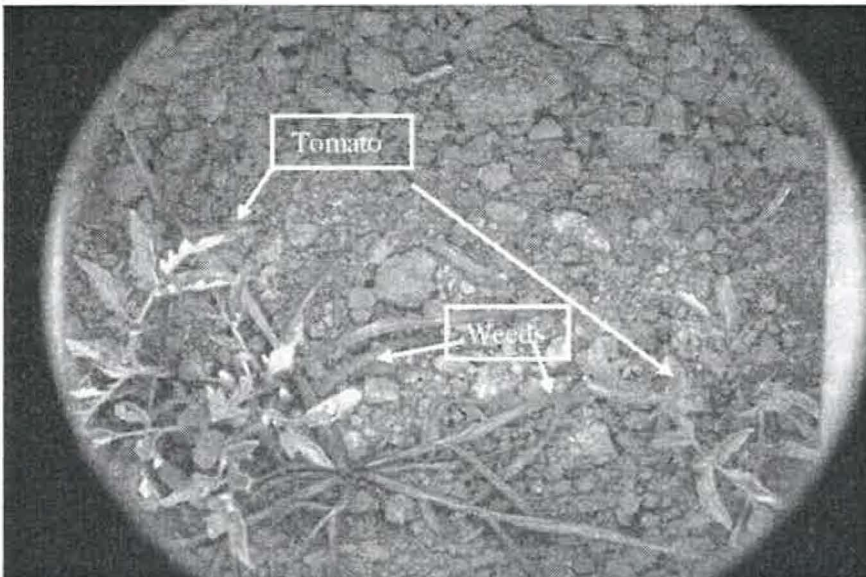


Fig. 1 Image of young tomato plants and weeds showing proximity and need to minimize splashing.

stain size to spray droplet size to estimate spread factors in agricultural field settings to determine spray cloud coverage and potential drift over treatment sites. One of the main drawbacks with using stain size estimates is the effect of overlap, that is, multiple drops impinging over the same area or in close proximity so that application rates are difficult to predict. Current digital imaging technology has enhanced the ability to estimate deposition stain sizes that are representative of measured areal empirical results. Results presented in the current study are concerned with extent of microdrift, represented as deposit outside the target area, that can occur during specific application conditions using pulsed jets.

One aspect that is of concern in the current research is the effect, or result, of liquid jet impingement onto foliar surfaces and the extent of coverage and production of splash from the target that might deposit liquid on adjacent nontargets (crops). Prior work has considered droplet impacts on foliar and artificial surfaces [11–13]. The physical nature of leaf surfaces as well as age of the leaf can influence wettability of the surface [11], and this may in part be due to the microroughness on leaf surfaces due to acicular crystals from straight-chain paraffins, alcohols, etc., in addition to the extent of leaf wetness during an application of liquid material [12, 13]. Single droplet impactations onto solid flat surfaces have been interpreted recently from visual results of deposit that exhibit prompt splash, corona splash, receding breakup, partial rebound, and rebound based on liquid properties, surface, and velocity of droplet [14]. Although these results do not apply directly to the current study, observations presented by these researchers will be discussed in light of the effects seen in the current research.

Previous work [15] has considered the effect of splatter on flat solid surfaces due to liquid jet impingement. This work showed that the *We* number and the dimensionless number representing the ratio of nozzle-to-target distance/nozzle orifice diameter described the mass fraction of jet splattered. Additionally, the results indicated that surface tension did not affect splattering. The experimental setup for the reported work described a timed continuous jet stream used to measure flow rates in addition to the volume of splatter, thus enabling an estimate of mass splattered. These measurements were inherently different than those in the current study, which used a discrete volume of a liquid jet impinging onto a flat surface. However, several concepts and results presented in the cited work are comparable to the current study.

Previous work on robotic machine vision for pest control strategies in commercial fields for cotton and processing tomatoes has been reported [4–6]. Based on work presented by these researchers, a system that allows centimeter-scale application of herbicides will likely include an image-based crop/weed discrimination system to inspect the seed line from the vertical direction to locate and distinguish weeds and crop, and a precision dosing system to simultaneously and exclusively apply any number of pest control agents to crop targets, weed targets, or combinations.

GOAL AND OBJECTIVES

The present work was done to establish liquid properties and jet conditions that could be used in a field setting to adequately wet targets (weeds) and minimize splash onto adjacent crop plants. This work was not done solely to establish nondimensional mathematical models, but rather to determine conditions over a finite range of parametric conditions that could be used to establish operational criteria for use in an applied field equipment setting.

To that end, biological efficacy depends on a precise target area covered when microliter volumes are applied on a centimeter scale. Additionally, minimization of splash, or microdrift, to avoid undesired phytotoxic damage to the adjacent crop is a critical constraint in the current work. Based on these criteria, the objectives of this research were:

1. Determine the volume dose per pulse for a centimeter-scale "spot" sprayer under different pulse durations of liquid jet emission, spray liquid adjuvants, and orifice diameters
2. Quantify the deposition area and centimeter-scale splashing (microdrift) using Kromekote™ card targets for different spray adjuvant formulations, different jet conditions, and different orifice-to-target distances
3. Establish liquid properties that may provide effective weed control in addition to protecting adjacent crops by minimizing microdrift

EXPERIMENTAL DESIGN

The herbicide rate used in this study was 0.75% v/v glyphosphate (Rodeo™ Monsanto Co.) and was added to all tested formulations except the water reference liquid [physical parameters for water in this test are a temperature range of 19–23°C, pH range of 7.6–8.4, and hardness range of 70–590 (ppm as CaCO₃)]. Glyphosphate (or glyphosate) is a common, nonselective, postemergent herbicide used in agricultural, landscape, homeowner, and right-of-way weed control. The spray adjuvants used were a silicone surfactant at 0.25% v/v (Silwet-L77, Loveland Industries, Inc.) and an emulsified oil-based adjuvant at 5% v/v (Herbimax, Loveland Industries, Inc.). The polymers that were added to formulations were a polyethylene oxide polymer (Polyox WSR N-60K, 2,000,000 MW, Union Carbide) at 0.03% v/v and polyacrylamide polymer (Target LC, > 20,000,000 MW, Loveland Industries, Inc.) at 0.05% v/v. The diluent for all formulations was municipal water. Liquid parameters for diluent, herbicide, surfactant, and polymer mixtures are given in Table 1 (the following abbreviations are used for formulations in all tables and figures: W = water, S = 0.25% Silwet L-77, SPEO = 0.25% Silwet L-77 with 0.03% polyethylene polymer (PEO), STLC = 0.25% Silwet L-77 with 0.05% polyacrylamide

Table 1 Physical Properties of Liquid Formulations and Dimensionless Flow Numbers for 70-kPa Liquid Supply Pressure and Two Orifice Sizes^a

Formulation	ρ (kg/m ³)	μ (mPa·s)	σ (N/m)	Orifice diameter = 0.508 mm				Orifice diameter = 1.194 mm			
				U (m/s)	Re	We	Oh $\times 10^{-3}$	U (m/s)	Re	We	Oh $\times 10^{-3}$
W	998.9	1.078	0.0723	6.621	3117	308	5.628	7.997	8848	1055	3.671
S	999.8	1.116	0.0263	6.414	2919	794	9.656	7.526	8050	2571	6.298
SPEO	999.6	1.395	0.0263	6.242	2272	752	12.07	6.745	5771	2065	7.874
STLC	1000.4	2.980	0.0278	6.230	1062	710	25.07	7.344	2944	2317	16.35
H	986.5	1.019	0.0338	6.621	3256	650	7.830	7.648	8840	2038	5.107
HPEO	988.2	1.317	0.0337	6.472	2467	624	10.13	6.939	6217	1686	6.605
HTLC	990.3	2.805	0.0337	6.681	1198	666	21.54	7.847	3308	2160	14.05

^a Physical properties were measured at 22°C. Jet velocities are for a steady-state condition integrated over a 10 s sample period.

polymer (TLC), H = 5% Herbimax, HPEO = 5% Herbimax with 0.03% PEO, HTLC = 5% Herbimax with 0.05% TLC).

Test parameters for the experiments were the liquids listed in the previous paragraph, jet orifice diameter, jet pulse duration, and orifice-to-target distance. The jet orifices were constructed of 16- and 21-gauge stainless steel hypodermic tubing, with 1.194 and 0.508 mm inside diameters, respectively. Liquid was supplied to the orifices at a constant 70 kPa pressure. Jet pulse durations were 6 and 20 ms. The liquid supply consisted of a pressurized plastic container. The sprayer generated pulses by using a direct-acting two-way DC solenoid valve with a LuerTM lock fitting close-coupled to the valve outlet [16]. All orifice tips were 12.7 mm long and attached to the solenoid valve at the Luer lock outlet. The 6- and 20-ms pulses refer to the duration of the electrical signal sent to the valve. Since the valves require approximately 3 ms to open or close, the 6-ms pulse time represented a transient condition for the jet. The 20-ms pulse represented substantially more steady-state time for the jet emission. The test conditions were selected based on typical and expected operating conditions for a vehicle-mounted automatic sprayer system [4–6] where a typical 10-ms spray jet emission is used and the resolution of the imaging system results in spray treatment cells with dimensions of 12.7 × 6.4 mm.

“One-shot” mass measurements were made by collecting the discharge from 6- and 20-ms pulses from the orifice with a Sartorius scale (model BP61, Sartorius AG) with a resolution of 0.1 mg and calibrated based on manufacturer recommendations. Several representative shots of liquid were collected, averaged, and converted to volume using the measured density of each formulation. The “one-shot” measurements are reported as the volumetric doses in Table 2. Steady-state flow rate measurements were made for each parametric condition and each formulation by collecting flow for a 10-s time frame. The steady-state values were used to calculate the velocity, Re , We , and Oh values in Table 1. Since the actual transient behavior of the pulsed jet emission and the resulting partial flow conditions were not measured directly in the study, the steady-state values represent maximum values.

For each parametric condition, the jet orifice was positioned at 5 and 20 cm above the target cards. These distances were chosen to represent the likely range of distances at which equipment might operate above the target level when deployed on a moving vehicle in the field. The spray targets were smooth Kromekote cards with a size of 21.6 cm × 27.9 cm. A spray colorant (SignalTM Precision Laboratories, Inc.) was added at 1.0% v/v to solutions for stain visualization on the Kromekote cards. After each deposition application, the cards were allowed to air-dry and then were scanned (Epson[®] Perfection 1200U Photo Scanner, Epson, Inc.) for conversion to digital images using Scion ImageTM and subsequent numerical processing described in a previous publication [10]. After the digital images were collected, the stains produced by the spray deposition were quantified as follows. The total stain (TS) was defined as the total projected area covered by the deposition from the impacted jet. The primary stain (PS) area was defined as the area of largest single contiguous stain produced by the jet impaction. A relative index of the “spread” of the deposit was calculated as PS/V , where V was the volume of fluid emitted in the pulsed jet. The microdrift (μD) was defined as the difference between the TS and PS values; μD represented the “splash” or deposition not directly in contact with the PS. Similarly, the relative amount of microdrift in the total jet deposit was quantified by calculating the fractional microdrift, μD_f , as $\mu D/TS$. In addition to the deposition area covered, the extent of splash, or microdrift, was quantified by normalizing discrete microdrift

Table 2 Dispensed Volume and Deposition Results from Pulsed Jets of 6- and 20-ms Duration and 0.508- and 1.194-mm Diameters for Applications onto Kromekote Cards at 5-cm Orifice-to-Target Distance

Formulation	V (μL)	PS (cm^2)	TS (cm^2)	μD (cm^2)	PS/ V (cm^{-1})	DS ₅₀ (cm)	μD_f
<i>D</i> = 0.508 mm, 6-ms pulse							
W	26.4	0.88	2.56	1.68	33	8.7	0.66
S	32.7	8.72	10.47	1.75	267	10.7	0.17
SPEO	35.1	9.66	9.66	0.00	276	0.0	0.00
STLC	28.6	12.61	12.61	0.00	441	0.0	0.00
H	25.3	1.35	5.03	3.68	53	9.4	0.73
HPEO	24.1	0.76	0.76	0.00	31	0.0	0.00
HTLC	36.0	1.75	3.33	1.58	48	8.5	0.47
<i>D</i> = 1.194 mm, 6-ms pulse							
W	128.6	5.01	6.28	1.27	39	2.1	0.20
S	123.4	37.39	39.39	2.00	303	9.9	0.05
SPEO	103.1	29.79	29.79	0.00	289	0.0	0.00
STLC	100.5	29.09	29.58	0.49	289	12.5	0.02
H	117.7	10.29	11.36	1.07	87	7.9	0.09
HPEO	104.0	5.44	5.44	0.00	52	0.0	0.00
HTLC	111.1	10.39	11.46	1.07	94	6.5	0.09
<i>D</i> = 0.508 mm, 20-ms pulse							
W	58.1	1.37	3.87	2.50	24	8.2	0.65
S	61.3	17.35	22.04	4.69	283	10.8	0.21
SPEO	49.2	18.13	18.13	0.00	369	0.0	0.00
STLC	47.8	15.30	15.30	0.00	320	0.0	0.00
H	60.0	2.42	11.62	9.21	40	9.7	0.79
HPEO	57.8	1.37	1.37	0.00	24	0.0	0.00
HTLC	62.0	2.87	6.43	3.57	46	9.0	0.56
<i>D</i> = 1.194 mm, 20-ms pulse							
W	280.9	7.33	8.12	0.79	26	8.7	0.10
S	290.5	68.08	71.25	3.18	234	12.1	0.05
SPEO	298.6	58.21	58.21	0.00	195	0.0	0.00
STLC	303.8	72.40	72.50	0.10	238	8.6	0.001
H	309.3	20.40	21.89	1.49	66	9.3	0.07
HPEO	277.4	10.23	10.23	0.00	37	0.0	0.00
HTLC	301.3	15.96	17.80	1.85	53	8.9	0.10

stains. Knowledge (from the software) of the coordinates of the centers of microdrift stains enabled the distance of the microdrift deposit from the center of the primary stain to be calculated. The technique was to accumulate the spray deposition between the outer boundary of the PS and the maximum distance outward of the microdrift deposition. When the accumulated μD was plotted against the distance from the maximum extent of μD inward toward the PS center, the result was analogous to the classic "spray drift" curves used in larger-scale agricultural field research. Several representative curves showing primary stains with microdrift, control of microdrift, and lack of microdrift control appear in Figs. 2–4. In addition to the results shown in the continuous curves, a DS₅₀ value was calculated as the radial distance outward from the center of the primary stain within which 50% of the μD was contained.

In addition to the stain analysis, behavior of the jets impacting a leaf surface was visualized through a series of photographs during impacting events. A leaf sample of a waxy plant (*Dietes iridioides*) was positioned to create a horizontal surface 5 cm below a 0.508-mm orifice. Jet pulse time was extended to 100 ms. A digital camera (D1H, Nikon) was triggered at a sequence of time intervals after jet emission to provide a sequence of images of the jet impaction. Images were collected for the water (W), silicone surfactant solution (S), and surfactant + polyethylene oxide (SPEO) solution.

RESULTS AND DISCUSSION

The measured liquid properties and calculated dimensionless numbers Re , We , and Oh are shown in Table 1. The effects of the adjuvants were as expected. The relatively low concentrations of adjuvants produced negligible change (<2%) in the mass density of the resulting solutions. Addition of the silicone surfactant to water and polymer solutions reduced surface tension to 0.027 N/m; similarly, addition of the oil-based surfactant reduced surface tension to 0.034 N/m. Addition of the polyethylene oxide and polyacrylamide polymers increased shear viscosity to 1.35 and 2.85 mPa·s, respectively. Addition of PEO increased the viscosity of the Silwet and Herbimax adjuvants by 25% and 29%, respectively. Addition of TLC increased the viscosity of the Silwet and Herbimax adjuvants by 160% (recognize that these are static measurements under low shear viscosity and, as discussed below, deposition and impaction processes may be better explained with respect to dynamic surface tension and high shear rate measurements). The data indicate that steady-state velocities for the different formulations are relatively equivalent. For the small orifice, the largest difference in velocities was 0.45 m/s (7%), whereas for the larger-diameter orifice, the maximum difference in velocities was 1.25 m/s (16%). Re values for the 0.508-mm diameter orifice ranged from 1 to 3×10^3 , indicating that flows were laminar or transitional, while flows from the 1.194-mm orifice were proportionately higher and into the transitional - turbulent range [17].

Measured and calculated results from the tests are shown in Tables 2 and 3 for the 5- and 20-cm target-to-nozzle spacings, respectively. The emitted liquid volume (dose) per jet pulse was strongly dependent on pulse duration and orifice diameter and less affected by liquid formulation. For the 0.508-mm orifice, 6- and 20-ms pulses emitted volumes of the order of 30 and 55 μL , respectively. Since the emitted volumes for the 20-ms pulse were not proportionally larger than for the 6-ms pulses, it was hypothesized that the transient cycle (opening/closing) time of the valve was greater than the 6-ms electronic pulse. Since the valve is normally closed, the electrical solenoid opens the valve and the valve is subsequently closed by a mechanical spring. Additionally, the jet orifice tube, with a length/diameter ratio of 25, provided considerable resistance to flow in series with the metering valve. These effects would likely cause nonlinearity between the emitted volume and the valve pulse, especially at brief pulse durations. For the 1.194-mm orifice, 6- and 20-ms pulses emitted volumes of the order of 110 and 300 μL , respectively. With the 1.194-mm-diameter orifice, the overall resistance to flow downstream of the valve is less and the length/diameter ratio of the jet tube is less; consequently, the relationship between emitted volume and pulse duration was more proportional than with the smaller orifice.

Data in Tables 2 and 3 show several clear trends with respect to effects of orifice size, pulse duration, and orifice-to-target distance on deposition characteristics. Results for the

5-cm orifice-to-target distance showed that primary stain area increased greatly as orifice size and pulse duration increased; this was expected since the individual effects and combination of these effects resulted in greater volumes emitted per jet pulse. Calculation of the PS/V value normalized the area to the amount of liquid dispensed and allowed relative effects to be analyzed. The PS/V values varied over an order of magnitude and clearly illustrated the effectiveness of the silicone surfactant, even when the PEO and TLC polymers were present in the formulation. The oil-based surfactant was less effective, as observed, with lower PS/V values; however, this is consistent with the design objective of the liquid, which is to increase penetration of chemical into the plant rather than increasing spread of the deposit on the plant surface. Results for the 20-cm orifice-to-target distance showed similar trends to those from the 5-cm spacing. Microdrift increased as transit

Table 3 Dispensed Volumes and Deposition Results from Pulsed Jets of 6- and 20-ms Duration and 0.508- and 1.194-mm Diameters for Applications onto Kromekote Cards at 20-cm Orifice-to-Target Distance

Formulation	V (μL)	PS (cm^2)	TS (cm^2)	μD (cm^2)	PS/V (cm^{-1})	DS_{50} (cm)	μDf
<i>D</i> = 0.508 mm, 6-ms pulse							
W	26.4	0.75	3.81	3.07	28	7.3	0.81
S	32.7	11.71	22.82	11.11	358	7.5	0.49
SPEO	35.1	12.73	12.73	0.00	363	0.0	0.00
STLC	28.6	9.57	9.61	0.03	335	5.7	0.003
H	25.3	1.37	6.51	5.15	54	7.9	0.79
HPEO	24.1	1.82	2.10	0.28	75	2.1	0.13
HTLC	36.0	2.00	4.35	2.35	55	6.6	0.54
<i>D</i> = 1.194 mm, 6-ms pulse							
W	128.6	3.96	10.33	6.37	31	7.4	0.62
S	123.4	29.33	39.16	9.83	238	10.1	0.25
SPEO	103.1	26.93	27.00	0.08	261	7.0	0.003
STLC	100.5	18.67	31.25	12.58	186	8.3	0.40
H	117.7	6.74	16.72	9.99	57	9.7	0.60
HPEO	104.0	5.29	6.06	0.77	51	2.5	0.13
HTLC	111.1	6.20	10.40	4.19	56	8.6	0.40
<i>D</i> = 0.508 mm, 20-ms pulse							
W	58.1	1.32	6.86	5.54	23	8.2	0.81
S	61.3	15.12	32.69	17.57	247	8.5	0.54
SPEO	49.2	16.25	16.25	0.00	331	0.0	0.00
STLC	47.8	11.18	11.29	0.11	234	2.4	0.01
H	60.0	2.10	14.03	11.93	35	8.4	0.85
HPEO	57.8	2.65	2.90	0.25	46	1.3	0.09
HTLC	62.0	3.08	9.77	6.69	50	9.1	0.69
<i>D</i> = 1.194 mm, 20-ms pulse							
W	280.9	10.60	20.96	10.36	38	7.0	0.49
S	290.5	58.98	82.89	23.91	203	10.8	0.29
SPEO	298.6	70.75	89.51	18.77	237	11.2	0.21
STLC	303.8	34.19	46.88	12.69	113	10.6	0.27
H	309.3	16.17	32.83	16.66	52	9.6	0.51
HPEO	277.4	14.59	20.12	5.53	53	6.1	0.27
HTLC	301.3	13.79	25.72	11.93	46	10.1	0.46

distance increased; however, no general trend was observed with primary stain size and increased transit distance.

No general trend was observed from the addition of PEO to the silicone surfactant (SPEO formulation) with respect to primary stain size. SPEO controlled microdrift completely in all cases, except for the extreme case of longest pulse duration, largest orifice diameter, and highest transit distance. HPEO controlled microdrift for all conditions at the 5-cm orifice-to-target distance, with minimal splashing at the 20-cm orifice-to-target distance, except for the extreme case. Also, HPEO decreased primary stain size at the 5-cm orifice-to-target distance; however, no trend was observed for the higher transit distance. STLC tended to control microdrift for all conditions except the extreme case, and tended to decrease primary stain size for the highest transit distance. HTLC showed microdrift for all conditions studied.

Inspection of the DS_{50} and the μD values provide insight into the potential damage that adjacent nontargets such as crop plants could suffer from the pulsed jet applications. The combination of DS_{50} and the μD indicates the amount of microdrift deposit and the distance of microdrift deposit from the target area. Based on these results, use of the silicone surfactant without any polymer would be undesirable, since significant volumes of liquid are displaced relatively significant distances away from the target deposit. Additionally, use of the large jet diameter and long pulse duration produced the greatest potential microdrift hazards to nontargets. Generally, the empirical results show that control of microdrift is not as evident with TLC as with PEO, especially with the oil-based surfactant. Based on these results (and possible implications discussed below), it is likely that PEO will be the preferred adjuvant to control microdrift in future field studies using the microspray system. However, weed control bioassay experiments must precede the final selection of the adjuvants, in order to confirm that they do not reduce efficacy to unacceptable levels.

Graphic representations of the actual deposit on cards and the microdrift results appear in Figs. 2–4, which show quantitative estimates of the distance microdrift occurs from the primary stain center. Figure 2 shows water and Silwet applications for 0.508-mm orifice diameter, 20-ms pulse duration, and 20-cm orifice-to-target distance. Immediately evident is the increased surface coverage by surfactant and extent of microdrift that occurred. Figure 3 shows SPEO and HPEO for the same application conditions as in Fig. 2. PEO is shown to control microdrift for both surfactants, however, SPEO shows complete control when compared to HPEO. Figure 4 shows the extreme conditions of 1.194-mm orifice diameter, 20-cm orifice-to-target distance, and 20-ms pulse duration, and the inability of PEO to control splashing. Figure 4 also illustrates the different characteristics of the microdrift when the polymers are added. In Fig. 2 the microdrift is observed as a high number of small, individual droplets, whereas in Fig. 4 the microdrift is seen as large contiguous ligaments and fractured ligaments.

Figures 5 and 6 show photographic images of exiting jet streams and resulting spreading, splashing, and onset of microdrift, in addition to jet stream characteristics at the end of an application for some of the test formulations. In Fig. 5, water is shown to accumulate on the surface prior to the end of the jet stream breaking off and producing droplets which promote splash and microdrift. This behavior is typical of a high-surface-tension liquid on a waxy leaf surface. Figure 5 also shows the effect of the silicone surfactant and the more extreme nature of microdrift production after the initial portion of the jet stream impinges on the surface. The lower surface tension leads to a greater tendency to form smaller droplets upon jet breakup [18], and this effect is evident in the microdrift

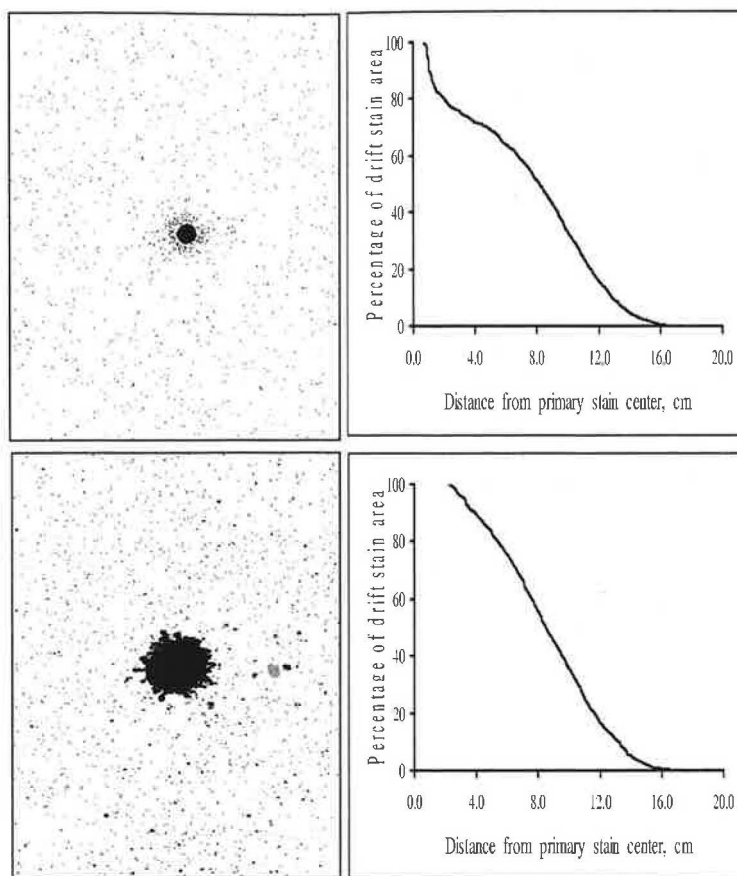


Fig. 2 Results showing primary stains and microdrift for W (top) and S (bottom) at 70-kPa liquid pressure, 0.508-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

results for the silicone surfactant presented in Tables 1 and 2 and previously in Fig. 2. Figure 6 shows images of the silicone surfactant with PEO polymer and the effect surfactant has by increasing spread of the deposit and effectiveness of polymer to control microdrift at the onset of the jet impinging on the surface. Additionally, the sinuous and beading nature of the jet stream during the end of an application can be observed. The lack of microdrift produced is due to polymer addition; there is less of a tendency to form small droplets on breakup [18] due to the dampened energy transfer during impaction and due to the increased extensional viscosity of the liquid. From these results, it is evident that an increase in viscosity overrides the tendency to form small droplets due to the lower surface tension during the initial jet impingement upon the surface. Additionally, the increased spreading of material (due to silicone surfactant) is not dampened to a great extent by addition of the polymer. Application of HTLC may have a slower exiting tail of the jet stream, leading to increased droplet and dripping production (especially in light of the Re numbers for these formulations). This effect is evident in Tables 2 and 3 with the μD term, where the increase in microdrift stain area is likely due to drops impinging on a wetted flat surface.

RESULTS IN RELATION TO PREVIOUS STUDIES

In an earlier study, Rioboo et al. [14] discussed and classified the effect of droplets applied to different surfaces. Also, the report discussed previous work and attempts to classify criteria for a splash/deposition limit by defining the dimensionless number K' ($We Oh^{-0.4}$). Although their results were for a single droplet, consideration of the dimensionless numbers presented in the present study (Table 1) for the small-orifice nozzle shows similar results for the splash/deposition limit criteria. Water on glass (with deposition) had a K' value of 5340, ethanol on glass had a K' value of 2080 (with corona splash), and water on PVC had a K' value of 1240. In the present study, with a discrete volume of a liquid jet impinging on Kromekote paper, set on a rigid surface, the K' value for SPEO was 4401 (deposition), for Silwet was 5080 (deposition with corona splash), and for water was 2446 (deposition and receding breakup). Obviously, the experimental techniques presented with these comparisons are different, and as the previous research [14] has indicated, there is an inherent complexity of interaction between the physical parameters describing liquids, and

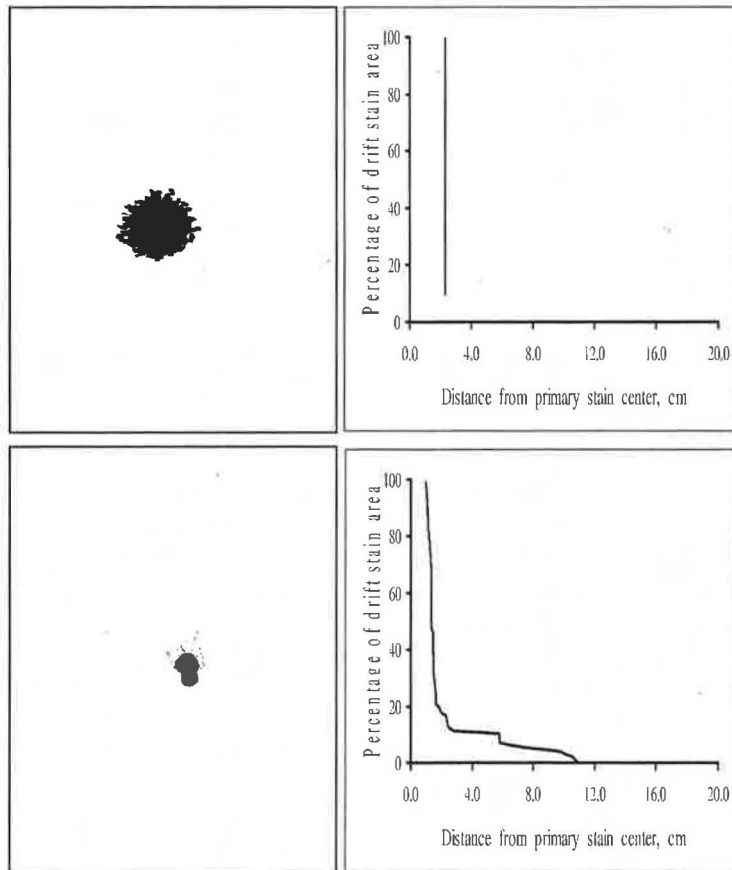


Fig. 3 Results showing primary stains and microdrift control due to polymer addition for SPEO (top) and HPEO (bottom) at 70-kPa liquid pressure, 0.508-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

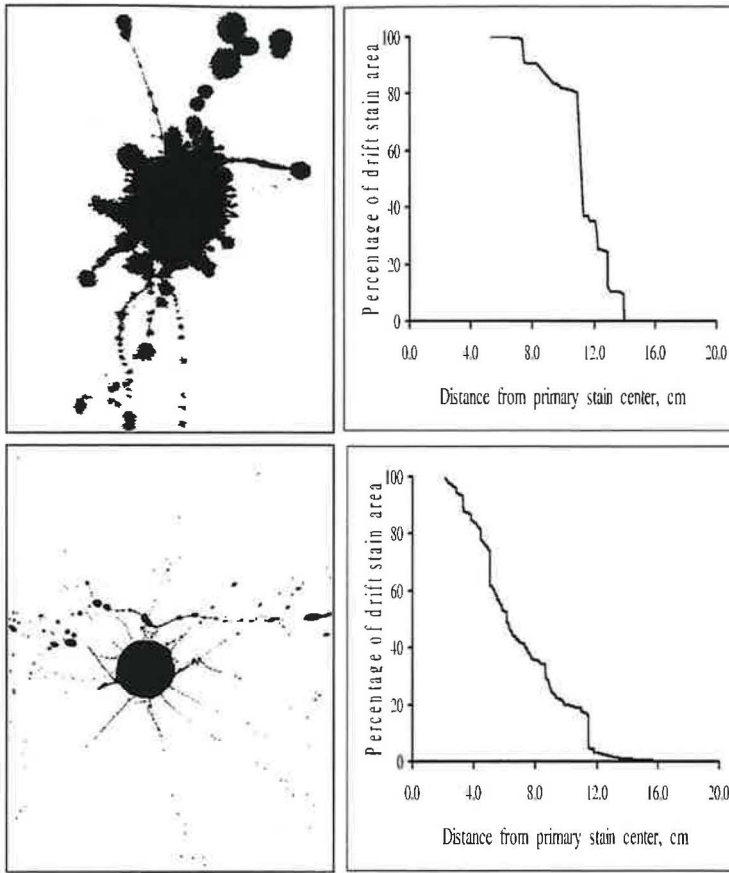


Fig. 4 Results showing primary stains and lack of microdrift control due to polymer addition for SPEO (top) and HPEO (bottom) at 70-kPa liquid pressure, 1.194-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

resulting deposition, splash, and wettability, in addition to basic deficiencies and an oversimplification that may exist in current models.

A model was developed to estimate splattering of turbulent liquid jets impacting on solid targets [15], based on the We number and nozzle-to-target distance. Although the work used a continuous stream impinging on a flat hard surface, the authors discussed several concepts that may explain some of the results observed in the current study. The present work observed microdrift with the liquid formulations containing TLC, and this may be due to disturbances from capillary instability. Also, Bhunia and Leinhard [15] report that traveling waves originate near the jet impingement point and travel outward on the liquid film (forming hydraulic jumps), and when the jet disturbances are sufficiently large, these waves can sharpen and break into droplets. Although it is not readily observable with the silicone surfactant in Fig. 5, Fig. 6 shows the formation of a traveling wave (or hydraulic jump); however, the effect of the PEO polymer addition prevents splash or microdrift from occurring. Since the experimental setups were relatively different and Bhunia and Leinhard [15] were using a continuous jet stream (as opposed to a discrete

volume of liquid jet), there was difficulty in comparing the present results with those reported based on We and nozzle-to-target distance. However, it is interesting to note that Bhunia and Leinhard found that the presence of surfactant did not alter splattering, whereas this study produced an opposite result. Considering the results (μD_p) presented in Tables 2 and 3, it appears, at first glance, as if surfactant does not increase microdrift (splash, splatter) when normalizing the μD term to the total stain area measured. However, the μD term is substantially larger in terms of splashed stain area outside of the primary

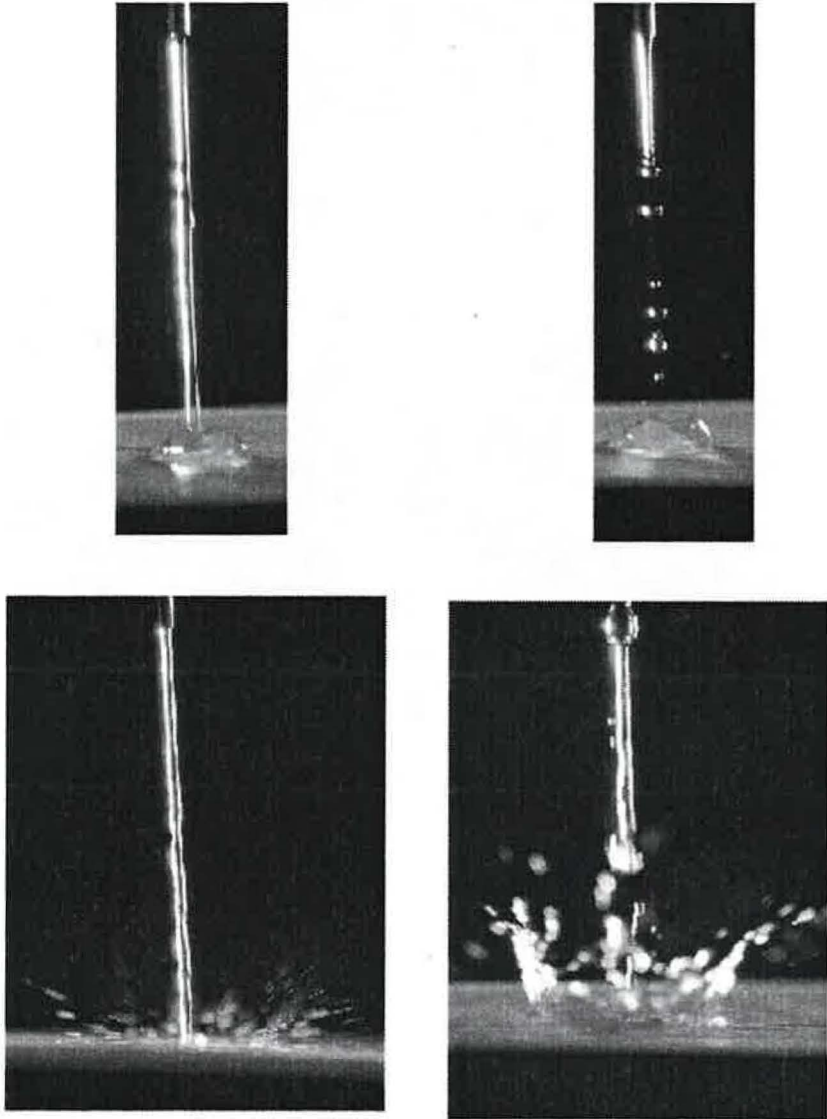


Fig. 5 Images of W (top) and S (bottom) showing differences of microdrift onset at 70-kPa liquid pressure, 0.508 mm orifice diameter, and 5-cm orifice-to-target distance.

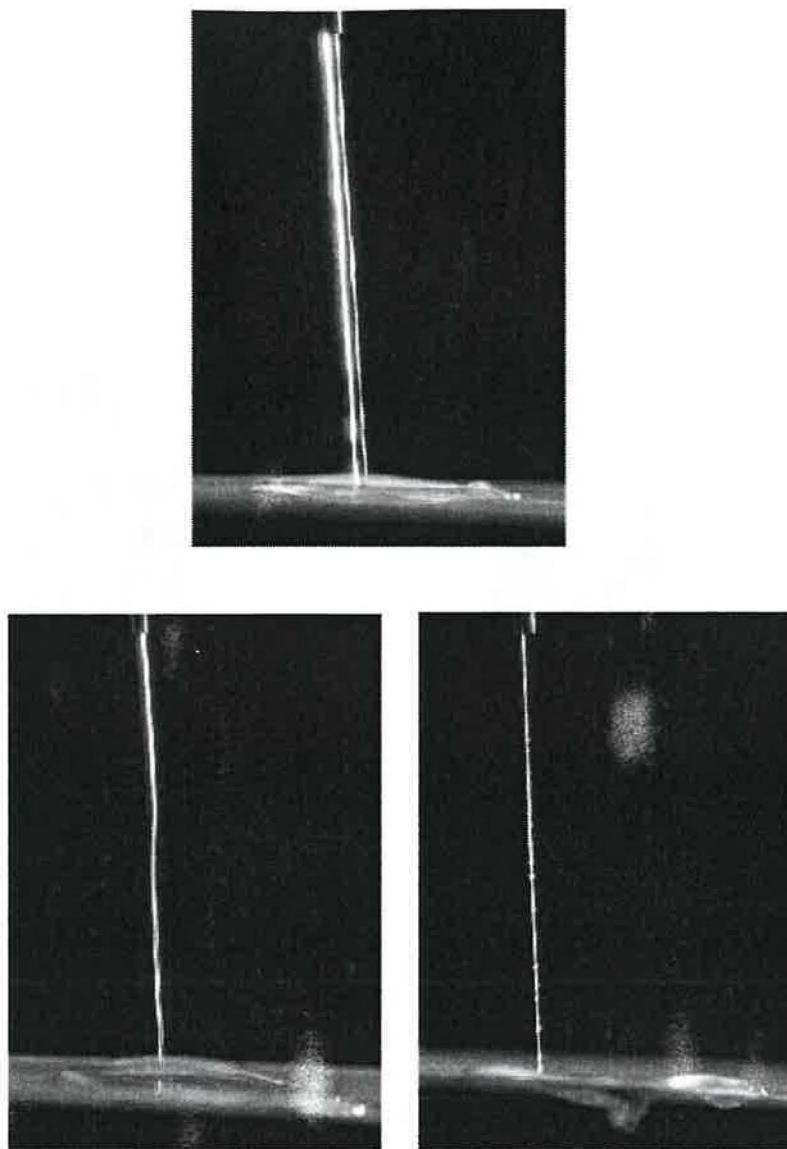


Fig. 6 Images of SPEO showing spreading (top), sinuous wave production along the jet (bottom left), and beading of jet stream at the end of an application (bottom right) at 70-kPa liquid pressure, 0.508-mm orifice diameter, and 5-cm orifice-to-target distance.

deposition area covered when compared to water. Bhunia and Leinhard additionally implied that their observations may be due to the fact that surfactant does not diffuse fast enough from the bulk fluid to the free surface (along the liquid jet stream) and this free surface remains unsaturated, or retains the surface tension of pure water. This may have been the case for their study (soap and water); however, one can speculate an alternative effect in view of the microdrift observed with the current study. It is possible that hydrogen

bonding of their surfactant to water slowed the rate of diffusion of surfactant to the free surface, thus preventing any splash occurring, whereas diffusion of surfactant, used in the present study, to the free jet surface occurs at a much faster rate, enabling the effect of a lower surface tension to be seen (Fig. 5, silicone surfactant) soon after jet impingement onto the surface.

Recent information has been found that may describe the impaction and deposition process with respect to additional physical properties of solution [19]. Impaction, spread, and splash under the operating parameters reported in this work occur within 20 ms. Surfactants can take a significant time to diffuse to the liquid-air surface to reach equilibrium concentration. As the two adjuvants studied in this work have similar surface tensions, yet have markedly different effects with respect to spreading and splash, the discrepancy may be better explained with dynamic surface tension measurements in light of the dimensionless quantity of PS/V (ratio of primary stain area to volume applied). Additionally, the similar viscosity values reported here are based on a low-shear-rate measurement method. The PEO solutions were able to control splash better than the TLC solutions, and this effect is not indicated by the measured viscosities we have reported. It is possible that the large differences in the deposition and splash in the results presented for the solutions here may be better explained by measuring extensional viscosity. Dexter [20] has presented a method for measuring extensional viscosity, in addition to reporting on the correlation of droplet size distribution with extensional viscosity. The results reported here may be further described based on extensional viscosity measurements, as the process of impaction and splash is an extensional or stretching process [19]. Differences in extensional viscosity may be much larger than differences in shear viscosity and could explain the large differences between the microdrift results reported.

As a means to classify the type of liquid jet stream observed in the current work, Lefebvre [21] has reported previous research to categorize spray atomization and reproduced the classification of modes of disintegration charts by other researchers. Based on these reproductions and data presented here (Table 1, Fig. 7), the liquid spray jet emissions reported for the 0.508-mm-diameter orifice and operating conditions can be categorized as sinuous wave breakup (or first wind-induced). This classification of modes of disintegration follows the jet-stream image results presented in Fig. 6 for the silicone surfactant and PEO polymer at the end of the exiting material. Results for the 1.194-mm diameter orifice and operating conditions are classified as wavelike break up with air friction (or second wind-induced).

CONCLUSIONS

The results presented in this work show that addition of a polyethylene oxide polymer (PEO) and a polyacrylamide polymer (TLC) can effectively reduce microdrift from deposited pulsed jets for a spot sprayer system applying material at 5- and 20-cm transit distances. Primary stains of silicone surfactant were at least 5 times greater in area than those for water; however, the effect of microdrift does not warrant use of this material without addition of polymer. Addition of PEO and TLC to the silicone surfactant solution controlled microdrift in all cases except for the large (1.194-mm-diameter) jet orifice, longest pulse time (20 ms), and greatest transit distance (20 cm). Also, primary stains of both formulations measured were at least 5 times those for water, indicating that polymer

addition did not affect the spreading nature of silicone surfactant. Future studies will analyze the effect of extensional viscosity measurements on microdrift with respect to the different formulations considered in this work.

Primary stains of the oil-based penetrant and surfactant were comparable to water, and additionally, PEO added to Herbimax controlled the onset of microdrift much better than HTLC and Herbimax alone. The recommendations for field studies are to use PEO as the sole microdrift reduction agent, used in conjunction with Silwet L-77 and Herbimax, to directly target weed plants adjacent to high-value crops for the spot sprayer system.

The results presented in this work will enhance the ability to precisely target noxious weeds with a precision spraying system. Knowledge of the extent of areal coverage of a formulation a priori, and use of this information to apply a precision chemical dose over the specific area, will minimize chemical application in the environment, in addition to providing a cost savings for materials. As seen in Fig. 1, proximity of a weed to young tomato plants implies the need to minimize microdrift, in addition to precisely targeting chemicals to limit their deposition on bare soil.

These results are preliminary with respect to field application trials, and may be different in an actual field setting due to the pliant nature of a leaf surface versus a hard surface. The logical next step in the process is to assess behavior in the field of formulations studied in this work. However, knowledge deduced from the presented results will enable several of the parametric conditions to be eliminated in future studies. That is, the dripping nature of an exiting jet due to polymer addition (HTLC) should not be used with a precision dosing system that is moving, due to the likelihood that material would be deposited off-target. Future field tests are warranted to ensure that physical applications are precisely and accurately deposited over a selected target with microdrift control, minimization of material applied to bare soil, with a high percentage of weed control and crop protection.

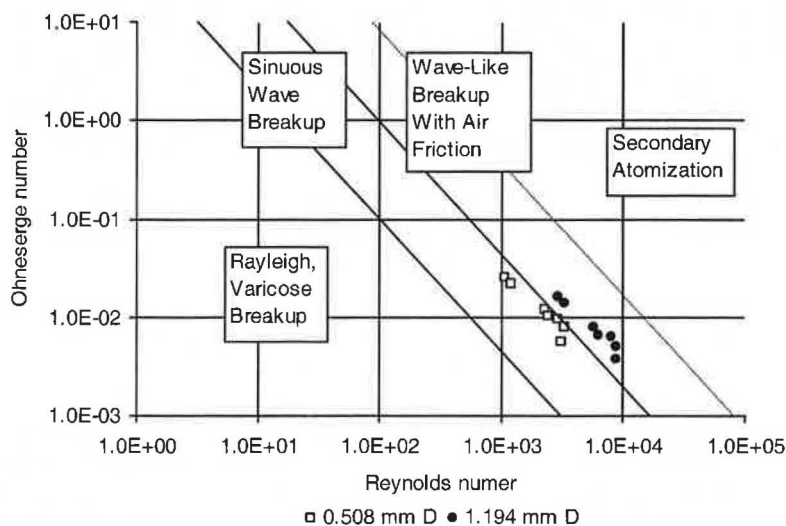


Fig. 7 Atomization regions based on Re and Oh numbers [from Ref. 8, Fig. 2-7] and conditions used in this experiment.

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EXHIBIT E



5-2003

Design and Evaluation of a Seed-Specific Applicator for In-Furrow Chemical Application

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University of Tennessee, Knoxville

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I am submitting herewith a thesis written by John H. Hancock entitled "Design and Evaluation of a Seed-Specific Applicator for In-Furrow Chemical Application." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

John Wilkerson, Major Professor

We have read this thesis and recommend its acceptance:

William E. Hart, D. Raj Raman

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

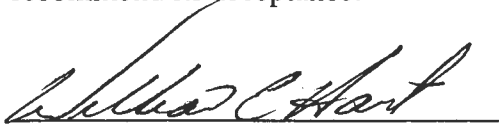
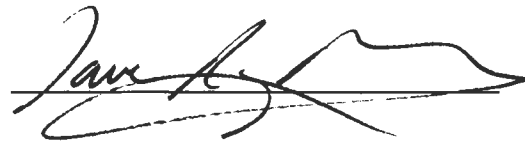
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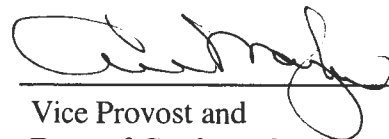
I am submitting herewith a thesis written by John Houston Hancock entitled "Design and Evaluation of a Seed-Specific Applicator for In-Furrow Chemical Application." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.


John Wilkerson, Major Professor

We have read this thesis and
recommend its acceptance:

Accepted for the Council:


Vice Provost and
Dean of Graduate Studies

**DESIGN AND EVALUATION OF A
SEED-SPECIFIC APPLICATOR FOR
IN-FURROW CHEMICAL APPLICATION**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

John Houston Hancock
May 2003

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DEDICATION

This thesis is dedicated to my parents, John B. Hancock and Dot Hancock. They have been lifelong sources of encouragement, providing endless love, support, and understanding. Through their words and actions, I learned about the important things in life – showering family and friends with love and attention, treating others as you wish to be treated, and completing all tasks to the best of one's ability.

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ABSTRACT

Recent trends in planting, toward lower seeding rates and more distance between seeds, are generating opportunities for improved application efficiency of in-furrow chemical inputs. In-furrow chemicals such as fungicides and insecticides are currently applied as a continuous band along the length of the furrow. However, research suggests that the material may only be necessary in a small zone around each seed. Eliminating or minimizing the material applied between seeds could produce substantial chemical savings and improve environmental stewardship, while maintaining current levels of efficacy.

A seed-specific applicator has been developed to apply discrete pulses of liquid chemical to individual seeds at planting. An optical seed sensor located on the planter seeding tube detects each seed as it falls toward the furrow. Following detection, discrete-event tracking circuitry, implemented using a Motorola 68HC11 microcontroller, tracks each seed in time to the point of chemical application. As the seed lands in the furrow, a high-speed valve applies a discrete pulse of liquid chemical to the seed and surrounding soil. The seed sensor and discrete-event tracking circuitry improve system functionality in two ways: (1) detecting the seeds ensures compatibility with irregularly-spaced seeds, and (2) the tracking algorithm allows the seeds to be detected well-ahead of the point of chemical application.

The system was prototyped in the UT Sensors and Controls Lab and field-tested in Spring 2002. First, the concept of seed-specific fungicide application was evaluated using side-by-side comparisons of conventional and seed-specific application methods. In cotton plots inoculated with *Rhizoctonia solani* and *Pythium spp.*, stands averaged less than one

viable cotton plant per five row-feet in the untreated check. Statistically, there were no differences between the seed-specific and conventional treatments, even though seed-specific application reduced chemical use by 50%. Next, applicator accuracy was evaluated over a range of planting speeds (2, 4, 6 mph) and spray band lengths (1, 1.3, 1.5, 2.0, and 2.6 in.) to assess how it might perform in actual planting conditions. Accuracy increased with spray band length, and ranged from 71-98%, 70-96%, and 55-90% at 2, 4, and 6 mph, respectively. Properly calibrated, a 2-in. spray band would adequately cover over 85% of planted seeds at any of the tested speeds.

A conceptual design for a multi-row seed-specific applicator has been developed. It includes a mathematical model for calculating calibration values and a simplified, low-cost user interface for user feedback and calibration.

Refinements are needed to improve system accuracy. Relocating the seed sensor closer to the tube outlet should minimize seed drop time variability, while new seed tubes may be required to minimize seed bounce in the furrow. Additionally, a new, corrosion-resistant valve is needed to withstand the rigors of the planting environment. Future testing should evaluate the seed-specific concept with other chemicals, such as insecticides and starter fertilizers, and other crops, such as corn.

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CHAPTER I. INTRODUCTION

Justification for Research

Recent technological advances in the electronics, defense, and automotive industries have provided agricultural engineers with new tools to maximize production efficiency. Tools such as Global Positioning Systems (GPS), variable rate controllers, and real-time sensors are allowing producers to address variability within fields and to focus chemical applications where the material will be the most beneficial. For example, producers can divide large fields into smaller areas for unique treatments, or treat individual clusters of weeds while ignoring the adjacent bare soil. Technological advances will likely improve the resolution of treatment area even further, to point where individual plants and seeds receive specialized treatments.

At the seed level, significant opportunities for improved application efficiency exist for in-furrow application of cotton fungicides. Cotton producers currently apply a continuous band of fungicide along the length of the furrow, as shown in Figure 1. However, Newman (1998) and Uniroyal (2001) suggest that fungicide applied between cottonseeds is wasted. Experts believe that fungicide is only required in a 1- to 1.5-in. zone around the seed. Assuming this is true, substantial savings could be realized by minimizing or eliminating the wasted material.

Current trends in planting are actually increasing the potential for such savings. Before the advent of transgenic seeds, producers typically planted at high seeding rates (five to eight seeds per row foot) because seed costs were low. Seeding costs increased

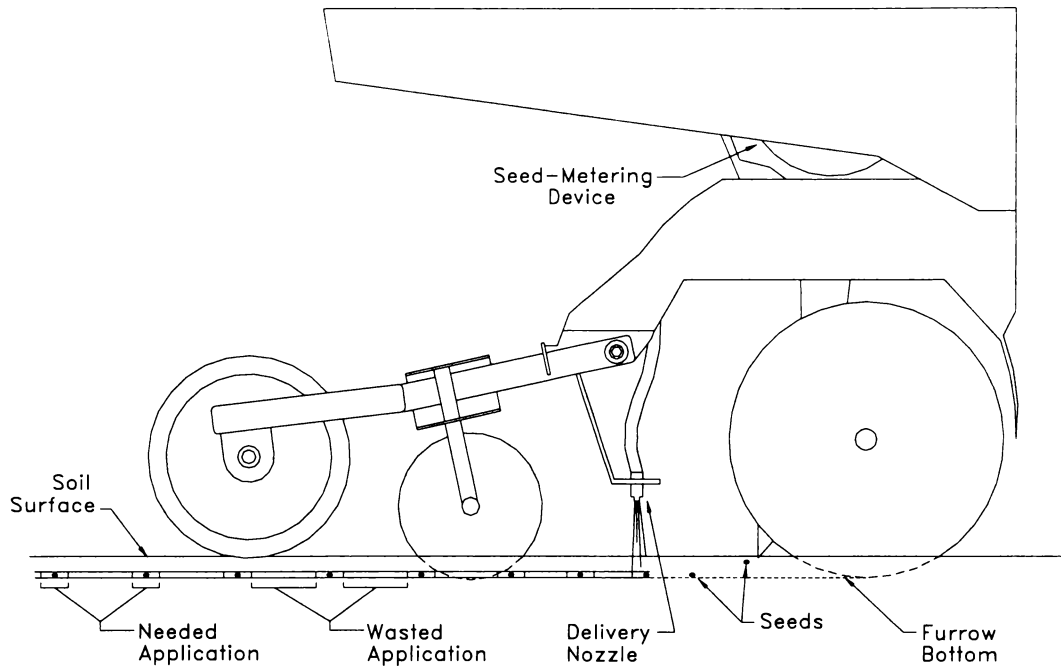


Figure 1. Conventional method of in-furrow chemical application and the potential for reduced waste.

with the introduction of transgenic seeds. Producers who plant genetically-modified seeds must pay a technology fee, in addition to the seed cost. To offset cost increases, producers are cutting seeding rates dramatically – down to two seeds per foot, in some cases. This increases the distance between seeds, which increases the amount of wasted chemical in a continuous application system. As shown in Figure 2, the potential for chemical savings increases linearly with decreased seeding rates. For example, applying fungicides seed-specifically would result in material savings of 75% at the two-seed/ft rate, assuming each seed received a 1.5-in. chemical-band length.

Modern technologies present opportunities to treat seeds on a seed-specific basis. Modern planters are equipped with optoelectronic seed sensors, which output electrical pulses each time a seed is planted. Fast response valves are readily available in the

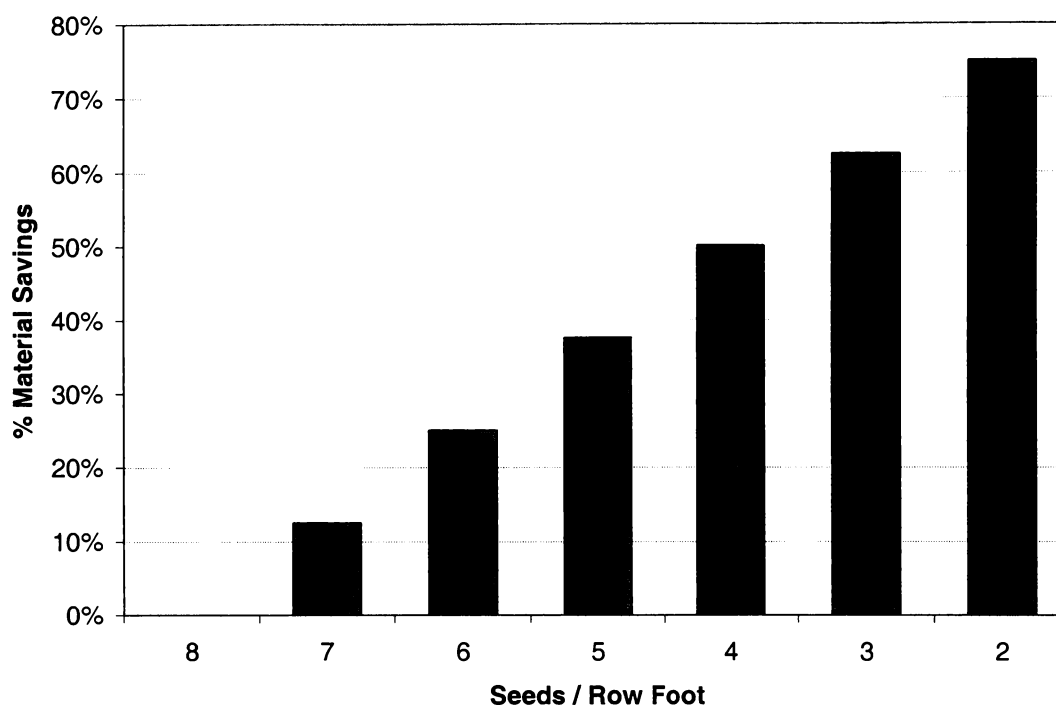


Figure 2. Relationship between seeding rate and the chemical savings associated with seed-specific application (based on 1.5-in. spray band length).

automotive and industrial controls industries. By combining these two technologies – using a sensor to detect the seed as it falls toward the furrow and a valve to apply a discrete pulse of chemical over the seed and surrounding soil when it lands – a seed-specific, in-furrow chemical application system could be realized.

The advantages of seed-specific chemical application are numerous. From an economic standpoint, eliminating the wasted chemical between seeds should reduce in-furrow chemical inputs by 50% or more. The environmental benefit, although not easily quantifiable, is that fewer chemicals are being applied to the soil. This technology could also facilitate the labeling of new chemicals, which were previously cost-prohibitive to produce or unable to obtain environmental approval. Clearly, this technology could

redefine in-furrow chemical application by reducing costs, decreasing environmental impact, and opening the market to new chemicals.

While the above discussion of seed-specific application focused on in-furrow fungicides, this technology could be beneficial with other in-furrow chemicals, as well. Roberts et al. (1998) investigated the precision placement of in-furrow insecticides for controlling early-season thrips. They concluded that precisely placing the insecticide at the seed provided comparable protection to the conventional method; however, they noted that no device currently exists to apply chemicals in this fashion. Precisely placing in-furrow starter fertilizer at the seed could provide similar benefits, although no reported research has evaluated this concept.

Objectives

The primary goal of this project was to develop and evaluate a control and delivery system that applies discrete pulses of chemical to seeds and the surrounding soil, as seeds are planted. To achieve this overall goal, specific sub-objectives were defined as follows:

1. Quantify seed drop-time variability in quasi-static (laboratory) and dynamic (in-field) situations.
2. Design a control system that detects and tracks cottonseeds between the seed hopper and furrow, and then applies a pulse of liquid chemical to each seed as it lands in the furrow.
3. Evaluate the accuracy and efficacy of the system described in objective #2.
4. Develop a multi-row control strategy utilizing the agricultural equipment industry's communication standard, per SAE J1939.

Conceptual Design

Design Overview

Figure 3 illustrates the basic components of the proposed system, which operates as described below. First, a sensor (**A**) in the seed tube detects each seed falling from the seed hopper. Following detection, discrete-event tracking circuitry (**B**) tracks each seed along its path down the seed tube and to furrow. As the seed lands in the furrow, the tracking circuitry actuates a high-speed valve (**C**), which delivers a discrete pulse of liquid chemical to the seed and surrounding soil.

Implementation Challenges

The conceptual design of the seed-specific applicator is quite simple. However, there are several challenges to implementing this design. First, a sensing apparatus is

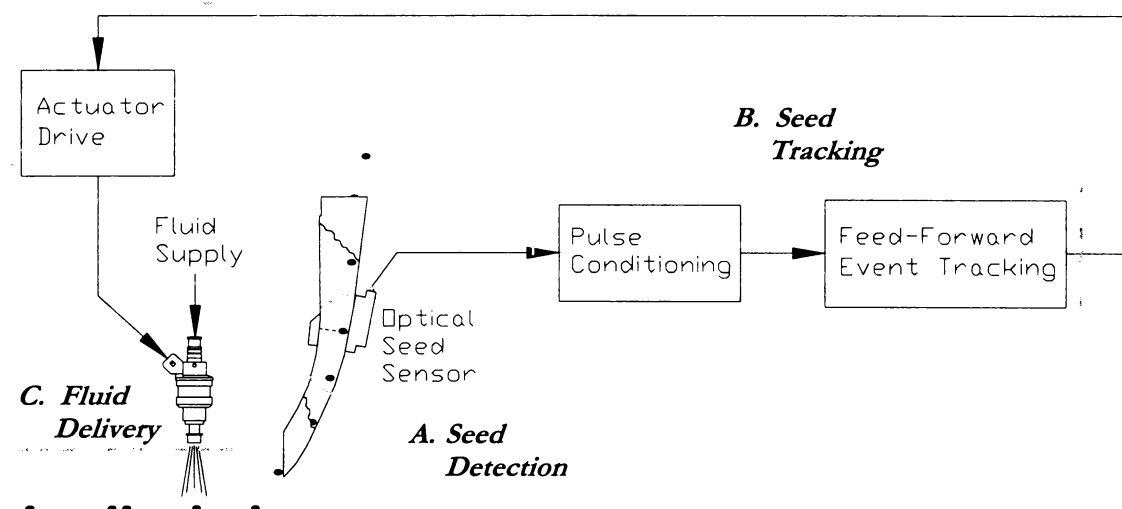


Figure 3. Block diagram of proposed seed-specific applicator design.

required to detect each seed as it falls from the planter's seed meter to the furrow. Since the seeds do not fall uniformly in time, a mechanical-timing method synchronized to the revolution of the seed singulator is not adequate.

Seed sensor placement presents additional challenges. The existing seed sensor on most planters is located 8 to 12 inches above the seed tube outlet, as shown in Figure 3. Using the existing seed sensor for seed detection is economically attractive, as it would reduce the complexity of the envisioned seed-specific applicator. However, with the seed sensor located so far from the point of chemical application, variability in planter speed or in the seed's travel path through the seed tube could affect the accuracy of the spray burst. Variability in seed drop-times between the existing seed sensor and tube outlet must be analyzed to determine if the existing location is acceptable, or if the seed sensor must be relocated closer to the tube outlet.

Another challenge associated with locating the sensor far from the chemical application point is that multiple seeds could become located between the sensor and application point. For example, when the sensor is positioned as shown in Figure 3, and the planter is traveling at six miles per hour, up to 12 seeds could be in-flight between the sensor and valve. This dictates that the seed-specific applicator incorporate a seed tracking system capable of tracking multiple seeds.

Finally, an on/off fluid valve capable of high frequency operation is required. At a seeding rate of six seeds per foot and a speed of six miles per hour, approximately 50 seeds are planted each second. Assuming a spray-band length of 1.5-in. is desired, the valve would need to cycle at 50 Hz, with an ON time of 15 ms and an OFF time of 5 ms (75% duty cycle). Therefore, the minimally acceptable valve response time would be 5 ms.

Thesis Organization

This thesis is organized to address the four project sub-objectives defined above. First, relevant literature is reviewed (Chapter 2). Next, a complete description of seed drop-time variability experiments, which were used to analyze seed sensor placement, is presented (Chapter 3). The design of the seed-specific chemical applicator is discussed in Chapter 4; a field evaluation of the designed system's performance, including both biological and applicator accuracy components follows in Chapter 5. The preferred embodiment of the design is then described, outlining how the seed-specific applicator might be implemented on a multi-row planter (Chapter 6). Finally, the project is summarized, and recommendations for future work are suggested (Chapter 7).

CHAPTER II. REVIEW OF LITERATURE

Cotton Seedling Disease

Cotton seedling disease is a serious concern in cotton production. In most years, it causes the largest yield losses of any cotton disease in the United States. In 1997, various seedling diseases claimed 3.5% of the total U.S. cotton crop (Blasingame, 1998). This translates into 635,000 lost bales with a market value exceeding \$247 million. While these loss estimates appear large, Newman (2001) suggests that actual losses are probably much higher, as the costs of replanting fields totally decimated by disease are neglected. Figure 4 illustrates the losses attributed to seedling diseases in the major cotton-producing states.

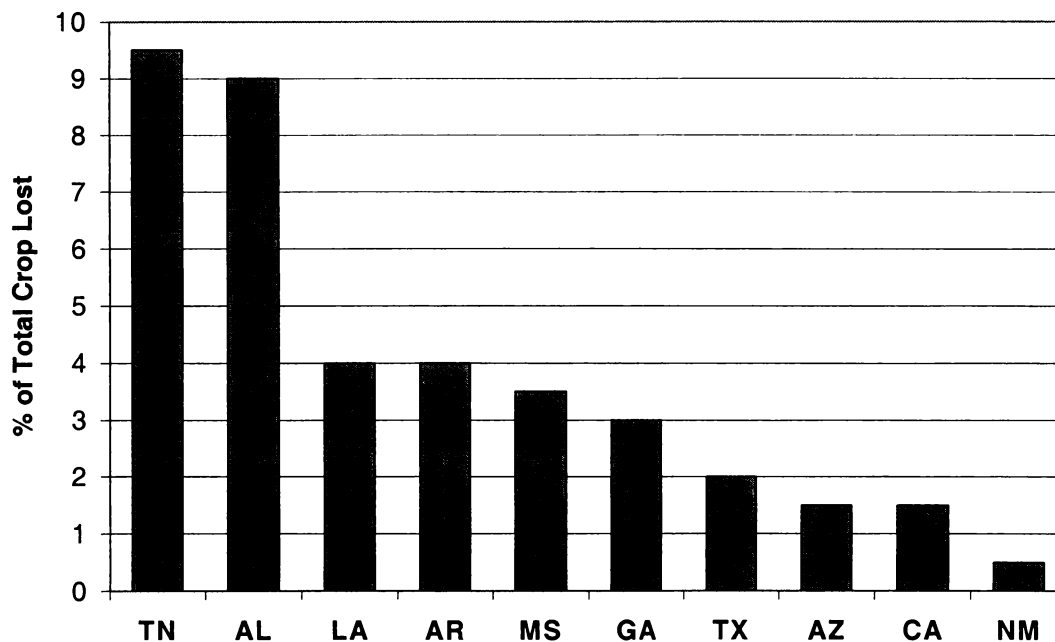


Figure 4. Crop losses resulting from seedling disease, by state – 1997 data (Blasingame, 1998).

Hillocks (1992) defines seedling disease complex as “any pest that debilitates or kills the plant between planting and one month after emergence”. In the Southeast, three soil-borne fungi – *Pythium*, *Fusarium*, and *Rhizoctonia solani* – are responsible for the majority of seedling disease damage. These pathogens can attack the seed within hours of planting (Killebrew, 1998). McLean and Gazaway (2000a) described four ways in which seedling diseases may affect cottonseeds or seedlings: (1) decay of the seed before germination; (2) pre-emergence damping off, occurring after germination but before the seed breaks the soil surface; (3) post-emergence damping off, wherein the young seedling dies after emerging; and (4) seedling root rot, wherein the main tap root of the plant dies, resulting in a weak plant with a limited root system.

The level of damage varies widely from area to area, and from year to year. Given appropriate weather and environmental conditions, these diseases can destroy an entire field, sometimes requiring the producer to replant (Bell, 1999). In other fields, a few plants may die, while the surrounding plants grow healthy and strong. Plant spacing is typically very irregular in fields affected by seedling diseases, resulting in reduced yields and inefficient use of crop amendments.

Factors Influencing Seedling Diseases

Seedling diseases are most prevalent in cool, moist conditions (Koenning, 2001; McLean and Gazaway, 2000a). There are two reasons for this. First, the pathogens that cause the disease, especially *Pythium spp.*, seem to prefer cool, wet environments (Bell, 1999). Secondly, these conditions negatively impact seed germination and seedling development, thereby increasing the plant’s susceptibility to soil-borne pathogens. Coyler

et al. (1991) suggested that cool temperatures might be the more important of the two factors. He observed the most severe incidence of seedling disease when soil temperatures were coolest.

Weather is not the only factor influencing the severity of seedling disease. Planting cotton in the same field, year-after-year, also increases the odds of developing seedling disease (McLean and Gazaway, 2000a). Further, fields with a past history of seedling disease are likely to exhibit continued disease pressure. Koenning (2001) identifies other risk factors, such as planting too deep, poor seedbed conditions, and nematode pressure, which all increase the risk of developing seedling disease by applying additional stress on the developing seedling.

Producers who practice no-till cotton production further increase their risk of developing seedling disease. No-till is a practice that eliminates all tillage operations, leaving residue from previous crops on the soil surface (Christensen and Norris, 1983; Young, 1982). While the residue aids in the prevention of soil erosion, it also holds in moisture and prevents the soil from warming (Koenning, 2001). Therefore, no-till practices lead to a cool, moist seedbed – optimum conditions for seedling diseases.

A 10-year study by Chambers (1995) showed that seedling disease damage was more severe in no-till than in conventionally-tilled plots. In one test, no-till plots planted at five to six seeds per row-ft resulted in stands averaging less than 0.5 seeds per row-ft. Chambers also observed lower stands counts and plant vigor in no-till cotton, even in years with optimal planting conditions (warm, dry weather).

Seedling Disease Management

Due to the severity of seedling diseases, producers in some states must adopt disease management strategies to minimize the effects of disease pressure. Two basic methods are available – (1) concede that some percentage of the seeds will be lost to disease, and increase the seeding rate accordingly; or (2) use fungicides to protect the seed and young seedling from soil-borne pathogens. Both methods are described below.

Increasing Seeding Rate

The traditional method of combating seedling disease was to plant at double the recommended seeding rate (Newman, 1998). Producers practicing this strategy concede that seedling diseases will devastate half of the planted seeds, hopefully leaving the other half to grow to full maturity. While an adequate stand count may be achieved, the stand is typically very uneven. Some rows have no plants, while others have double the optimal population. Yields across the entire field may suffer due to uneven stands.

When seed costs were low, it was cheaper to increase seeding rate than to apply a chemical fungicide. However, the advent of transgenic seeds has minimized or nullified the cost advantage this method once enjoyed. Transgenic seeds, which have built-in resistance to some herbicides and insects, have transformed the seed industry. A technology fee is added to these seeds, in addition to the seed costs. The fee is calculated based on the recommended seeding rate for a given area. By planting lower than the recommended seeding rate, producers can offset a portion of the costs associated with the technology fee. However, producers who plant higher than the recommended rate are penalized. Thus, varying seeding rate is no longer a cost effective approach to managing seedling disease.

In-furrow Fungicides

Most cotton production guides for the Southeast, particularly those in Tennessee, recommend the use of an in-furrow granular or liquid fungicide, applied as the cotton is planted (Newman, 2001; Koenning, 2001; Killebrew, 1998; McLean and Gazaway, 2000a). To protect against seedling diseases, the fungicides must form a “zone of protection” around the just-planted seed (Uniroyal Chemical Co., 2001). Newman (1998) described the “zone of protection” as a cylinder with a 1- to 1.5-in. diameter, centered on seed and extending upward to the soil surface. The fungicide on and around the just-planted seed protects against seed rot by hindering pathogen activity in the soil. After the seed germinates, the fungicide from the protective zone is absorbed by the young seedling, and is concentrated in the outer cells of the seedling tissues (Uniroyal Chemical Co., 2001). As the seedling grows upward through the zone of protection, seedling tissues absorb additional fungicide. Both granular and liquid fungicides work in this manner, however each has advantages and disadvantages that are discussed below.

Granular fungicides are applied in the furrow when cottonseeds are planted. The granules are placed in a hopper behind the seed hopper, and the metering mechanism is mechanically attached to the seed meter. As seeds fall from the planter, the granules are metered out in a continuous stream. Many researchers have verified the effectiveness of this disease management strategy. Chambers (1994) compared various treatment methods and concluded that granular in-furrow fungicide treatments increased stands over those in untreated plots, regardless of tillage practice. In plots inoculated with *Rhizoctonia* and *Pythium*, McLean and Gazaway (2000b) observed similar results, noting that all fungicides

treatments (five granular and two liquid fungicides) improved yields, with the average treated plot yielding 3200 lbs/ac of seed cotton, compared to 2100 lbs/ac for the control.

Unfortunately, granular chemicals have a negative environmental impact. Birds often feed on uncovered seeds in newly planted fields. Palmer and Bromley (1992) note that birds, unable to distinguish the chemical granules from seeds, often ingest the granules that land on top of the furrow. Toxic chemicals in the granules can kill the birds or cause their eggs to have soft shells. Some experts expect to see increasing restrictions on granular chemical use (Newman, 1998).

Due to environmental concerns associated with granular application and technology fees associated with transgenic seeds, in-furrow liquid fungicides seem to be the best approach to seedling disease management (Newman, 1998). Like granular fungicides, liquid fungicides protect by providing a “zone of protection” for cottonseeds. However, instead of being applied via the fertilizer hopper, agricultural spray nozzles are attached to the planter unit, and the fungicide is applied as a continuous spray band directly over the open seed furrow. Applying fungicides in this manner ensures complete treatment of all soil that contacts the seed. Killebrew (1998) suggested that liquid fungicides applied as an in-furrow spray provide optimum protection against seedling disease. He reasoned that spray application might provide better mixing between the soil and the fungicide, thus improving soil coverage in the protection zone.

McLean and Gazaway (2000c; 2000d) evaluated various liquid fungicides in central and northern Alabama and observed substantial yield increases over the untreated control. In central Alabama, four plots treated with liquid fungicides (Quadris, Terraclor 2E, and a Ridomil/Terraclor combination) produced an average seed cotton yield of 3200 lb/ac,

compared to 1200 lb/ac for the control (McLean and Gazaway, 2000c). The results were similar in northern Alabama, where treated plots averaged 3100 lb/ac, compared to 1500 lb/ac for the control (McLean and Gazaway, 2000d).

Clearly, liquid fungicides have distinct advantages over their granular counterparts. The conventional application method, in which fungicides are applied as a continuous spray band along the furrow, results in total coverage of the furrow. Yet, the fungicide is only needed in a 1- to 1.5-in. zone around each seed (Newman, 1998; Uniroyal Chemical Co., 2001). This suggests that the current method of applying liquid fungicides is inefficient. By eliminating the wasted spray between seeds and applying the fungicide seed-specifically, the economic efficiency of this method would improve significantly.

Technologies Available to Implement Seed-Specific Application

While the concept of precisely applying fungicide where it is needed, and not along the entire row is simple, there are several challenges to implementation. First, applying a discrete pulse of chemical to each seed requires knowledge of when each seed lands in the furrow, so that the valve can be actuated. Additionally, a high-frequency on/off fluid valve with a response time less than 5 ms is required to accommodate the planting speeds and seeding rates currently employed by producers. Existing technologies could be used to overcome the challenges associated with seed-specific chemical application. These include seed sensors for detecting the presence of falling seeds, and high-speed fluid valves with response times less than 3 ms.

Seed Sensors

Agricultural equipment manufacturers have long recognized the need for accurate seed detection during planting. Young (1959) developed one of the first seed sensors in 1957. Years before electronics would become commonplace on agricultural machines, Young's sensor consisted of a sensitive mechanical switch, which protruded into the seeding tube. Seeds falling down the tube would strike the switch, momentarily closing it. This, in turn, allowed current to flow to a light bulb located in view of the operator. In this way, Young's sensor provided operators with a visual indicator of the planter's status. While the lights flickered on and off, the operator was assured that seeds were being planted. If the flickering ceased, the operator was alerted to a potential problem, such as a clogged seeding tube or empty seed hopper.

Since Young's first seed sensor, a variety of sensors have been developed to address the shortcomings associated with the mechanical design. Schenkenberg (1970) noted the problems, including malfunctions of the mechanical switch due to dust and moisture exposure. He developed an improved, optoelectronic sensor, which consisted of a light source and a photosensitive element located on opposite sides of the seeding tube in optical alignment. Seeds falling down the tube passed between the light and photosensitive element, changing the amount of light received by the photocell. The photocell translated the change in light into a change in voltage, which was conditioned into a digital pulse.

Recognizing the superiority of optical sensors in the rugged planting environment, future seed sensors incorporated optoelectronic designs. Steffen (1976) refined the sensor enclosure and electronics, incorporating a rugged, weatherproof housing and solid-state electronics. Steffen and Goeckner (1981) made further improvements, adding additional

electronics so that the sensor could accurately detect various seed types at a wide range of seeding rates. This sensor is described below.

The sensor of Steffen and Goeckner (1981) was designed to individually detect both low-rate large seeds, such as corn, and high-rate small seeds, such as soybeans. Previously, a special sensor had been required for each seed size. Figure 5 illustrates the seed sensor's placement on a typical seed tube, while Figure 6 shows the simplified electrical schematic for such a sensor. The light source (LEDs) is located on one side of the seed tube, and three photosensitive elements (phototransistors) are located directly opposite on the other side of the tube. When no seeds are present, light from the LEDs strikes the light-active area of the phototransistors, allowing current to flow from collector to emitter. In this default state, sensor output is LOW (0V, logic 0), indicating that no seed is present.

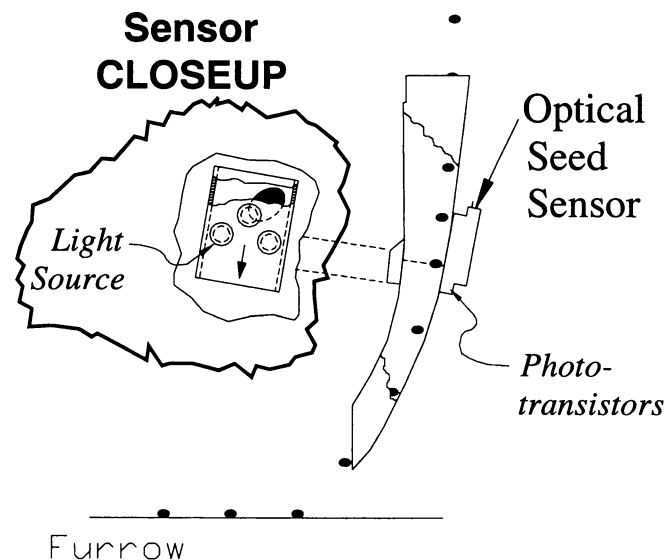


Figure 5. Seed sensor placement on a standard planter tube.

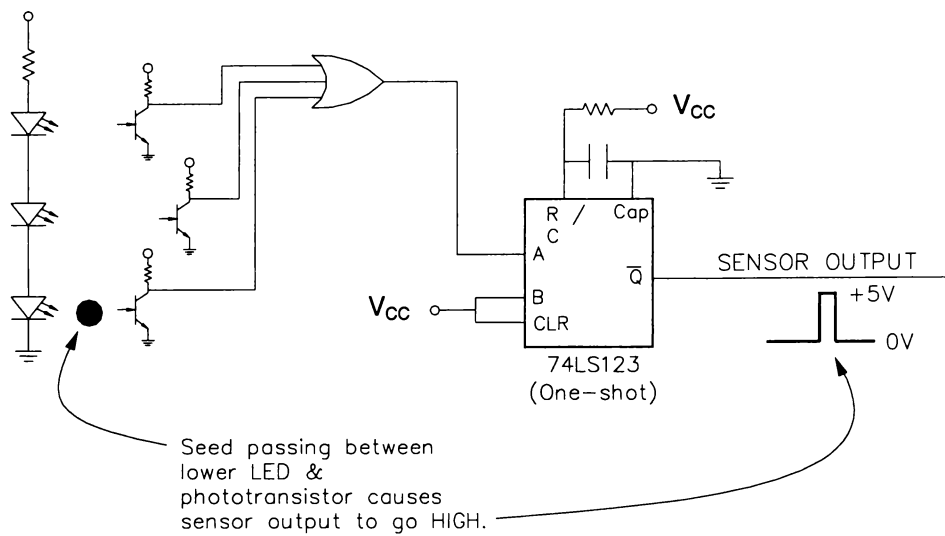


Figure 6. Simplified electrical schematic for a typical seed sensor.

As a seed falls through the seeding tube, it passes between the sensor LEDs and phototransistors, changing the amount of light that strikes one or more phototransistors. In this state, the output of the blocked phototransistor(s) is pulled HIGH (5V, logic 1). Each phototransistor signal is connected to an OR gate input, such that if light to any phototransistor is blocked, the OR gate output will be HIGH. The OR-gate output actuates a one-shot (74LS123), which emits a pulse of sufficient width to ensure that a single seed will not generate multiple pulses.

Similar seed sensors are standard equipment on modern planters. A monitor, located on the tractor that pulls the planter, receives the sensor signals and monitors the frequency of LOW-HIGH transitions. If the monitor stops receiving edge transitions, the operator is alerted to a potentially clogged seed tube or empty seed hopper. The same seed sensor could be used in the seed-specific applicator to detect individual seeds, with a LOW-HIGH edge-transition indicating that a seed is approaching the furrow.

High-Speed, Fluid Valves

High-speed fluid valves refer to a class of fluid control devices that rapidly open to full flow when energized and rapidly close to no flow when de-energized. Rapid developments in digital electronics and microprocessors created a need for fast-response actuators in a variety of industries (Klapper, 1997). Since they operate at either the fully-open or fully-closed position, digital valves have built-in stops to provide true control of the valve's position (Klapper, 1997).

The response time of a valve indicates the amount of time required to reach the desired state – open or closed – after receiving the control signal. Hesse and Moller used a “ball” element in designing a fast-acting on-off valve in 1972. Their valve had a 1-ms response time, while providing flows less than 1 gpm. Using a poppet-type valve, Luo et al. (1987) was able to achieve flow rates up to 2.25 gpm, but response time increased to greater than 3 ms. Klapper (1997) reported that currently-available “fast” digital solenoid valves respond in less than 1 ms, while “slow” valves typically take 20 to 30 ms to respond. He also noted that a valve's minimum response time is related to several factors, including the efficiency of the wire coil, poppet mass, and spring force.

Giles and Comino (1989) developed a pulse-width modulation (PWM) flow control valve for agricultural applications. Their valve combined a standard dc solenoid valve with an agricultural nozzle body. Operated at frequencies of 7.5, 10, and 12.5 Hz, the valve delivered flows from 0.3 to 3.0 lpm, depending on operating pressure, nozzle, and duty cycle. Valve response time varied with operating frequency and nozzle type. For a solid cone nozzle at 12.5 Hz, it required 9.0 ms for the magnetic field to build up (time to reach 10% of operating pressure), and another 2.6 ms for the valve to open to 75%, for a

combined “time to open” of 11.6 ms. The “time to close” was considerably longer, requiring 36.1 ms for the magnetic field to collapse and an additional 4.2 ms for the valve to close. Response times reported in Giles and Comino (1989) suggest that their valve could achieve a maximum operating frequency of 20 Hz.

At a planting speed of 6 mph and seeding rate of 6 seeds per row-ft, approximately 54 seeds are planted each second. This suggests that the ideal valve should be capable of cycling at least 50 times per second. While the valve of Giles and Comino (1989) could not achieve this frequency, other valves are available that show promise. Specifically, automotive fuel injectors can achieve these cycling rates, have a design life of millions of cycles, and are available in the flow rates required for seed-specific chemical application.

Fuel injectors include a fluid flow path, a solenoid assembly, and a metering orifice. The fluid flow path provides a passage for the metered fluid through the valve. Fuel system pressures are typically 36 to 72 psi (SAE, 1989), which is consistent with pressures used in agricultural spray applications. The solenoid coil produces a magnetic field when current flows through it, producing the force to lift the solenoid armature. The armature controls fluid flow by opening and closing a valve (SAE, 1989). Figure 7 shows a cross-sectional view of a typical top-feed injector. Most high-speed valves include the same basic components and operate in a similar manner. However, the fuel injector is optimized to produce response times much faster than standard valves.

SAE Recommended Practice J1832 (1989) covers gasoline fuel injectors. It specifies a standard test period of 10 ms/pulse for testing injectors. This equates to a cycling frequency of 100 Hz – double the required frequency for the proposed application.

Graphs of representative injector performance suggest that opening times of 1 to 2 ms are attainable, with closing times of approximately 0.5 ms.

The injector driver circuit greatly influences valve opening and closing times in fuel injectors and other solenoid-based valves (SAE, 1989). Minimizing response time requires an understanding of how the solenoid responds to the control pulse. Fulks (1989) noted that two distinct phases of power control are required to maximize performance. During the 'boost phase', high current is required to overcome the plunger's inertia and set it in motion. This is followed by the much lower-current 'hold phase', because less current is required to hold the plunger open (Fulks, 1989). Lowering the current during the hold

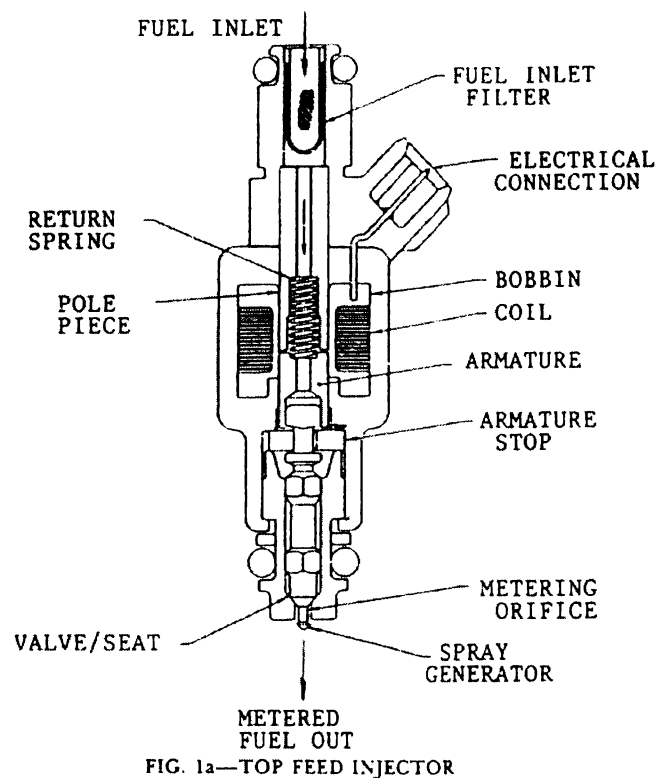


Figure 7. Cross-sectional view of a top-feed injector, as illustrated in Figure 1a of SAE J1832 (1989).

phase weakens the solenoid's magnetic field, allowing the plunger to close much faster when the OFF signal is received. A peak-and-hold driver utilizes this dual level control, providing an initial, high-current "peak" pulse to rapidly open the injector, and a lower current "hold" pulse to keep the injector open. In an un-optimized system, the same current is maintained throughout the injector's energized state. A saturated driver is an example of this type control system. The saturated driver consists of a power transistor that turns fully on for the entire ON pulse. These drivers are much simpler electrically, but have longer response times at closing and use more power than peak-and-hold drivers (SAE, 1989).

Other Attempts at Seed-Specific Application and Related Approaches

The need for an in-furrow, seed-specific application system is not specific to fungicides. Significant material savings could be realized with other in-furrow inputs, such as starter fertilizers and insecticides. Roberts et al. (1998) investigated the precision placement of in-furrow insecticides for controlling early season thrips, and observed results equivalent to the conventional method. Perhaps in response to the work being done in this area, Romans (2001) developed a chemical metering apparatus to coordinate deposits of in-furrow granular chemicals with seed singulation. Romans' system has several shortcomings, but the spray control concept developed by Buschor (1984) for use in the automated painting industry could be adapted to implement seed-specific chemical application. Each of these issues are discussed below.

Roberts et al. (1998) investigated the precision placement of in-furrow insecticides for controlling early-season thrips. The experiments involved cotton planted in groups of 2 to 4 seeds, with each group spaced 9 to 15 in. apart – a practice known as hill-drop

planting. Insecticides for thrips are currently applied in a continuous band along the furrow's entire length, just like fungicide sprays. Roberts et al. precisely applied Temik in the hill, eliminating the insecticide typically spread between the hills. The precisely-placed insecticide provided protection equivalent to the conventional method at a significant cost savings. However, Roberts et al. noted that no applicator currently exists to precisely apply insecticides as tested in their experiment.

The chemical metering apparatus developed by Romans (2001) was a unique attempt at seed-specific chemical placement. Basically, the design was an improvement on the existing granular meter found on modern planters. Instead of applying a continuous stream of chemical, the system synchronized the metering of granular chemicals with seed drop events. Romans' system was totally mechanical, consisting of a separate insecticide meter that mounted coaxially with the seed meter. In this way, revolutions of the insecticide meter were synchronized with the seed meter, such that a dose of chemical was dropped each time a seed was dropped into the seeding tube.

While Romans' chemical meter represents a significant improvement over existing granular meters, it still has several potential shortcomings. The most notable of the potential problems is that both the seed and the chemical are expected to fall by gravity from a height of approximately 18 in., travel down separate tubes, and then arrive in the furrow at the same time. Since seed mass and density are significantly different from that of the granular chemical, this assumption may or may not be valid. The time between seeds must be uniform for a mechanical timing method to work; however, Hancock (2001) suggests significant variability exists in the time between seeds. Figure 8 illustrates the variability in time between seeds at the upper seed sensor, a mere eight inches below the

seed singulator (Hancock, 2001). Considering that the average time between seeds was 60 ms, the variability shown in Figure 8 suggests that many chemical doses would actually fall in front of or behind the seed. Alternatively, the variability associated with seeding times could correlate with the variability in chemical drops; however, no published research concerning the accuracy of Romans' system was available to evaluate these ideas.

While Romans' system (2001) may not be acceptable for precision seed-specific placement, an approach similar to that of Buschor could make seed-specific chemical placement a reality. Buschor (1984) designed a unique spray coating control system for automatically spray-coating objects on hangers attached to a conveyor belt, as the conveyor moved the objects through a paint cell. A sensor located outside the paint cell detected each hanger some distance ahead of the paint cell. Following detection, each hanger was

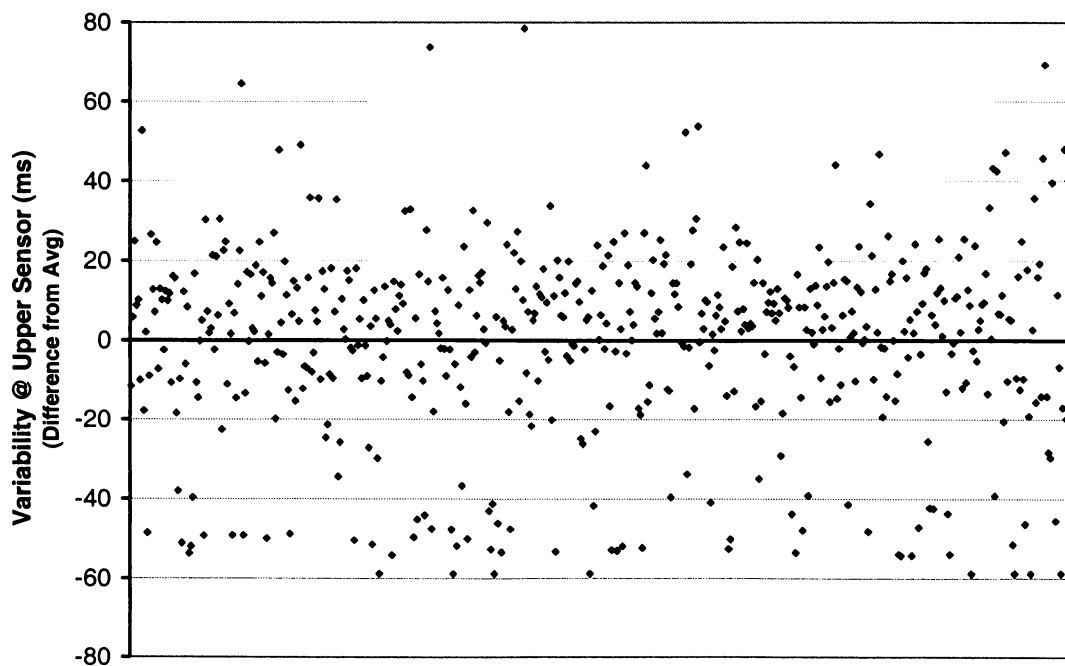


Figure 8. Variability in the time between cottonseeds, as measured at the upper seed sensor, with $y=0$ representing the average (Hancock, 2001).

tracked in time to the initial coating position. This was possible because the conveyor moved at a constant speed, and because the location of the hanger sensor was fixed in relation to the paint cell. As the hanger reached the paint cell, the tracking circuit activated the sprayer control circuit, which then issued an actuation signal to the sprayer. The width of the actuation pulse was equal to the time required for the object being sprayed to completely pass the spray nozzle (Buschor, 1984).

While Buschor's system tracked hangers traveling at constant velocity down a conveyor belt, a similar control system could be developed to track seeds traveling down a seed tube. By combining this control strategy with seed sensors and high-speed fluid valves, a precision seed-specific chemical applicator could be developed to precisely apply fungicides or other in-furrow chemicals.

CHAPTER III. EVALUATION OF SEED

DROP-TIME VARIABILITY

Overview

Seed drop-time refers to the amount of time required for a seed to travel from the point of detection at the seed sensor to the seed tube outlet. Ideally, this time would be exactly the same for each seed planted; however, in reality there is variability in drop-times. In this project, drop-time variability is analyzed to evaluate the OEM-standard seed sensor placement, as shown in Figure 9. If the variability in drop-time is small, the seed can be accurately tracked with the seed sensor in its OEM-standard location. However, large drop-time variability would have necessitated moving the sensor closer to the tube outlet to minimize tracking errors.

Drop-time is affected by a variety of factors, including the distance between the sensor and tube outlet, initial seed velocity, and the seed's travel path between the sensor and tube outlet. Figure 9 illustrates three possible trajectories that the seed could take in the lower half of the tube. The coefficient of restitution between seed and tube, the impingement angle between the seed and tube, and dynamic movement of the planting unit all influence the seed's path in the tube, and therefore the average drop-time. Path A (solid line) shows the most direct route the seed could take, while paths B (long dashes) and C (short dashes) represent alternate trajectories if the seeds were to bounce around in the seed tube. Drop-time variability is not affected by which trajectory the seed follows, but by how consistently the seed follows any path.

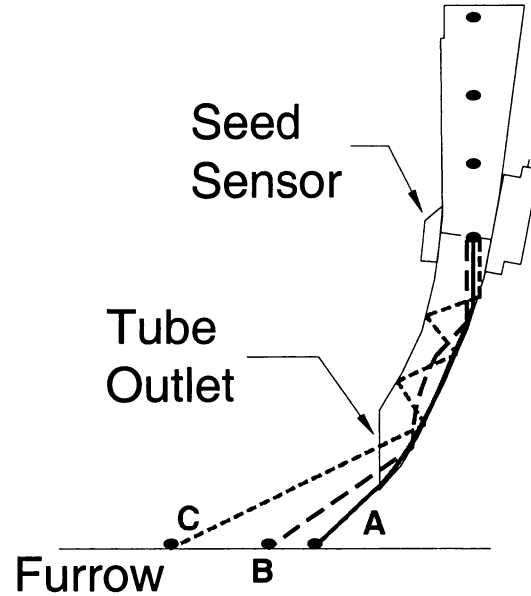


Figure 9. Possible seed trajectories following detection by the seed sensor.

To evaluate seed sensor placement for the seed-specific applicator, seed drop-time variability was evaluated. Drop-times were first measured in a quasi-static, laboratory setting. Next, drop-times were measured in-field during planting to determine the impact of planter dynamics on drop-time variability. Test procedures and results are described below.

Laboratory Evaluation

Seed drop times were first measured in the laboratory to evaluate drop-time variability under the best-case conditions, with the effects of planter dynamics removed. Specific objectives were as follows: (1) obtain information on seed drop-times and drop-time distribution; (2) evaluate how drop-times vary for different cotton varieties; and

(3) compare drop-time variability for a single seed dropped many times to multiple seeds dropped one time each.

Seed Tube Instrumentation

A seed tube was instrumented to measure seed drop-time requirements in the laboratory, as shown in Figure 10. The seed tube (John Deere, Part# A56784) and seed sensor (John Deere, Part# AA41595) were obtained from an agricultural equipment dealer. The tube was mounted on a stand in an orientation similar to that resulting from installation on a John Deere MaxEmerge Plus series planter.

A second seed sensor was positioned at the seed tube outlet. This sensor consisted of a linear array of photodiodes (Motorola MRD500) paired with LEDs (AND 180CRP). A reverse-bias voltage was applied to the photodiodes, as shown in Figure 11. While light

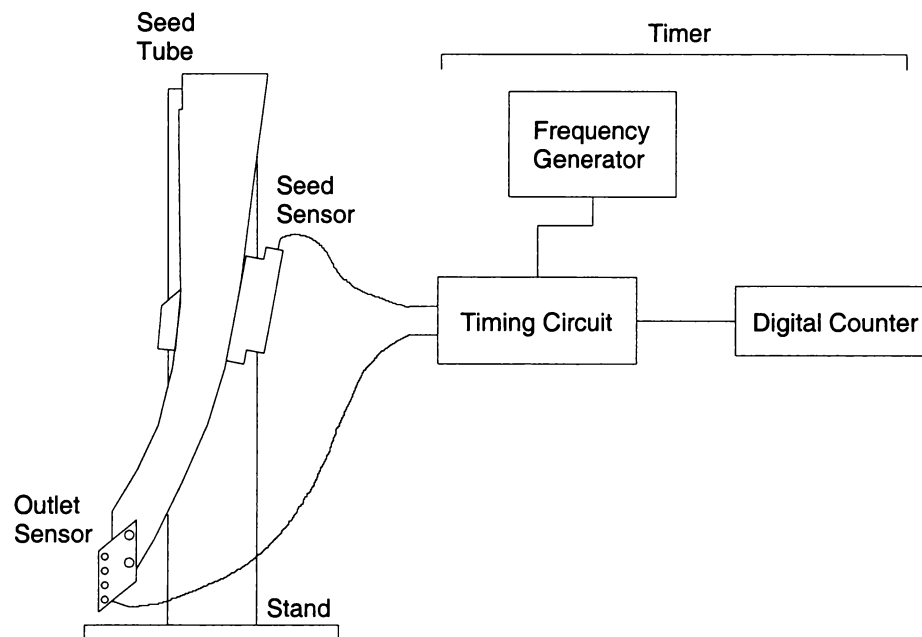


Figure 10. Test apparatus used to evaluate seed drop-time requirements.

struck the photodiodes' active areas, current flowed through them, generating a voltage drop across the series resistor. As seeds passed between the LEDs and photodiodes, light beams between the optical elements were blocked. This resulted in decreased current flow through the photodiodes, and increased output voltage accordingly. Output voltage from the photodetector circuit was compared to a reference voltage (V_{Ref}) using a comparator IC (LM339), which translated the analog output into a single-bit TTL signal.

Signals from both the commercially-available seed sensor and the outlet sensor were connected to an SR flip-flop circuit (74LS00N). Flip-flop output was LOW until a seed passed the upper seed sensor. This action generated a HIGH-to-LOW transition on the SET flip-flop input, which toggled the flip-flop output to a HIGH state. The output remained HIGH until the same seed passed the outlet sensor, resetting the flip-flop to its original LOW state. Flip-flop output was ANDed with a 10-kHz clock such that pulses were output at 10 kHz while a seed was between the upper and outlet sensors. Output from

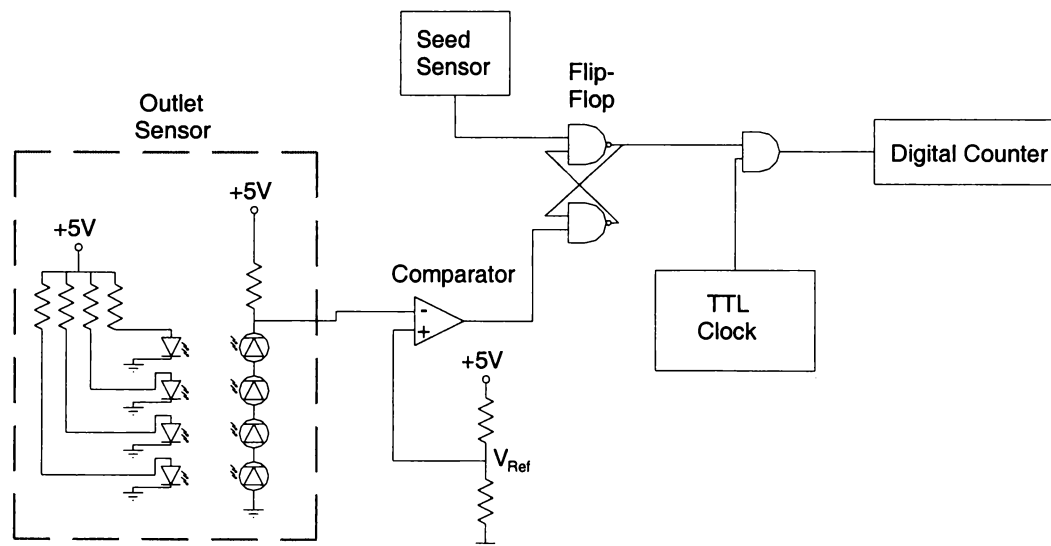


Figure 11. Seed drop time measurement circuit (laboratory).

the AND gate was connected to a digital counter. Drop-time (in seconds) was calculated using the following equation:

$$T_{Drop} = \frac{\# Pulses}{f} \quad (1-1)$$

where: T_{Drop} is the drop time (sec); $\# Pulses$ is the number of pulses recorded by the digital counter; and f is the clock frequency (Hz).

Testing Procedures

Using the test stand illustrated in Figure 10, each seed was dropped by hand from a height of two inches above the seed tube inlet, approximately in the center of the tube's inlet opening. The drop height was chosen arbitrarily, as two inches above the tube represented a convenient location for dropping seeds. In retrospect, the seeds should have been dropped from the height that the seed singulator releases them, as this would have allowed a more direct comparison with the in-field tests. Following each seed drop, the number of counts registered on the digital counter was recorded, and the counter was cleared to zero prior to each subsequent drop. Equation 1-1 was used to calculate each seed's drop-time.

To obtain information on seed drop-times and their distribution, 200 cottonseeds (DP 5409) were dropped through the seed tube. Next, drop-times for 16 cotton varieties were measured by dropping 100 seeds of each variety through the seed tube. In the final test, designed to determine drop-time variability when the same seed is dropped multiple times, nine cottonseeds (DP 5409) were selected, and each seed was dropped 100 times.

Results of Laboratory Testing

In the first test involving 200 seeds, a mean drop-time of 105.5 ms with a standard deviation of 2.9 ms was observed. Drop-time distribution from the test is shown in Figure 12. Drop-times were normally distributed with a very slight positive skew, resulting from a few seeds taking much longer than the others.

In the next test, one hundred seeds from each of 16 different cotton varieties were dropped. Initial inspection of the data revealed several outliers, all of which were much greater than expected. The largest two or three measurements in each set were more than five standard deviations from the mean drop-time. To eliminate these outliers, the two largest time measurements for each variety were eliminated, leaving a data set with 98 observations per variety. The mean drop-time for the entire data set (all varieties included) was 105.8 ms with a standard deviation of 3.5 ms. Mean drop-times ranged from 104.3 to 107.9 ms – a difference of less than 4 ms between the average values. To determine if

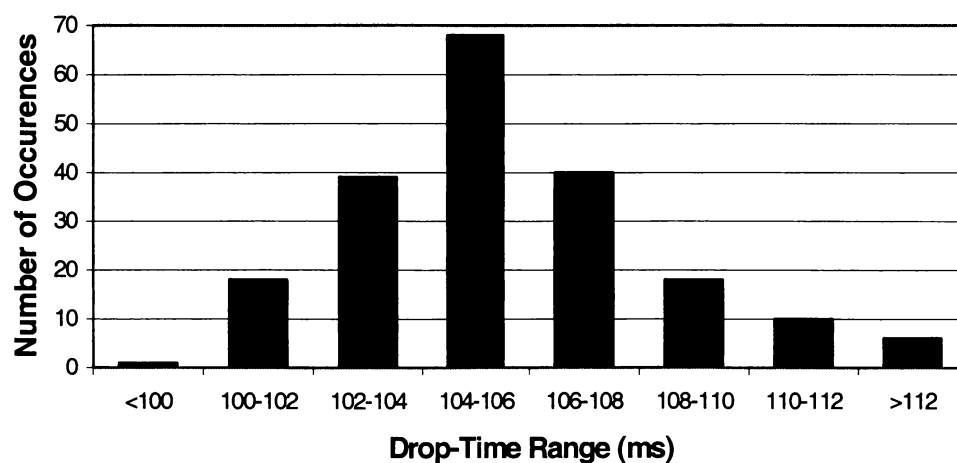


Figure 12. Drop-time distribution for seeds dropped in the lab.

drop-time means between varieties were statistically different, an analysis of variance was performed. Statistical differences were detected ($p < 0.05$), and a mean separation was performed using Least Significant Differences ($\alpha = 0.05$). Average drop-time, standard deviation, and statistical grouping for each variety are shown in Table 1.

In the final test, nine cottonseeds (DP 5409) were randomly selected, and each was dropped 100 times. Extreme outliers were again present, so the two largest observations for each seed were discarded. Mean drop-time and standard deviation were calculated for each seed. This information is summarized in Table 2. Drop-time means ranged from 100.3 to 105.5 ms, while standard deviations ranged from 2.4 to 3.7 ms. An analysis of

Table 1. Descriptive statistics for seed drop times, by variety.

Cotton Variety	Mean Drop-Time (ms)	Grouping (LSD, $\alpha = 0.05$)	Sample Standard Deviation (ms)
DP 425 RR	107.9	a	3.1
ST BXN 47	107.8	a	3.1
DP 420 RR	107.3	a	4.0
DP 422 BGRR	106.2	b	2.7
PM 1220 RR	106.1	bc	2.7
SG 125 RR	106.0	bc	3.2
DP 5409	105.8	bcd	3.3
SG 501 BGRR	105.7	bcd	4.4
PM 2280 BGRR	105.4	bcde	4.1
PM 2326 BGRR	105.4	bcde	2.6
DP 409 BGRR	105.4	bcde	3.5
FM 989	105.1	cdef	3.1
ST 474	105.0	def	3.3
SG 521 RR	104.7	ef	3.6
PM 1220 BGRR	104.7	ef	3.1
DP 429 RR	104.4	f	3.6

Table 2. Mean drop time and standard deviation for nine seeds dropped 100 times.

Seed # (DP 5409)	Mean Drop-Time (ms)	Sample Standard Deviation (ms)
1	102.9	2.6
2	101.0	2.4
3	104.1	3.7
4	100.7	2.7
5	101.0	2.7
6	100.3	2.6
7	105.5	3.4
8	105.5	3.0
9	102.7	3.5

variance detected some statistical differences in mean drop time from seed to seed ($p < 0.05$), but these differences were again small.

Conclusions from Laboratory Testing

The results obtained in the laboratory evaluation of seed drop-time variability lead to several important conclusions. The distribution of drop-times in the second test suggests that seed drop-times are normally distributed about a mean. From statistics, 95% of seed drop-times should be within the interval defined by $\bar{x} \pm 2\sigma$. The average standard deviation of drop-time across the 16 varieties was 3.5 ms, therefore 95% of seeds will drop within a 14.0 ms interval ($4 \times \sigma$). Converting to the length domain, 14 ms translates to 1.5 in. at a planter speed of 6 mph. This analysis suggests that a minimum spray-band length of 1.5 in. is required at 6 mph to prevent seed drop time variability from affecting the accuracy (i.e., the percent of seeds sprayed) of the proposed seed-specific applicator.

Relocating the seed sensor closer to the seed tube outlet could reduce drop-time variability, although this has not been tested.

While differences in drop-time means between the seed varieties were statistically significant, the differences were very small, with only 3.6 ms separating the extreme means. If these differences prove to be of practical importance, they can be adjusted for during system calibration.

Finally, seed drop times vary, not only from seed-to-seed, but also from observation-to-observation when a single seed is dropped multiple times. This suggests that there is a degree of randomness in the drop-times, which cannot be explained by differences in seed properties such as density, surface area, weight, etc.

In-Field Evaluation

While little variability in seed drop-times was observed in the laboratory, field tests were necessary to confirm that planter dynamics during planting would not inflate variability. The purpose of the field tests was to confirm that the OEM-standard, seed sensor placement would allow seeds to be accurately tracked in time between the sensor and tube outlet. A significant increase in drop-time variability would dictate moving the seed sensor closer to the seed tube outlet. Specific test objectives included the following: (1) determining the effect of planter speed on drop-time variability and (2) determining the effect of seeding rate on drop-times.

Instrumentation for In-Field Measurement of Seed Drop Times

Measuring seed drop times in real-time on a planter required several modifications to the measurement system used in the laboratory. A more compact sensor was designed to

detect seeds exiting the seed tube, and an automated data acquisition system was developed to automatically record drop times. The redesigned seed sensor and data acquisition system are described below.

Lower Seed Sensor Design

Due to space limitations on the planter, the outlet seed sensor shown in Figure 10 could not be used in this test. A new outlet sensor that consisted of a linear array of six side-looking phototransistors (Optek, Part# OP550A) arranged directly opposite six side-looking LEDs (Optek, Part# OP140A) was developed. Clearances of less than 5 mm around the seed tube outlet required relocation of the outlet sensor, as shown in Figure 13 (see Outlet Sensor CLOSEUP).

The overall function of this sensor is similar to that of the original outlet sensor. Figure 14 shows the electrical circuit for the outlet seed sensor. When no seed is present, light from the LEDs strikes the light-sensitive area of the phototransistors, closing the transistor base and allowing current to flow to ground. This generates a voltage drop across the series resistor. When a seed blocks the light to any phototransistor, that transistor's base is open, preventing current flow in the photodetector circuit, and increasing output voltage. A comparator IC (LM339) compares the output voltage to a reference voltage, and translates the analog output into a TTL signal.

Errors in sensor construction resulted in misalignment between some phototransistors and their mating LEDs. For this reason, the upper three phototransistors were tied together as one photodetector, while the lower three sensors formed a second photodetector. This allowed separate adjustments of the reference voltage, such that the sensitivity of each photodetector could be maximized. Comparator outputs were ANDed

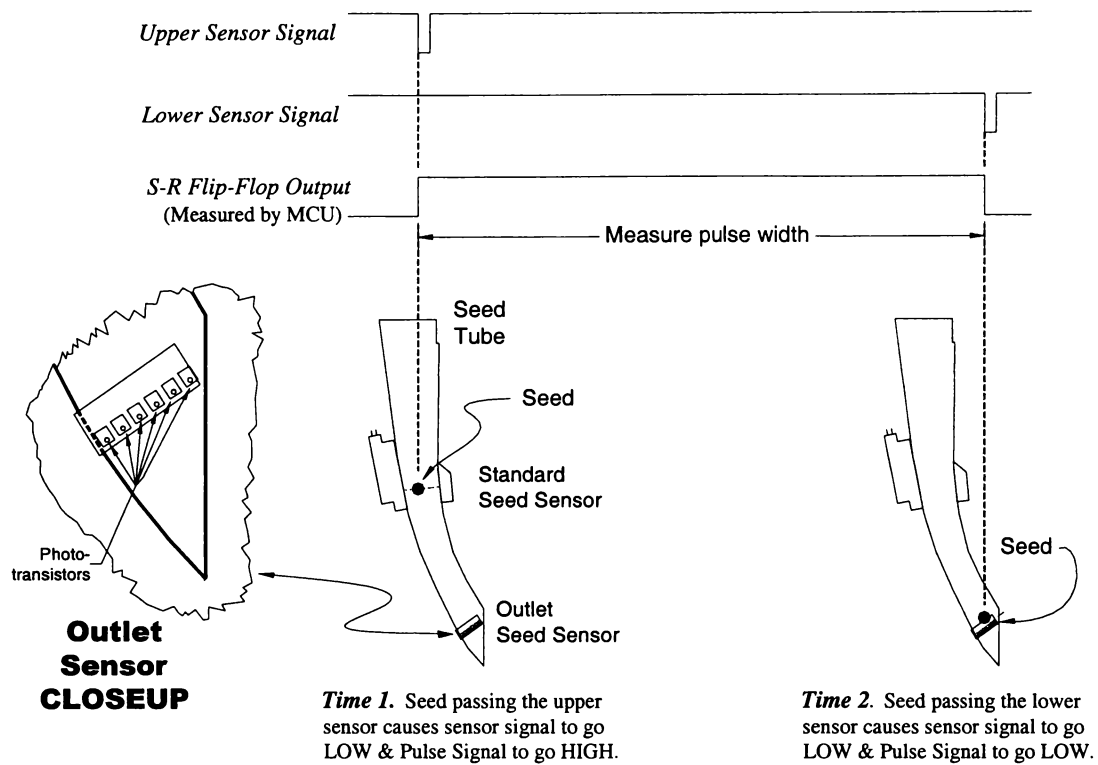


Figure 13. Automated data acquisition of seed drop-times, and revised placement of the outlet seed sensor.

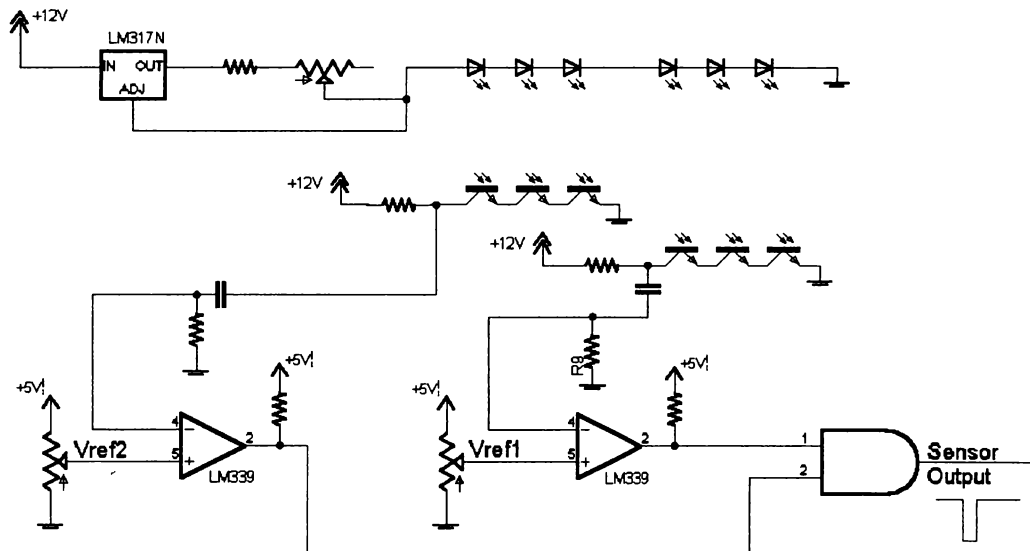


Figure 14. Electrical circuit for outlet seed sensor.

together, such that sensor output is HIGH while no seed is present and LOW when a seed blocks one or more phototransistors.

Data Acquisition

A microcontroller evaluation board (Axiom Manufacturing, Part# CME-11E9-EVBU) employing Motorola's MC68HC11E9 microcontroller unit (MCU) was used for in-field acquisition of seed drop-times. Both sensor outputs are HIGH while no seed is present. When a seed passes either sensor, the output goes LOW. These signals are gated using an SR flip-flop. This generates a pulse, whose width equals drop-time, as shown in Figure 13.

Drop-times were measured with a resolution of 0.008 ms using the MCU's free-running, 16-bit counter (TCNT), in conjunction with its input capture functions. The flow diagram for the MCU program is shown in Figure 15. Flip-flop output was connected to an MCU input capture pin. When a rising-edge (LOW-to-HIGH transition) occurred, the TCNT value at that instant was latched to a 16-bit input capture register, and an interrupt was generated. In the interrupt routine, the input-capture register was stored to a temporary buffer, and the input capture function was re-configured to detect falling edges. When the seed passed the lower sensor and the flip-flop output returned LOW, the TCNT value was again latched. By subtracting the TCNT value latched on the rising edge from the TCNT value latched on the falling edge, pulse width, and thus drop-time, was determined. The pulse width was stored to a memory buffer, and the input capture function was again re-configured to detect rising edges. Following acquisition of all drop-times, the contents of the memory buffer was serially output (ASCII) to a personal computer for data processing.

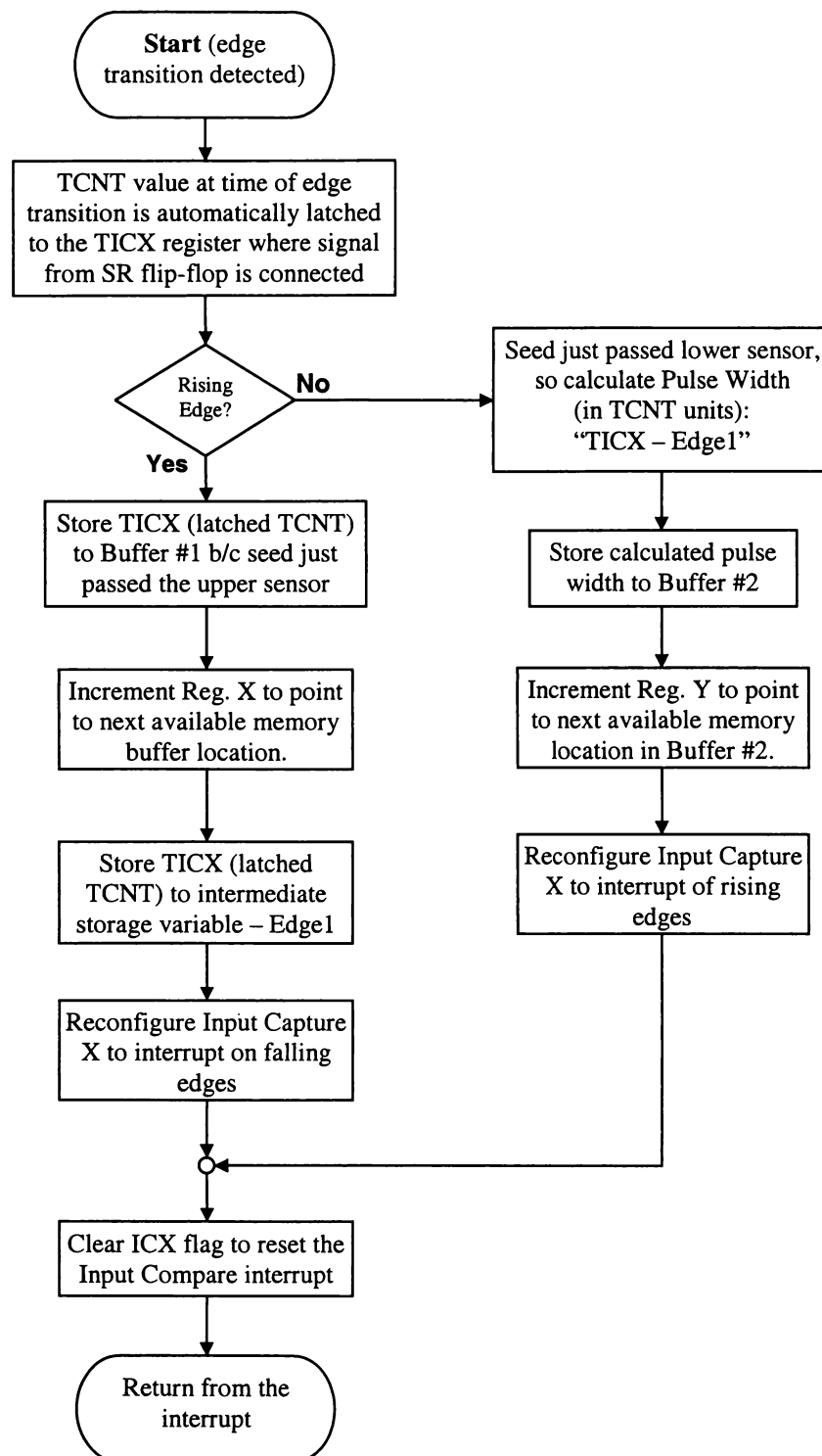


Figure 15. Flow diagram of the MCU program used to measure seed drop times.

Testing Procedure

In-field evaluation of seed drop-time variability was conducted at the Plant and Soil Science Farm of the UTIA (University of Tennessee Institute of Agriculture) Knoxville Experiment Station. Seeds were planted using a one-row planter, which consisted of a single, John Deere MaxEmerge Plus row-unit. The seed singulator was driven by a Rawson ACCU-RATE drive (Rawson Control Systems, Oelwein, IA). The ACCU-RATE drive is a variable rate controller that utilizes a variable speed, hydraulic motor for real-time adjustments of seeding rates. It implements a closed-loop control system, adjusting the speed of the drive motor as planting speed changes so that the correct seeding rate is maintained. The ACCU-RATE drive was used because it eliminated the need for an expensive planter drive transmission. A ground-speed radar unit (Dickey-John, Part# 456401911) was mounted to the planter toolbar and supplied true ground speed information to the ACCU-DRIVE drive.

The instrumented seed tube shown in Figure 13 was used in all tests. It included the standard John Deere seed sensor (Part# AA41595) and revised outlet sensor. The seed plate (John Deere, Part# A56251) was modified to deliver one-fifth its usual rate by placing tape over four out of every five seed cells. Fifty-two of the 64 seed cells were taped, leaving only 12 open cells to carry seeds. This was necessary to prevent the condition wherein multiple seed are in-flight between the two seeds sensors. If this condition were allowed to occur, the seed exiting the tube to reset the SR flip-flop would not correspond to the seed that initially set the flip-flop; therefore, the pulse width of the flip-flop pulse would not correspond to the drop-time of a single seed (refer to Figure 13). This modification ensured that no more than one seed would be between the two sensors at any instant.

Two seeding rates (3 and 4 seed/ft) and four speeds (0, 2, 4, and 6 mph) were evaluated, for a total of eight tests. The zero-mph data was collected using the Rawson drive's 'Calibrate' function, which rotates the planter driveshaft at its field speed equivalent, based on user-specified speed, seeding rate, and row length, while the planter itself remains stationary. Each moving test consisted of four, 250-ft passes across a representative field, producing data sets with 600 to 900 drop-time observations. The pasture field was rougher than a tilled field, yet smoother than some no-till fields.

Results and Conclusions

Results of the dynamic seed drop-time test were first analyzed using descriptive statistics, as shown in Table 3. All drop-times were substantially smaller than the values observed in the laboratory for two reasons. First, the relocated outlet sensor was approximately one inch from the tube outlet, decreasing the distance traveled between sensors. Next, the seed singulator dropped seeds from a height of six inches above the tube inlet – four inches higher than seeds were dropped in the laboratory. The increased drop height caused seeds to gain extra velocity, and therefore decreased drop-times.

Drop-time variability increased slightly over that observed in the laboratory, with the standard deviations ranging from 3.8 to 5.4 ms. If laboratory and dynamic variability had been identical, the standard deviations in this test should have been lower than those observed in the laboratory because mean drop-times were lower. For example, the coefficient of variation in Laboratory Test 1 was 2.7%, compared to a CV of 4.8% in the 0-mph, 3-seed/ft field test.

Table 3. Descriptive statistics for seed drop-times, measured in the field.

Seed Rate (seed/ft)	Speed (mph)	Avg. Drop-Time (ms)	Std. Dev. - Time - (ms)	Std. Dev. - Distance - (in.)
3	0	80.0	3.84	-
	2	78.5	3.79	0.13
	4	79.7	4.10	0.29
	6	79.9	5.45	0.57
4	0	79.4	3.81	-
	2	80.6	4.43	0.16
	4	78.9	4.27	0.30
	6	79.3	5.28	0.56
<i>GROUPED</i>	0	79.9	3.84	-
	2	79.5	4.24	0.15
	4	79.0	4.23	0.30
	6	79.5	5.36	0.57

To determine if the drop-time means were statistically different by seeding rate, drop-times were grouped by seeding rate, and an analysis of variance was performed. The null hypothesis that mean drop-times were equal for all seeding rates was accepted ($p > 0.10$). This indicates that velocity imparted to the seed by the angular rotation of the seed singulator disk has a negligible effect on seed drop-time, and changes in seeding rate should not affect the calibration of a seed-specific planter.

Since there were no statistical differences in drop-time by seeding rate, drop-time observations were grouped by speed (see '*GROUPED*' seeding rate in Table 3), and an analysis of variance was performed to determine if mean drop-time varied with planter speed. The null hypothesis that mean drop-times were equal for all speeds was rejected ($p < 0.01$), so mean separation was performed (LSD, $\alpha = 0.05$). The results indicated that mean drop-times at 2 and 6 mph were statistically identical, while the values at zero and four mph were statistically different from those at all other speeds.

Although statistically differences in mean drop-time were detected for the four planting speeds, the differences are of little practical consequence. Mean drop-times for the four speeds ranged from 79.0 to 79.9 ms – a difference of less than one ms. In contrast, the variability in seed drop-times ranged from $\sigma = 3.8$ to 5.4 ms, easily outweighing the small differences in mean drop-time. This means that the differences in mean drop-time that are present with speed should not affect applicator accuracy, while drop-time variability will definitely affect accuracy. A 2.3-in. (4σ) spray band length would be required at 6 mph to prevent drop-time variability from affecting applicator accuracy.

In conclusion, if the standard seed sensor is used for seed detection in its OEM-installed location, there is a minimum bound on acceptable spray band length, if most (95%) of the seed must be covered.

Summary of Conclusions From Drop-Time Variability Tests

The laboratory and dynamic drop-time tests were conducted to obtain decision support information for designing a seed-specific chemical applicator. Results of these tests led to several important conclusions. First, it was concluded that sufficient time exists for a control system to actuate a high-speed fluid valve, after acquiring a pulse from a seed sensor. In a laboratory test involving 1600 dropped seeds, an average drop-time (time required to travel from the standard seed sensor to the seed tube outlet) of 105.8 ms was observed. Since high-speed solenoid valves have response times less than 5 ms, ample time exists to actuate the valve following detection at the seed sensor.

The laboratory drop-time tests led to a second important conclusion. While statistically significant differences in mean drop-time by variety are present, these

differences are quite small, with mean drop-times ranging from 104.3 to 107.9 ms over the 16 cotton varieties. These differences can be accounted for during applicator calibration, if they are of practical significance.

The effects of planter dynamics increased drop-time variability, with the coefficient of variation climbing from 3-4% in the laboratory to 4-6% in the field. Assuming worst-case variability ($\sigma = 5.4$ ms at 6 mph, in-field), these values suggest that 95% of all seeds should fall within an interval of 22 ms (4σ), which equates to 0.77, 1.50, and 2.25 inches at 2, 4, and 6 mph, respectively. This lead to the third conclusion – the effects of seed drop time variability on seed-specific sprayer accuracy should be minimal, provided the length of spray band is constrained to some minimum value, as noted above.

Alternatively, a new seed sensor could be placed much closer to the seed tube outlet to minimize drop-time variability. However, this solution would add substantial expense to the proposed seed-specific applicator, as it would require a complete redesign of either the planter row-unit or the seed sensor itself. Additionally, placing the sensor closer to the tube outlet could adversely affect sensor accuracy. The uncertainty and expense associated with this alternative led to the decision to use the OEM seed sensor in its factory-installed location, even though applicator accuracy may be compromised slightly.

CHAPTER IV. DESIGN OF A SEED-SPECIFIC CHEMICAL APPLICATOR

The small amount of variability observed in the seed drop time tests supported the conceptual design for a seed-specific applicator initially described in the Introduction. The concept is as follows: (1) detect each seed as it passes through the seed tube; (2) track each seed from the point of detection to the point of chemical application; and (3) apply a discrete pulse of chemical spray to each seed and the surrounding soil, as the seed lands in the furrow. A prototype, one-row seed-specific applicator was developed to implement this concept. The design and system components are described below.

Design Overview

To aid in the design and development of a prototype seed-specific sprayer, several criteria were outlined to define acceptable performance. Specifically, these criteria were identified as follows:

1. Accurately detect each seed, including those closely spaced due to double-drops by the seed singulator, and emit a discrete electrical signal for each seed.
2. Track up to 20 irregularly spaced seeds in the time domain, from the time the seed is detected in the seed tube until it lands in the furrow.
3. Deliver the fungicide as a spray band of adjustable length (0.5-6.0 in.) that completely covers the seed and adjacent soil, including the furrow sidewalls.

4. Allow quick, precise adjustments of delay time and spray band length to accommodate various installation geometries and planter configurations.

The prototype system, as represented in Figure 16, consisted of the following major subsystems: (1) a seed detection sensor; (2) a seed-tracking circuit; (3) a fluid delivery subsystem; and (4) a text-based user interface. Seed detection was accomplished using a commercially-available optical seed sensor, as factory-installed on a planter seeding tube. A microcontroller-based (MCU) algorithm, capable of tracking a plurality of irregularly-spaced seeds and providing a digital actuation signal for the high-speed valve, was used for seed-tracking. The fluid delivery subsystem was connected to the seed-tracking device and included components necessary to produce spray band lengths of 0.5 to 6 in. A laptop computer running terminal emulation software served as the text-based user interface, and allowed adjustments to seed delay time and spray pulse width with a one-ms resolution. An in-depth description of each subsystem is included below.

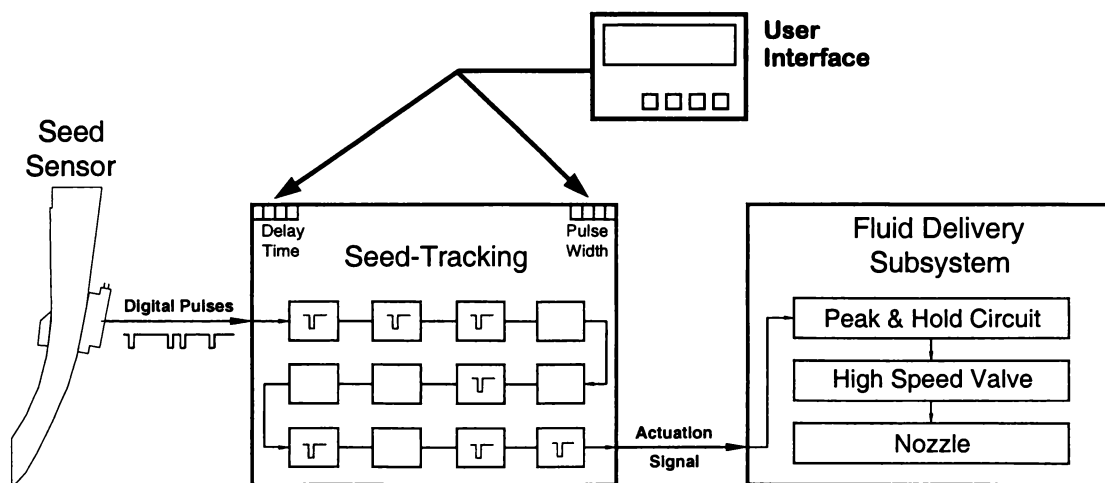


Figure 16. Block diagram of prototype seed-specific applicator.

Seed Detection

A key feature of the envisioned seed-specific applicator is its compatibility with irregularly-spaced seeds. Unlike Romans' system (2001), which coordinated chemical deposits with the revolution of the planter seed-singulation device, the proposed applicator applies chemical in coordination with actual seed drops. This feature uncouples applicator performance from planter performance, such that applicator performance is not dependent upon the planter's ability singulate seeds on a well-defined time interval.

Much research has focused on seed detection techniques, and numerous patents have been issued for seed sensors. Virtually all modern planters are equipped with opto-electronic seed sensors that emit a digital signal each time a seed is detected. Designed for the rigors of planting, these devices are rugged, robust, and very accurate. The accuracy of a representative manufacturer's standard seed sensor is reported to range from 95% to 100%, depending on seeding rate (John Deere Seeding Group, 2002).

Since commercially-available sensors are rugged, accurate, and patented, one of these sensors (John Deere, PN# AA41595) was selected for use in the prototype seed-specific applicator. The sensor's signal was open-collector output, so a pull-up resistor (10k to 5V) was used to produce a standard TTL-level signal that could be interpreted by the seed-tracking circuit. Output was normally HIGH, with a 2- to 3-ms LOW pulse generated each time a seed passed the sensor.

Although the results of the seed drop-time tests indicated that drop-time variability could affect applicator accuracy with the seed sensor installed in its OEM-standard location, the sensor was not relocated in the prototype seed-specific sprayer (see Figure 17). There were several reasons for this, most of which were planter-specific. The

compact design of the MaxEmerge Plus row-unit left little space for a seed sensor at the seed tube outlet. While relocating the sensor closer to the tube outlet may have improved performance, it would have required redesigning either the planter row-unit or the seed sensor. Additionally, either change would have been specific to the particular row-unit model used in this study. Spending substantial time redesigning planter-specific parts could not be justified until the concept of seed-specific placement was tested.

Seed Tracking

A discrete-event tracking circuit was developed to track seeds in the time domain between the seed sensor and the point of chemical application. The circuit receives the TTL-pulses produced by the seed sensor, waits the appropriate time until the seed lands in

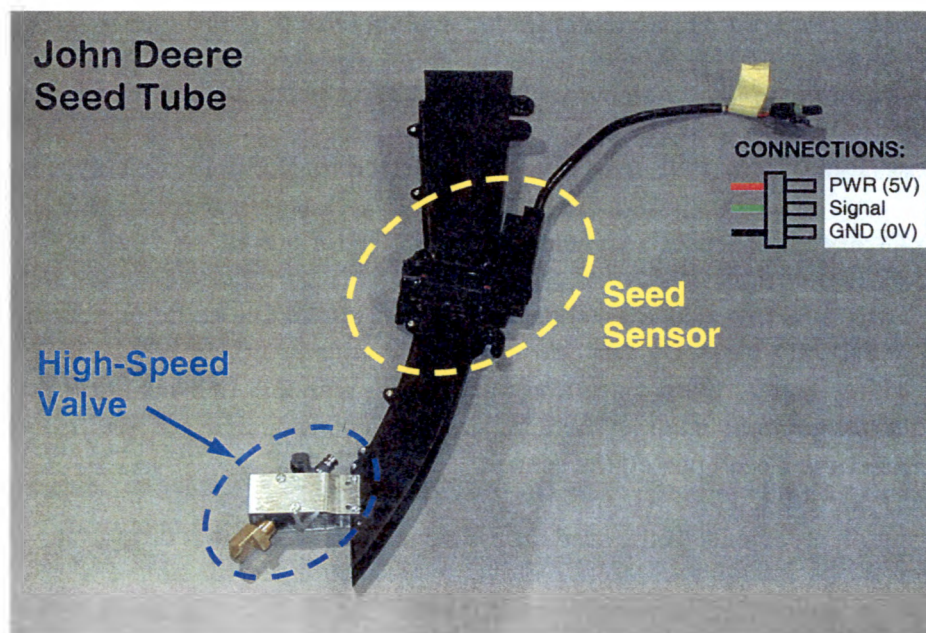


Figure 17. Seed tube from prototype seed-specific applicator, shown with seed sensor and high-speed valve installed.

the furrow, and then sends an actuation signal to the high-speed valve. The width of the actuation pulse equals the time that the chemical valve is to stay open.

Seed tracking is a unique and necessary aspect of this system due to the high speeds and seeding rates at which producers plant. Recall from the seed drop time tests that approximately 106 ms are required for a cottonseed to travel from the seed sensor to the seed tube outlet. When planting 75,000 seed/ac on 40-in rows at 6 mph, the seed drop rate is just over 50 seeds per second, which means that a seed passes the seed sensor every 20 ms. Therefore, at any point in time, there are a minimum of 5 seeds between the seed tube and the tube outlet. The actual number of seeds tracked is somewhat greater, depending upon where the high-speed valve is located relative to the tube outlet.

Seed Tracking Overview

Two methods of seed tracking were developed for the prototype seed-specific applicator. The first method was hardware-based, and utilized shift registers and a clock to implement pulse tracking. The second method was based on programmable microcontroller technology, utilizing the timer features of the Motorola MC68HC11E9 MCU. Microcontroller-based seed tracking best met the design criteria that adjustments to seed delay time and spray pulse width be fast and precise, so it was implemented in the prototype applicator. Both methods are described below.

Hardware-Based Tracking

Background Information

Hardware-based seed tracking was implemented with sequential logic components, which consisted of a bank of shift registers. The time between seed detection and chemical

application was divided into n bits of equal time, corresponding to the n bits of the shift register bank. Each bit represents a unit of time between seed detection and sprayer actuation (the tracking period). For example, if the tracking period was 100 ms and a 10-bit shift register was used, each bit would represent 10 ms of the total period.

The operation of the shift register is now described. A bit of data (the seed sensor signal, where 0 represents ‘no seed’ and 1 represents ‘seed detected’) is loaded into the shift register’s input bin, as shown in Figure 18, at ‘Clock Cycle = 0’. An external clock, cycling at a given frequency, is also connected to the shift register. On each clock cycle, data is shifted sequentially to the next-lowest bit (shifted right). After the data has been shifted sequentially through each bin of the register, it appears at the shift register output bin (see Figure 18, ‘Clock Cycle = 7’). The time (in seconds) required for a data bit to be shifted from the shift register input to its output is calculated as follows:

$$\text{Delay Time (seconds)} = \frac{[\# \text{ shift register bits } (n) - 1]}{\text{clock frequency (Hz)}} \quad (4-1)$$

By incorporating a variable frequency clock, the delay time, which should equal the tracking period (detection to sprayer actuation), can be adjusted. This allows the tracking system to be calibrated, such that delay time equals tracking period. For example, if a 32-bit shift register were used, the clock frequency would be set at 310 Hz for a 100-ms tracking period, versus 207 Hz for a 150-ms tracking period.

Implementation

Additional components were required to implement the three functions (receive seed detection signal, track signal in time, and emit valve actuation signal) of the seed-tracking system, as shown in Figure 19. The seed sensor signal was connected to a one-

	Input Bin								Output Bin							
Clock Cycle = 0	1															
Clock Cycle = 1	0	1														
Clock Cycle = 2	0	0	1													
Clock Cycle = 3	1	0	0	1												
Clock Cycle = 4	0	1	0	0	1											
Clock Cycle = 5	0	0	1	0	0	1										
Clock Cycle = 6	0	0	0	1	0	0	1									
Clock Cycle = 7	0	0	0	0	1	0	0	1								

Figure 18. Conceptual illustration of how a shift register tracks pulses representing detected cottonseeds.

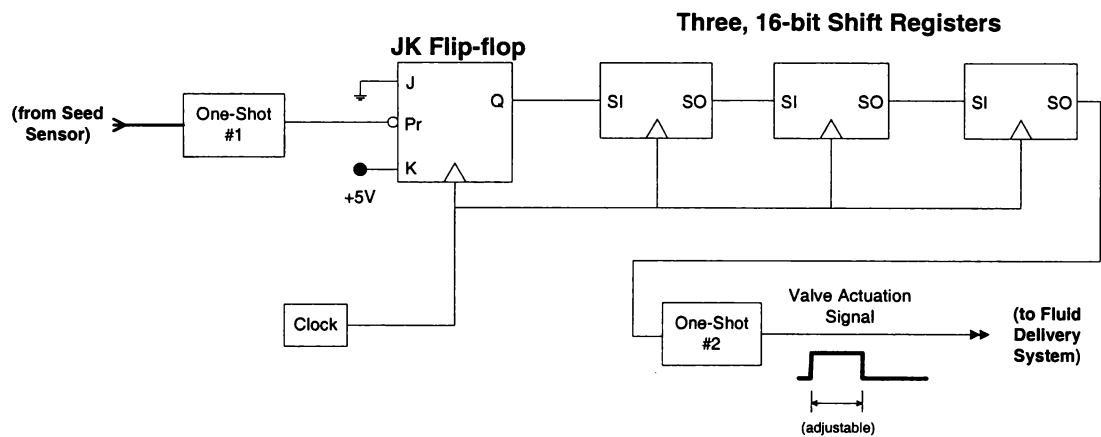


Figure 19. Simplified electrical schematic of the hardware-based seed-tracking system.

shot IC (74LS123). This ensured that each event (seed) only generated one pulse, and that the pulse's width was less than one-half the clock period. One-shot output was connected to a JK flip-flop to 'latch and hold' the pulse until the next falling edge of the clock, at which time the pulse was loaded into the shift register input bin. Three, 16-bit shift registers (74F676) were connected in a FIFO (first-in-first-out) configuration to provide 48 discrete time increments between seed detection and valve actuation. The output of the least-significant bit of the third shift register was connected to a second one-shot that controlled the actuation pulse width. Output of this one-shot was passed to the fluid delivery subsystem, and served as the valve actuation signal. A trimpot was included in the one-shot circuit, such that the actuation pulse was adjustable over a 15- to 52-ms range.

The circuit's clock consisted of a 555 timer IC. Its output clocked the JK flip-flop and all three shift registers. Clock frequency could be varied from 285 to 620 Hz by adjusting a trimpot in the timer circuit. Based on these frequencies and the 48 shift register bits, system resolution varied from 1.6 to 3.5 ms, depending upon the tracking period.

Performance Assessment and Evaluation

From a performance standpoint, hardware-based tracking gets high marks, in that there is no chance of a pulse getting lost. An actuation pulse will be emitted exactly *xx* ms, where *xx* corresponds to the shift register delay period, after the seed detection pulse enters the shift register. However, in this application, hardware-based tracking has two shortcomings. First, delay and actuation pulse-width adjustments are relative. The trimpots that control these values have two setting – more or less. It is difficult to obtain a precise setting without using an oscilloscope. Poor system resolution is the second shortcoming. While a resolution of 3.5 ms is superb in some applications, more precision

is required here. This basically introduces an error term up to 3.5 ms into seed detection, because there could be 3.5 ms between when the seed detection signal is latched and when it is shifted into the shift register. Another drawback was the sheer number of hardware components required to implement this circuit (see Figure 19). For these reasons, a second seed-tracking system was developed using programmable microcontrollers to overcome the limitations associated with hardware-based tracking.

Microcontroller-Based Tracking

Background Information

Microcontroller-based seed tracking was developed as an alternative to the hardware-based system described above. This method utilizes the timer features of the Motorola MC68HC11E9 MCU, which include a free-running timer/counter, input capture pins, and output compare registers. The free-running timer/counter (TCNT) is a 16-bit, read-only register with selectable rollover periods ranging from 32.768 to 524.288 ms. Input capture (ICx) is used to timestamp events. When enabled, the TCNT value is automatically latched to an MCU register at the instant a predefined edge transition (rising, falling, or any edge) occurs on the enabled ICx pin. Output compare allows precise timing of actions on the output compare (OCx) pins, via a writable, 16-bit, Timer Output Compare register (TOCx). When TCNT equals the value stored in TOCx, the MCU will automatically perform the desired action (set HIGH, set LOW, or toggle), or request an interrupt. A seed tracking system can be implemented using these features.

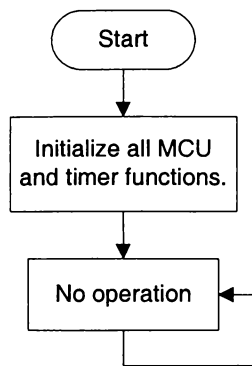
Implementation

In this implementation of seed-tracking, the MCU is the main component. The seed sensor signal connects directly to one of the MCU's ICx pins (PA2), and the MCU outputs valve actuation signals of a user-defined pulse-width on an OCx pin (PA6). MCU system settings are as follows: TCNT rollover period set to 524.288 ms, providing a system resolution of 0.008 ms; IC2 (pin PA2) set to capture on falling edges only, because the seed sensor output is normally HIGH; and OC2 set to generate an interrupt on successful 'TCNT = TOC2?' compares.

Figure 20 illustrates how seed tracking is performed in the MCU. When a seed passes the seed sensor, the TCNT value is latched to the input capture register, and an interrupt request is generated. A delay – representing the amount of time required for the seed to fall from the sensor to the furrow – is then added to the latched TCNT value and stored in a memory buffer. The stored number is the value that the TCNT will hold as the seed reaches the furrow. The memory buffer is a bank of 25, two-byte memory locations, which hold the TCNT times when the valve should be actuated to spray the seeds that are currently being tracked. When the next seed passes the sensor at time=TCNT2, the "TCNT2 + Delay" value will be stored to the next buffer location. The number of seeds that the MCU can track equals the size of the memory buffer where the "TCNTx + delay" values are stored.

Two output compare registers control ON-OFF timing of the valve actuation signal. Flow diagrams for these interrupt service routines are shown in Figure 21, and their operation is described below. The first OC register (TOC1) is loaded with values from the memory buffer, and thereby controls when the spray valve is turned on. When a match is

Main Program Routine:



IC2 Interrupt Routine (timestamps when seeds are detected)

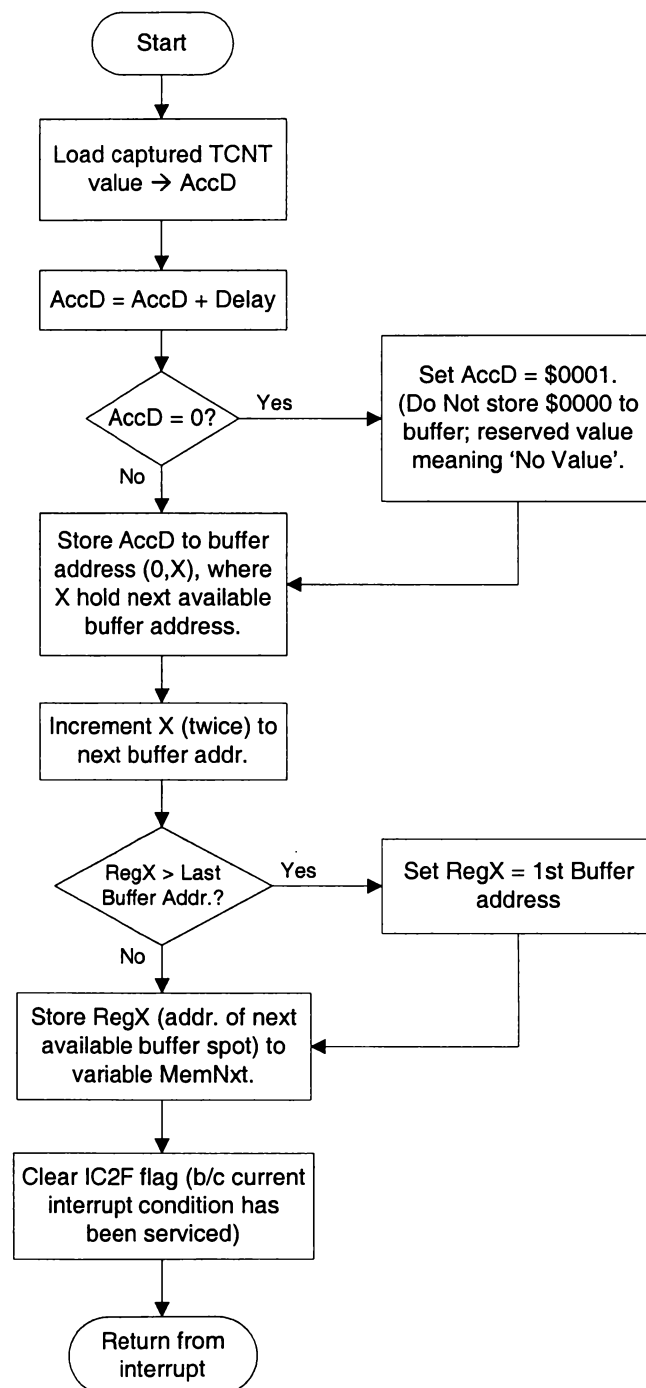


Figure 21. Flowcharts for all programs associated with MCU-based tracking (main program and IC2, OC1, OC2 interrupt service routines).

detected, an interrupt is generated, and the following sequence will occur: (1) set valve actuation signal HIGH; (2) read the current TCNT value and add desired pulse width to it; (3) store this 'TCNT + PulseWidth' to the second Timer Output Compare (TOC2) register; and (4) automatically reload itself (TOC1) with the next, sequential buffer value, provided one is available (buffer values $\neq$ \$0000). If the buffer is currently empty (i.e., no seed waiting to be sprayed), a special flag is set and TOC1 is loaded with a value of 'TCNT+10 ms'. In this way, an interrupt will be generated every 10 ms until a new value appears in the buffer.

The second OC register (TOC2) controls when the valve is turned off. It was enabled and loaded with 'TCNT + PulseWidth' in step 3 of the OC1 interrupt routine. An interrupt occurs when TCNT=TOC2, signaling that the actuation signal has been HIGH for PulseWidth ms. In the OC2 interrupt service routine, the pulse actuation signal is set LOW and future TOC2 interrupts are disabled.

Performance Assessment and Evaluation

MCU-based seed tracking addressed all three shortcomings of the hardware-based system. System resolution improved from 3.2 to 0.008 ms, assuring that delays in the seed-tracking system would not negatively impact applicator performance. Additionally, since the delay time and spray pulse-width values are now controlled by the MCU, they can be precisely adjusted via the user interface, which is discussed later in this chapter. Finally, the number of electrical components is reduced significantly. Only the MCU chip and a few peripherals are required. However, an MCU evaluation board (Axiom Manufacturing, Part# CME-11E9-EVBU) with a serial communication interface and other included peripheral chips was utilized in the prototype system.

In laboratory testing, the MCU-based system was 100% accurate in tracking all detected seeds. For these reasons, the MCU-based seed tracking system was used in the prototype sprayer. In applications where the events being tracked are further apart, and timing is not as crucial, the hardware-based system has distinct advantages.

Fluid Delivery Subsystem

The fluid delivery subsystem was responsible delivering the liquid chemical in 0.5- to 6-in. spray bands lengths around each seed, when the actuation signal from the seed tracking system was received. This subsystem included the following components: (1) a high-speed, electro-mechanical, fluid valve to control chemical flow; (2) a valve actuation circuit to interface the digital signal from the seed tracking system with the higher currents and voltages associated with the high-speed valve; and (3) a spray nozzle to distribute the chemical across the furrow's width. Additionally, valve-mounting hardware was developed to rigidly locate the valve with respect to the seed tube outlet. These components are described below.

High-Speed Electromechanical Valve

The concept of seed-specific actuation requires the ability to control fluid flows with near instantaneous response. Valve requirements for liquid fungicide application were continuous flow rates of 3-10 gallons per acre (5-24 gph, depending upon planter speed and crop row spacing) and response times less than 5 ms. A Bosch-type, peak-and-hold fuel injector (RC Engineering, Part# P82X-765) was selected that met both criteria. The selected valve delivers a nominal flow of 12 gph at 42 psi, and fully opens in

approximately 2 ms. The valve is electrically actuated by energizing the valve coil with 12VDC. A 3D rendering of the valve is shown in Figure 22.

Valve Actuation Circuit

The valve actuation circuit, illustrated in Figure 23, served as the interface between the seed tracking system and the high-speed valve. An optoisolator provided electrical isolation between the low-level input signal and the higher currents and voltages associated with the solenoid-based high-speed valve. A peak-and-hold IC (National Semiconductor, Part# LM1949) was used to control a power Darlington transistor (TIP120) that provided the high current to drive the valve solenoid. The peak-and-hold chip minimizes power and improves the valve closing time by initially saturating the transistor with a peak current to rapidly open the valve, and then reducing the current by 75% to hold it open for the

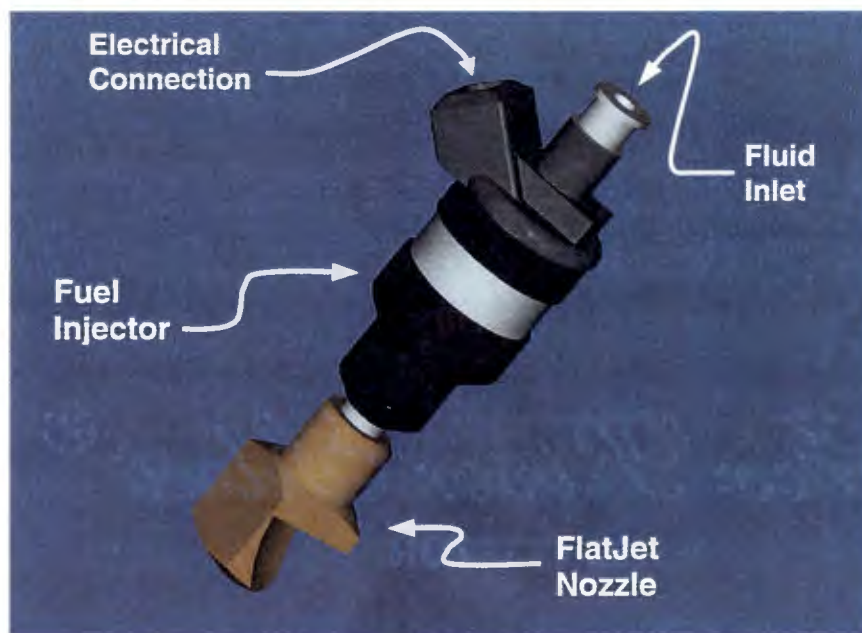
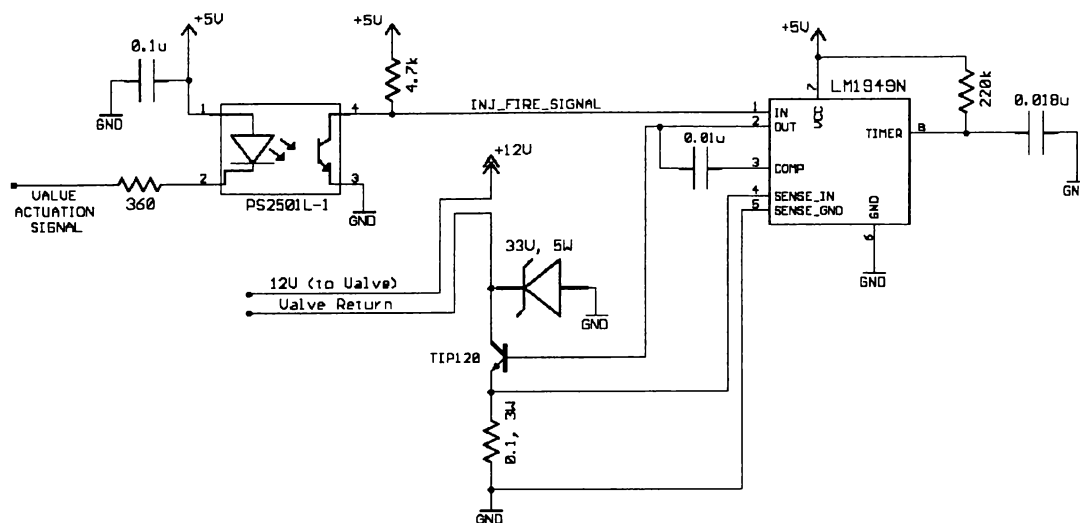


Figure 22. Rendering of selected fuel injector, with FlatJet nozzle.



remainder of the pulse. Closing response time improves significantly due to the weakened magnetic field that results from decreasing current through the solenoid.

The selected valve delivers fluid in a fine stream when actuated. While this method of delivery could be acceptable for some chemicals such as in-furrow insecticides, it is definitely unacceptable for in-furrow fungicide application. The method by which fungicides protect against disease requires all soil that the seed will contact (i.e., the furrow side walls) be sprayed with fungicide. A nozzle (Spraying Systems Co., Part# 5005-FlatJet) was added to the valve, as shown in Figure 22, to transition from the fluid stream produced by the valve to a spray band that covers the entire width of the furrow.

The opposite was true of the FloodJet nozzle. It formed a flat-type pattern virtually instantaneously; however, the width of the spray band was excessive due to the sharp impingement angle associated with that nozzle. The selected nozzle is of a deflector-type design, similar to the FloodJet, but the impingement angle is much shallower, generating a 50-deg flat-type pattern. Since the pattern is generated by deflecting the fluid off a curved surface, there is virtually no capacitance between the valve and nozzle outlets, thus reducing response times. Figure 24 illustrates the generally shape and orientation of the spray band produced by the 5005 FlatJet nozzle.

Valve Mounting

The valve/nozzle assembly was rigidly mounted just behind the seed tube outlet, as shown in Figure 24. A sheetmetal bracket and an aluminum collar were developed to

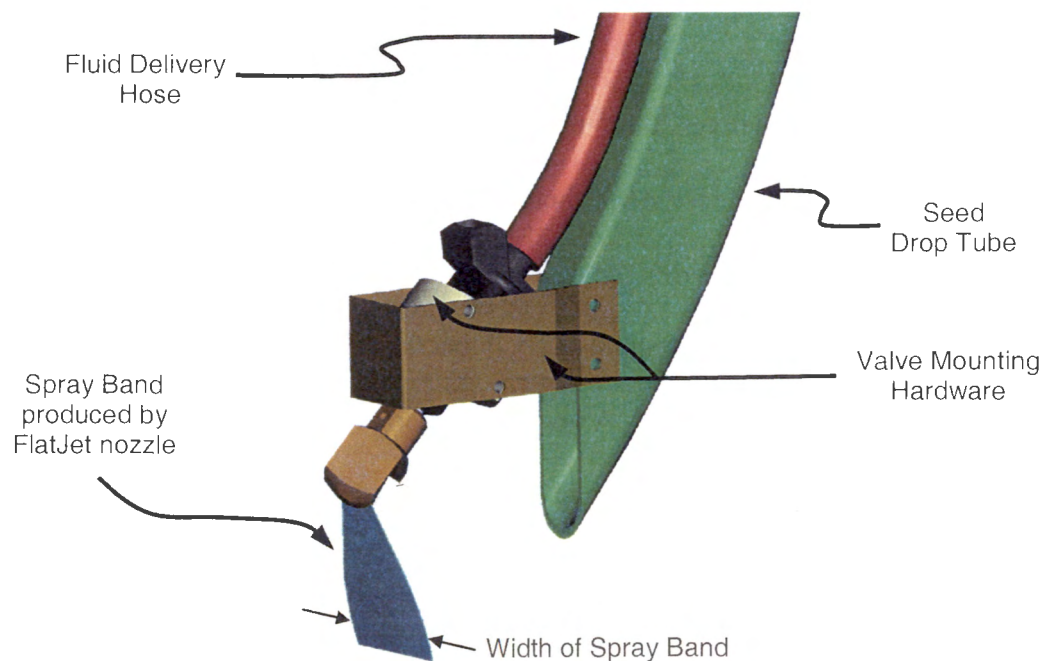


Figure 24. Valve positioning and spray band shape/orientation.

position the valve (dimensional drawings provide in Appendix A). Locating the valve close to the seed tube outlet had two advantages. First, it minimized the effect of ground speed variations on sprayer accuracy. If the valve were located a significant distance from the tube outlet, a system properly calibrated at one speed could start missing seeds if the planter's speed varied from the calibration speed. The second advantage associated with this position related to valve protection. When positioned as shown in Figure 24, the valve is located between the steel furrow-opening disks, protecting it from becoming damaged or misaligned due to collisions with crop stubble or rocks.

MCU User Interface

A text-based user interface was added to the prototype applicator to allow communication between the user and MCU. Specifically, it allowed the user to precisely adjust delay time (time between seed detection and valve actuation) and spray pulse-width (spray band length). The interface consisted of a laptop computer running terminal emulation software, with a serial RS-232 connection to the MCU. Each time the system's power was cycled, the user could enter a special programming mode. In this mode, system settings were displayed, and the user was prompted to change the values by entering new 3-digit, integer times (in milliseconds) via the keyboard. The MCU captured the keyboard input and converted the values to TCNT units, where 524.288 ms equals 2^{16} TCNT units. These values were then stored as 16-bit numbers in the MCU's non-volatile memory, for later referencing during interrupt routines.

Implementing the user interface required one additional IC. The Motorola MCU includes a 3-line serial communications interface (Rx, Tx, and Gnd), but a MAX232 line

driver was required to generate the RS-232 voltage levels for communication with the laptop. Additional code was added at the beginning of the MCU program to serially export system settings and descriptions in ASCII. User input was captured and echoed back to the terminal emulation screen. Times entered by the user were first converted from a 3-byte ASCII string to a 2-byte hexadecimal equivalent (in ms), and then to 2-byte TCNT equivalent. For example, if the user entered '280' as the delay time, the MCU would capture \$32-\$38-\$30, convert it to 280 in hex (\$0118), and finally to the TCNT equivalent of 280 ms (\$88B8).

CHAPTER V. FIELD EVALUATION OF THE SEED-SPECIFIC APPLICATOR

Overview

Field evaluation of the prototype seed-specific applicator involved two distinct phases. First, the biological concept of seed-specific fungicide application was evaluated, focusing on whether fungicides applied seed-specifically provided equivalent protection to those applied in a continuous band. The second stage of testing focused on the seed-specific applicator itself. Applicator accuracy was evaluated over a range of planting conditions to determine the effects of speed, seeding rate, and spray band length on applicator performance. Both tests and their results are described below.

Evaluation of the Biological Concept

Purpose

The primary objective of this test was to evaluate the concept of seed-specific fungicide application. Technical information about how fungicides work (Uniroyal, 2001) suggests that material applied between seeds is wasted; however, no field data existed to support that conclusion. This test was designed to either prove or disprove the seed-specific concept using side-by-side, field comparisons of conventionally-applied fungicides and fungicides applied seed-specifically at the same rate, resulting in a 50% chemical reduction.

Test Procedures and Experimental Design

Experimental plots were established on a producer's farm that had a history of seedling disease pressure in Jackson, TN. Cotton (DP451 BRR with Gaucho) was planted on 38-in. row spacing using the prototype one-row planter shown in Figure 25. The planter was equipped with the seed-specific applicator described in Chapter Four.

Eight fungicidal treatments were evaluated including an untreated check, two rates of Terraclor Super X (TSX) 2.5EC applied conventionally (48 and 64 oz/ac), two rates of TSX 2.5EC applied seed-specifically (same concentration as conventional treatments), and three hopper box treatments (Delta Coat AD @ 11.75 fl-oz/cwt, Frontline Protégé WP @ 0.6 oz/cwt, and System 3 @ 12 oz/cwt). Additionally, both inoculated and uninoculated rows were planted for each chemical treatment, generating 16 experimental treatments. The inoculum consisted of millet seed inoculated with *Pythium* and *Rhizoctonia*, and was applied at a rate of 15 mL per 30 row-ft using the planter's granular chemical hopper. Including inoculated rows ensured seedling disease pressure in the experiment.

Spatial variability of soil moisture within the field containing the plots suggested that disease severity could be affected by plot location. A randomized complete block design with five replications was used to adjust for this variability. Each block was 30-ft long and contained 16 plots, consisting of two rows each. Twenty-foot alleyways separated the blocks.

Since the primary objective of this test was to evaluate the seed-specific concept, planting conditions were chosen to optimize the performance of the prototype seed-specific applicator. Cotton was planted at three seeds per row foot (41,000 seeds/ac) at a speed of 3

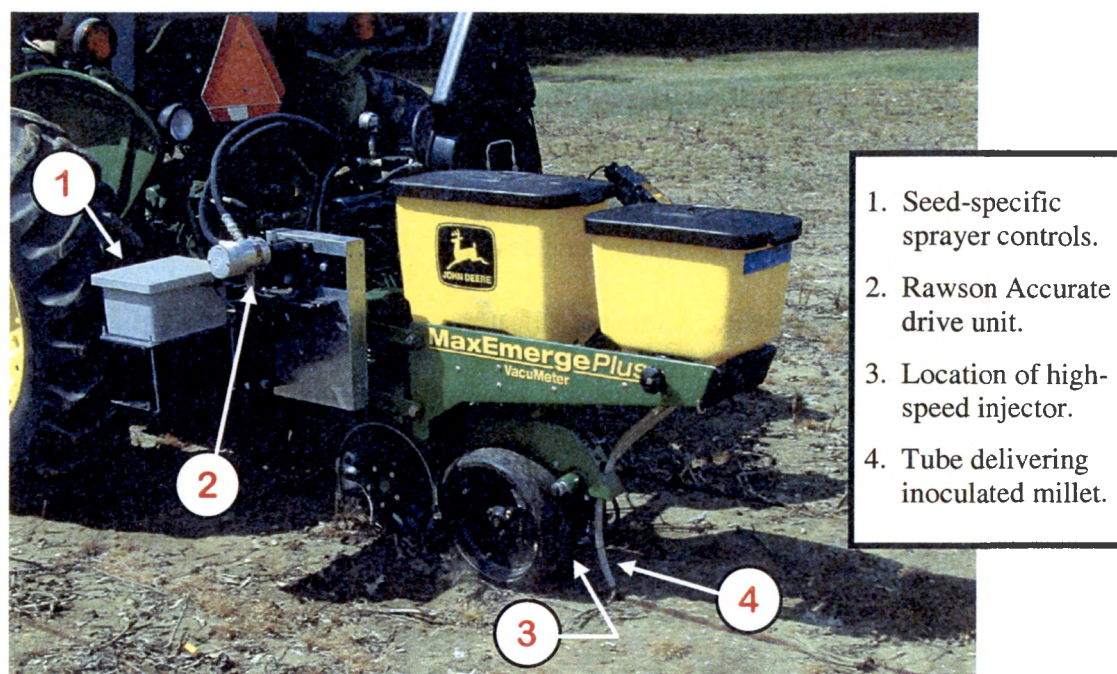


Figure 25. One-row planter with seed-specific chemical applicator.

mph. During conventional liquid fungicide application, a 40015 nozzle (Spraying Systems Co.) operated at 17 psi was used to deliver 5 gpa. The seed-specific applicator was calibrated (system settings: Pulse Width = 040 ms, Delay = 143 ms) to deliver a 2-in. spray band centered about each seed, on average. Five gallons per acre was insufficient flow to produce the desired spray pattern from the FlatJet nozzle; therefore, extra carrier (water) was added to increase the seed-specific application rate to 10 gpa, while maintaining the same rate of active ingredient as used in the continuous treatments.

Plots were planted on April 18, 2002. Stand counts were collected on May 9 (21 days after planting, DAP), May 29 (41 DAP), and June 13 (56 DAP). This information was used to evaluate the effectiveness of each treatment in protecting against seedling diseases, which typically reduce early season stand counts.

Results and Discussion

Stand count results (plants per 10 row-ft) at 21, 41, and 56 DAP are presented in Table 4. The data was analyzed at each data collection period to evaluate disease control throughout the season. To determine if the stand counts were statistically different, an analysis of variance was performed. Statistical differences were detected ($p < 0.01$) at all three observation periods, and a mean separation was performed using Least Significant Differences ($\alpha = 0.05$). The lower-case letters that follow stand count averages indicate the statistical groupings for each observation period (21, 41, & 56 DAP).

Table 4. Stand count results from the evaluation of the seed-specific concept.

Treatment	Rate (fl-oz/ac)	Plant Stand per 10 ft					
		21 DAP		41 DAP		56 DAP	
<i>Uninoculated Plots</i>							
Untreated Control		16.0	a	12.7	a	14.7	a
TSX, Continuous	48.0	15.8	a	12.1	a	14.9	a
TSX, Seed-Specific	48.0	15.6	a	12.9	a	14.2	a
TSX, Continuous	64.0	14.8	a	11.7	a	14.2	a
TSX, Seed-Specific	64.0	15.6	a	11.7	a	14.1	a
Delta Coat	11.75 fl-oz/cwt	13.8	a	11.8	a	13.1	a
Protege XT	0.6 oz-wt/cwt	13.6	a	12.0	a	12.8	a
System 3	12 oz-wt/cwt	14.4	a	12.0	a	12.8	a
<i>Inoculated Plots</i>							
Untreated Control		2.0	c	1.3	b	1.5	c
TSX, Continuous	48.0	14.7	a	13.0	a	13.6	a
TSX, Seed-Specific	48.0	12.5	a	10.7	a	11.3	a
TSX, Continuous	64.0	14.1	a	10.2	a	11.9	a
TSX, Seed-Specific	64.0	15.2	a	13.4	a	13.9	a
Delta Coat	11.75 fl-oz/cwt	6.9	b	4.7	b	5.6	b
Protege XT	0.6 oz-wt/cwt	4.9	bc	3.7	b	4.2	bc
System 3	12 oz-wt/cwt	5.0	bc	4.1	b	4.5	bc
<i>LSD ($\alpha=0.05$)</i>		<i>3.04</i>		<i>3.30</i>		<i>3.02</i>	

No statistical differences were detected in any of the uninoculated treatments. In fact, the untreated check produced among the highest populations. The exceptional performance of the control treatment, combined with the similar performance of all other treatments, suggested that there was no seedling disease pressure in the uninoculated rows. Since there was no disease pressure, the results of the eight uninoculated treatments were useless for comparing fungicidal performance; however, they did provide a baseline to which the inoculated treatments were compared. This was important because final stand counts were 50% lower than the seeded rate (3 seeds/row-ft), suggesting some other factor(s) influenced seedling emergence. Knowing the best-case, no-disease stand counts allowed an accurate evaluation of how well the inoculated treatments protected against disease.

Figure 26 illustrates how the eight fungicidal treatments performed under inoculated conditions. The bars on the boxes indicate the range of observations for the five replications. White boxes represent the untreated check (UTC), dark gray boxes represent the hopper box treatments, and the light gray boxes represent the liquid fungicides.

The inoculated plots revealed the importance of fungicides when seedling diseases are present. In the untreated check (UTC), stands averaged less than one viable cotton plant per five row-ft. Statistically, the UTC was grouped with Protégé and System3 hopper box treatments at all three observations. Delta Coat hopper box treatment performed better than the UTC at 21 and 56 DAP, but was grouped with the UTC at 41 DAP. The three hopper box treatments performed similarly at all three observations, with their average stand counts ranging from 3.7 to 6.9 plants per 10 row-ft.

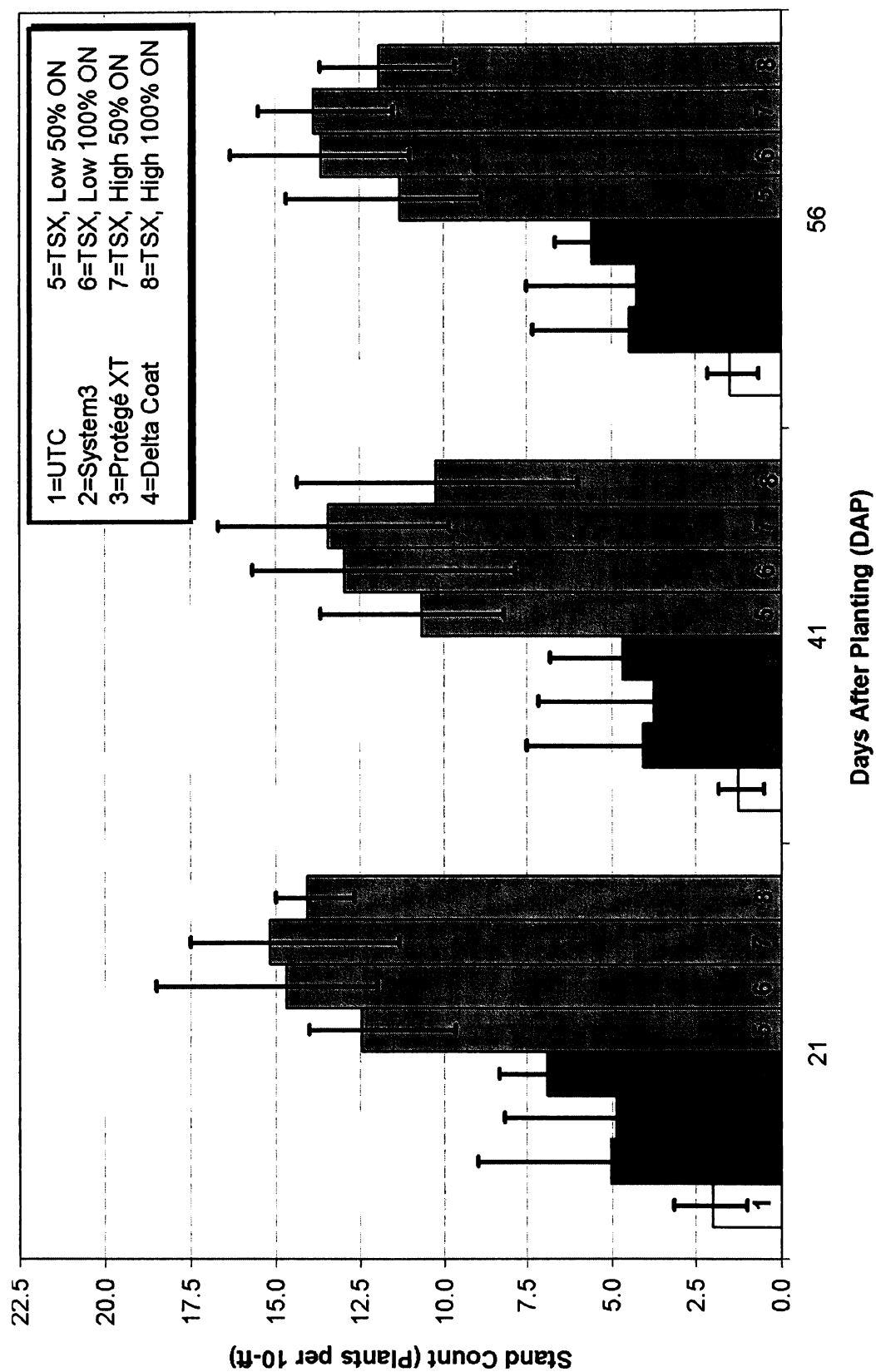


Figure 26. Performance of the eight fungicide treatments in which the soil was inoculated with seedling disease.

Statistically, there were no differences in any of the in-furrow liquid fungicides, regardless of application method or rate. All four TSX treatments provided excellent protection against seedling disease, as evidenced by the fact that these treatments were statistically grouped with the uninoculated treatments in which there was no disease pressure.

As shown in Figure 26, the fungicides applied seed-specifically (#5 and #7) produced stands statistically identical to those produced by the conventional, continuous band (#6 and #8). These observations support the theory that fungicides applied between seeds are unnecessary and can be eliminated without negatively impacting efficacy. Additionally, the liquid treatments far outperformed the newer and cheaper hopper box treatments, supporting conventional wisdom about the superiority of liquid in-furrow fungicides. Collectively, the four liquid fungicides averaged 14.1, 11.8, and 12.7 plants per 10 row-ft at 21, 41, and 56 DAP respectively, compared to 5.6, 4.2, and 4.8 plants per 10 row-ft for the hopper box treatments. This suggests that the liquid fungicides may be worth the extra 50% or so that they cost. While hopper box treatments provided some protection against disease compared to the control, the benefits were minimal. With final stand counts averaging less than one plant per two row-ft, the hopper box-treated plots would have probably warranted replanting in an actual production setting.

Conclusions

The results of the Jackson tests support the biological concept of seed-specific chemical application. Using the seed-specific applicator described in Chapter 4, cost

savings of 50% were realized with no adverse effects on fungicide efficacy. All liquid treatments produced stands equivalent to those in plots where no disease was present.

Evaluation of Applicator Performance

Purpose

The second phase of field evaluation focused on the seed-specific applicator itself. Specifically, the applicator's accuracy was evaluated over a range of planting speeds, seeding rates, and spray band lengths to assess how it might perform under actual planting conditions. A secondary objective was to determine the optimum spray band length to maximize chemical savings while adequately covering the majority of seeds.

Test Procedures and Experimental Design

Experimental Layout

Accuracy of the seed-specific applicator was evaluated at the Milan Experiment Station in Milan, TN. Planter speed, seeding rate, and spray band length were varied in the tests. The planter was operated at 2, 4, and 6 mph, representing the range of speeds at which most producers plant. Seeding rates of 3 and 4 seeds per row-ft (39,000 and 52,000 seeds/ac on 40-in. row spacing, respectively) were used, because the opportunity for reduced chemical input is highest at these rates. The tested spray band lengths were 33, 50, and 66% of continuous coverage. Calculating band length this way resulted in different band lengths at each seeding rate, because 100% coverage would be 4 in. at 3 seeds per ft, versus 3 in. at 4 seeds per ft. Actual bands measured 1.3, 2.0, and 2.6 in. at 3 seeds per ft,

and 1.0, 1.5, and 2.0 in. at 4 seed/ft. All possible combinations of speed, seeding rate, and band length were used, generating a total of 18 treatments.

For each treatment, a 300-ft row was planted. The first 50 ft and last 50 ft of each row were excluded from evaluation, as the planter was speeding up to the test speed or slowing down to stop during this time. The actual plot consisted of the middle 200 ft, as shown in Figure 27. Five, 10-ft segments along each row were randomly selected for evaluation. Within each segment, two datasets were collected. First, a discrete dataset was collected, in which each seed was visually inspected and classified as a hit or miss, depending upon whether it landed completely within a sprayed band of soil. Next, two measurements (see Figure 27) were taken for each single seed, forming a quantitative dataset. Spray-band length and distance from the band start to the seed center were

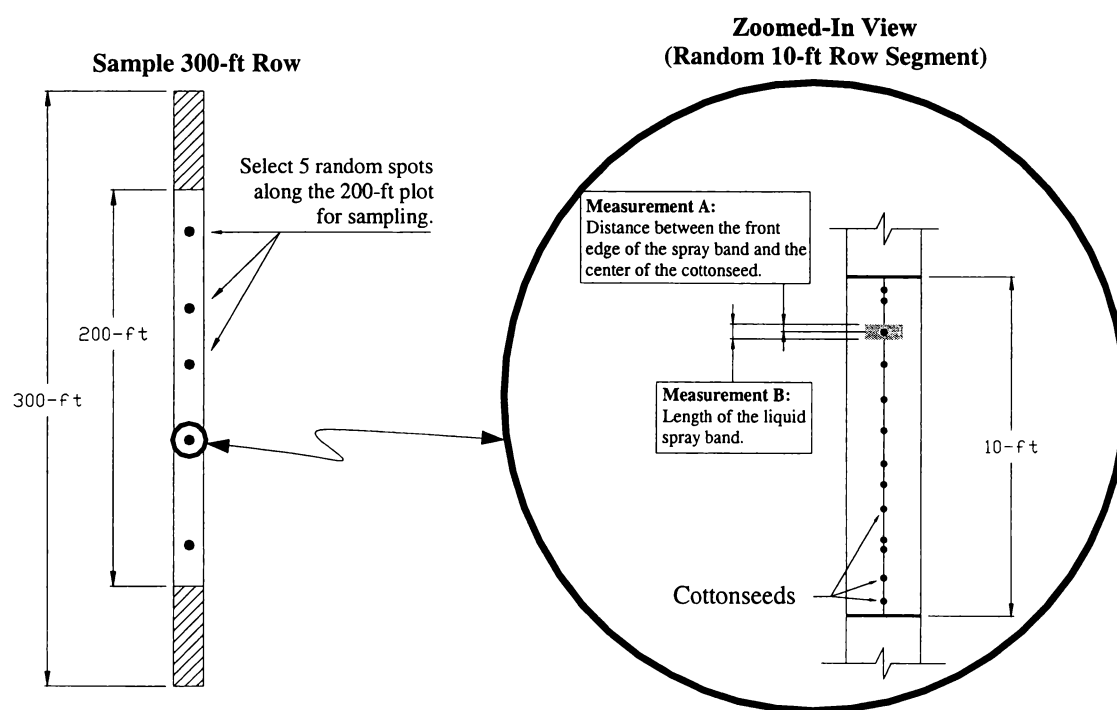


Figure 27. Example plot layout and testing procedure for collection of seed-specific sprayer accuracy data.

measured (± 0.1 in.), ignoring bands that contained multiple seeds. The discrete dataset provided an indication of how well the applicator performed overall, while the optimization dataset allowed verification of system calibration (seed delay times) and evaluation of how increasing/decreasing band length would have affected the spray target accuracy (%seeds sprayed).

The one-row planter shown in Figure 25 was used to plant all plots. Colored dye was used in place of fungicides, and the furrow was left open to aid in data collection.

In-field Calibration

Proper calibration of the delay time and spray pulse width values was crucial to achieve optimum system accuracy. Spray pulse width was a direct function of planter speed and desired length. This value was calculated as follows:

$$PulseWidth = 56.818 * \frac{[desired\ spray\ band\ (in.)]}{[speed\ (mph)]} \quad (5-1)$$

Unfortunately, no calibration equation had been developed for calculating the seed delay times, so these values were determined by trial and error. Before each plot was planted, the best-guess delay value was entered into the seed-specific sprayer, and 50 to 75 feet were planted. System accuracy at that setting was evaluated by visually inspecting the average seed location with respect to the spray bands. The delay time was then adjusted, and this process was repeated until seeds were landing in the center of the spray band, on average. The 300-ft plot was then planted at that setting.

Data Analysis

There were three aspects to the analysis of data collected in this test. First, the raw results (percent seeds hit/missed) were calculated using the discrete dataset to determine

how well the seed-specific applicator performed when calibrated using trial and error. Next, the quantitative dataset, consisting of measurements A and B for each seed (Figure 27), was used to determine whether the system calibration was correct. A MATLAB® program calculated the optimum delay time for each treatment (example of output results in Appendix D). This was accomplished by adjusting all band locations (Measurement A, Figure 27) forward and backward by one inch, in 0.1-in. increments. Following each adjustment, the percent of seeds adequately sprayed was calculated to determine whether accuracy increased or decreased at the new delay value. The optimum delay was the adjustment that yielded the highest seed coverage percentage.

The final aspect of data analysis was determining the required spray band lengths to achieve 85, 90, 95, and 99% seed coverage. This was accomplished using the same MATLAB® program that optimized delay time. First, all datasets were adjusted such that the average seed location (Measurement A, Figure 27) of each dataset was zero inches. Next, adjusted datasets were grouped by speed. Using this data, spray bands were adjusted from zero to four inches in 0.1-in. increments. Seed coverage was calculated at each band length to determine the relationship between spray band length and percent of seeds sprayed. Results of all seed-specific applicator accuracy tests are discussed below.

Results and Discussion

General Observations

As shown in Figure 28, the FlatJet nozzle delivered an acceptable spray band, thoroughly covering the sidewalls and upper edges of the furrow with liquid fungicide. Thorough coverage of all soil that the seed or seedling could contact is key to seedling

disease prevention. Additionally, the seed-specific sprayer functioned as designed in virtually all regards. The spray band was lengthened when double or triple seed drops occurred, as shown in Figure 29; and when the seed singulator skipped a seed, no spray was needlessly applied, as shown in Figure 30. Seed detection and tracking systems functioned perfectly, delivering a spray pulse for each seed. While the seed did not always land in the band of sprayed soil, there was a spray pulse for each seed planted.

Accuracy Results from Discrete Dataset (Observed Accuracy)

The discrete hit/miss information, collected as dataset one, was used as an initial indicator of sprayer accuracy for each treatment. Table 5 contains the percentage of sprayed seeds as a function of seeding rate, spray band length, and planter speed. These results represent how the system performed when calibrated in-field using trial-and-error. Sprayer accuracy was exceptional at 2 and 4 mph, hitting at least 70% of seeds in all tests. As drop-time variability results predicted, accuracy decreased at 6 mph. However, 80% to 90% of seeds were sprayed when the spray band measured 2.0+ inches. This is consistent with conclusions from drop-time variability tests regarding minimum required band length.

Table 5. Discrete sprayer accuracy, based on in-field calibration.

Spray Band Length (in.)	Spray Band (% Duty Cycle)	Seeding Rate (sd/ft)	% Seeds Adequately Sprayed		
			2-mph	4-mph	6-mph
1.00	33	4	71.2	70.2	55.2
1.30	33	3	79.4	76.5	63.6
1.50	50	4	85.5	89.9	78.6
2.00	50	3	94.5	87.9	78.7
2.00	66	4	91.8	92.3	88.8
2.60	66	3	98.2	95.7	89.0

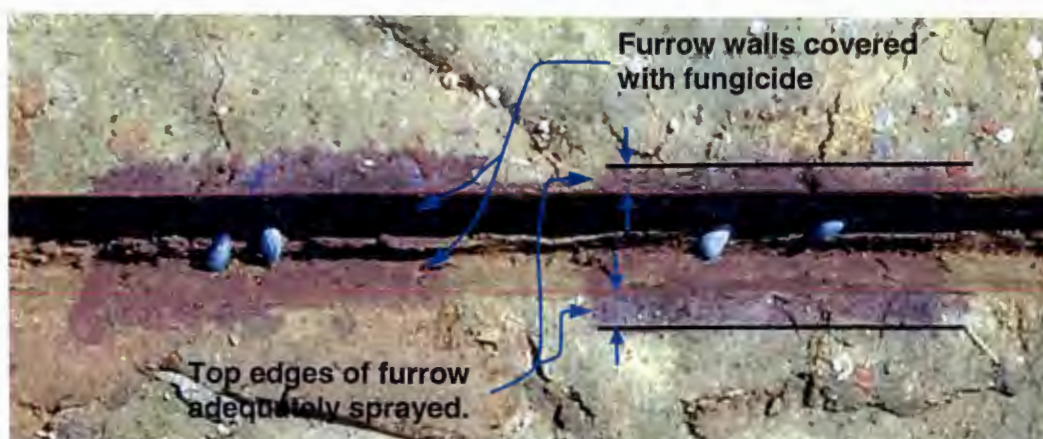


Figure 28. Spray band produced by the FlatJet nozzle covered the areas of interest – the sidewalls and top edges of the furrow.



Figure 29. Photo illustrating how the sprayer handled a multiple seed drop.



Figure 30. Photo illustrating that no spray is applied when the seed singulator fails to deliver a seed.

Accuracy Results from Quantitative Dataset (Optimized Accuracy)

It is important to note that the discrete accuracy results included all seeds within the five, 10-ft segments, including doubles and triples. In some cases, spray targeting accuracies reported above based on in-field calibration, were actually better than the optimized accuracies when post-processing was used to determine the optimum delay time (see Table 6). This is because the optimization dataset included significantly fewer data points, as no measurements were recorded for doubles or triples. Therefore, if the in-field calibration was close to the correct value, observed accuracy is probably higher than optimized accuracy because many disregarded doubles and triples were actually hits. For example, in Test #9 (4 mph, 4 seed/ft, 1.5-in. band) the field calibration was correct, and observed accuracy was 90% while optimized accuracy was 87%. In this example, the optimization dataset only included 64% of the 198 observations in the observed dataset.

System calibration settings were evaluated using the quantitative dataset, as described in the ‘Test Procedures – Data Analysis’ section. On average, the field determined delay times were 3.5 ms too low, ranging from 8.5 ms too low to 1.5 ms too high. The percent of seeds adequately covered was recalculated at the optimum delay times to determine optimized applicator accuracy. Table 6 presents the seed coverage information as a function of speed and spray band length. As previously noted, the optimized seed coverage values are often less than the observed seed coverage values because spray bands containing multiple seeds were excluded from the optimization process. This means that the percentages of seeds adequately sprayed at the optimized delay times are probably higher than the values shown in Table 6.

Figure 31 is a graphical presentation of the information contained in Table 6. The bars represent the percent of sprayed seeds, while the lines illustrate material saving at each spray band length. System performance at 2 and 4 mph was very similar. At these speeds, the shortest band length resulted in approximately 70% accuracy, with a near linear relationship between increased band length and increased accuracy. At the longest band length, virtually all the seeds were sprayed.

Applicator accuracy was poorer at 6 mph, particularly at the shorter band lengths. Approximately 50% of seeds were sprayed when a 1-in. band was used. Doubling the spray band to 2 in. increased accuracy to 90%, which was only slightly lower than the performance at 2 and 4 mph for this band length. This suggests that adequate performance can be obtained at faster speeds, but longer spray bands will be required.

The trends shown in Figure 31 are consistent with what we would expect. First, increasing spray band length increased performance at all speeds. Second, the system was more accurate at 2 and 4 mph than at 6 mph when short bands were used; however, performance was similar at the longer bands. These findings are consistent with the results of the seed drop time variability tests, which suggested that there was some minimum

Table 6. Optimized sprayer accuracy, based on post-calibration.

Spray Band Length (in.)	Spray Band (% Duty Cycle)	Seeding Rate (sd/ft)	% Seeds Adequately Sprayed		
			2-mph	4-mph	6-mph
1.00	33	4	69.2	64.9	48.1
1.30	33	3	75.6	82.9	56.7
1.50	50	4	81.7	87.4	75.9
2.00	50	3	95.6	93.0	87.1
2.00	66	4	90.9	92.4	94.2
2.60	66	3	96.9	98.1	91.4

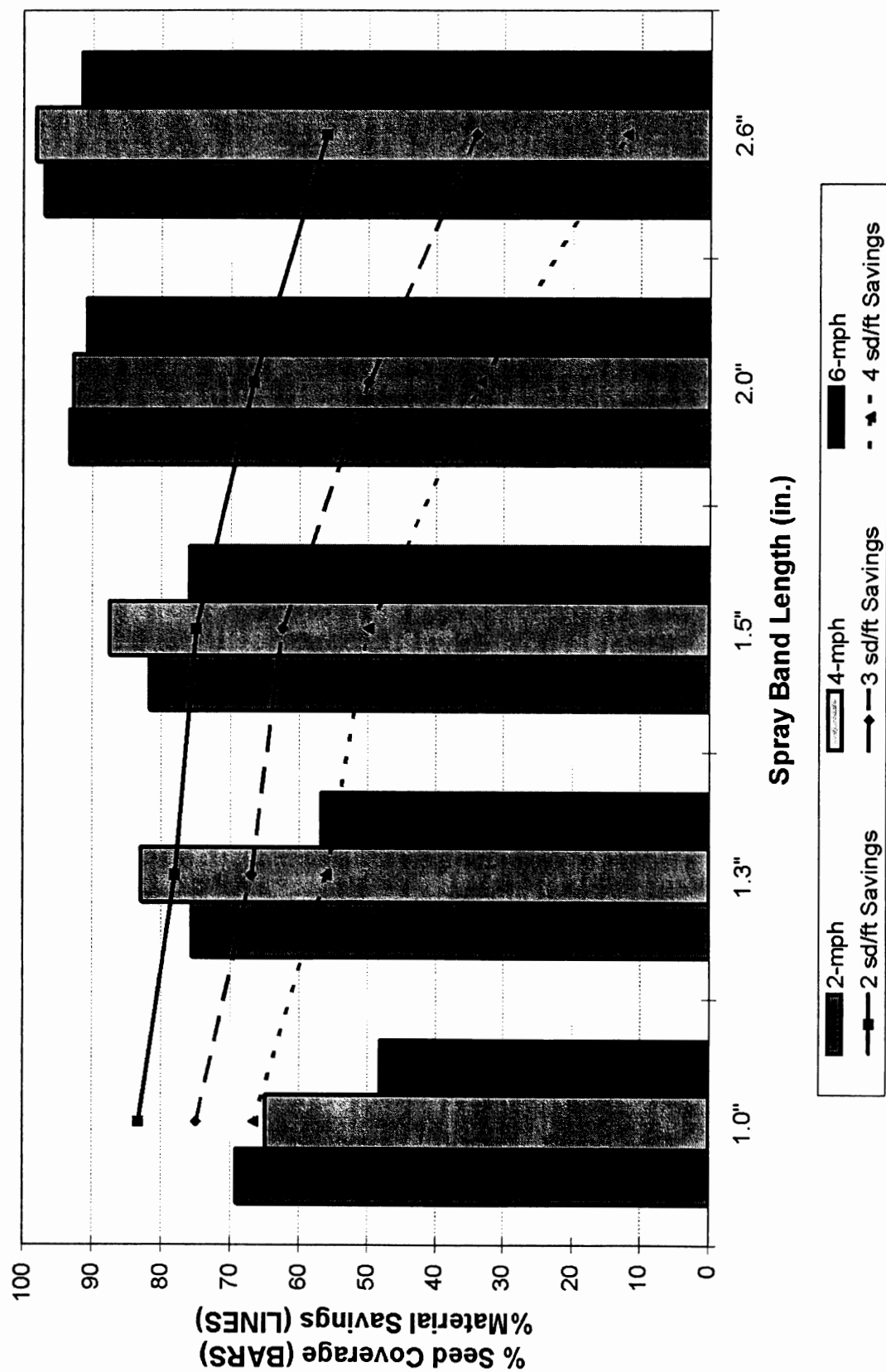


Figure 31. Chart of optimized sprayer accuracy, as a function of spray band length and speed.

spray band length necessary to assure that drop time variability would not affect system accuracy.

Optimization of Spray Band Length

Spray band lengths were optimized by speed, as described in the Data Analysis section of this chapter. Figure 32 illustrates the required spray band length to achieve 85, 90, 95, and 99% seed coverage at each speed. These values actually depend little on seed-specific applicator accuracy. Instead, seed drop-time variability and seed-to-soil interaction effects (i.e., what happens when the seed lands in the furrow) primarily influence these values. In fact, Figure 32 can be explained almost entirely using these two factors.

The required spray band at 4 mph is much shorter than the band required at 2 or 6 mph to deliver identical seed coverage. Initially, this seems to contradict the results shown in the previous section, wherein accuracy at 2 and 4 mph was virtually identical. Additionally, the drop time variability tests suggested that spray bands longer than 0.5 in. would eliminate most drop time variability at 2 mph. This leaves but one other source of variability – seed-to-soil interaction effects.

Field observations suggested that seeds planted at 2 mph often bounced rearward on landing in the furrow. The opposite effect was observed at 6 mph, where seeds seemed to bounce forward (i.e., chasing the planter). Analyzing seed tube shape and seed velocity at the tube outlet, it was discovered that the seed tube imparts a horizontal velocity component of 3.5 to 4 mph on the seed. The resultant seed velocities ($v_x = +v_{\text{planter}} - v_{\text{seed}}$) would be -2 and $+2$ mph at planting speeds of 2 and 6 mph, respectively. Since the seeds have a horizontal velocity component at 2 and 6 mph, conservation of momentum would cause the seeds to bounce forward or backward, just as observed.

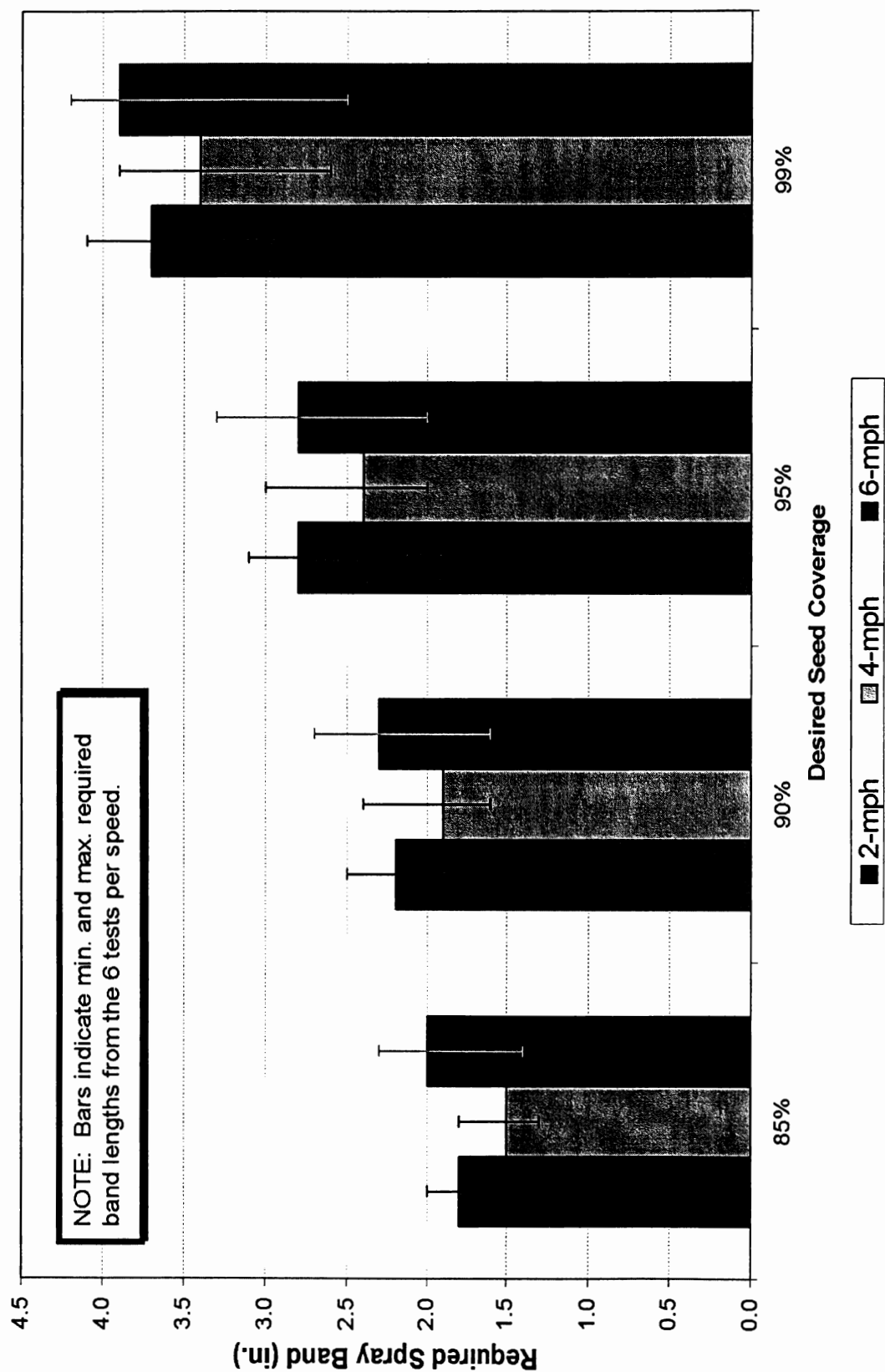


Figure 32. Chart of required spray band length to achieve desired seed coverage at 2, 4, and 6 mph.

Figures 33 to 35 illustrate the seed placement distribution at 2, 4, and 6 mph. These figures further support the findings discussed above. While all three distribution functions approximate the normal curve, the shape varies significantly from speed to speed. The 4-mph distribution (Figure 34) is tall, narrow, and symmetric, with virtually no skew (skew = +0.08). At 2 mph, there are several observations in the -1- to -2-in. region, and the graph is negatively skewed (skew = -0.22). The opposite is true at 6 mph; the +1- to +2-in. region contains many observations, and the overall graph is positively skewed (skew = +0.53). Although drop-time variability was unimportant at 2 and 4 mph, it further increases variability at 6 mph, as reflected in the shorter, wider shape of its placement distribution (Figure 35). This is also reflected in the chart of required band lengths

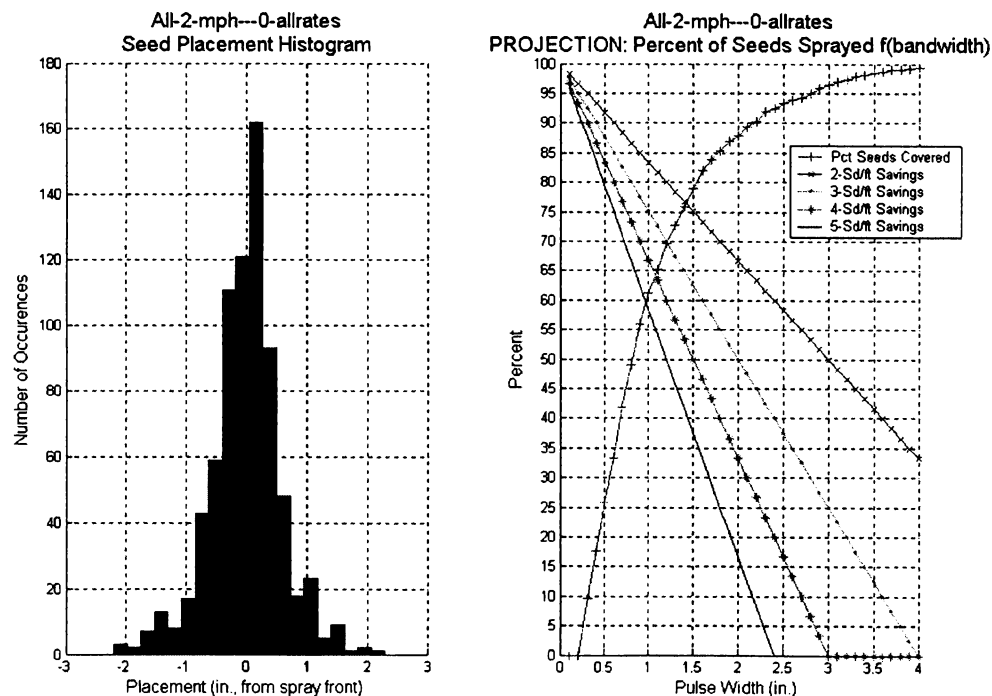


Figure 33. Seed placement distribution for all 2-mph treatments.

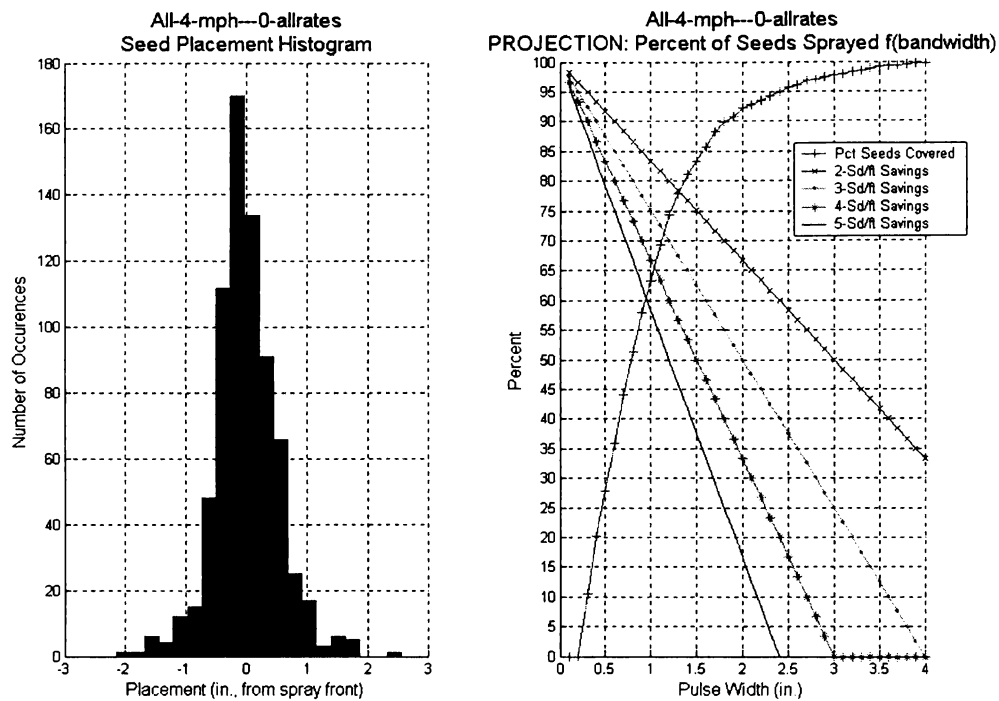


Figure 34. Seed placement distribution for all 4-mph treatments.

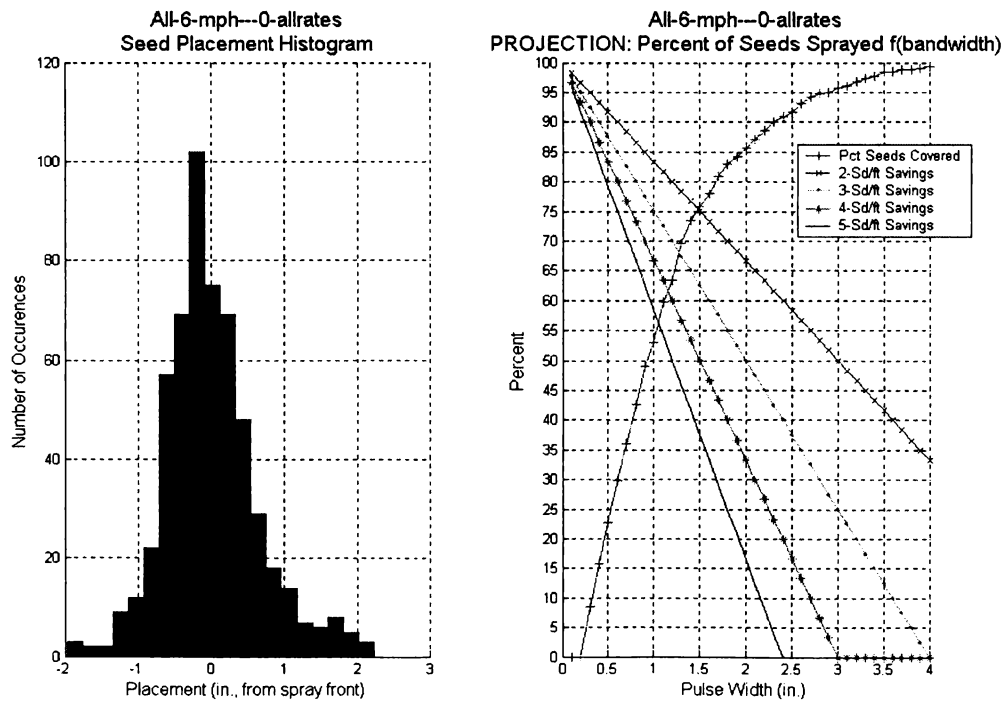


Figure 35. Seed placement distribution for all 6-mph treatments.

(Figure 32), in that seeds planted at 6 mph require the longest spray bands to achieve target seed coverage rates. Even with the variability in seed placement, Figure 32 suggests that a 2-in. spray band would adequately spray 85% of planted seeds, regardless of planter speed.

Figure 36 illustrates the potential for chemical savings (% reduction in chemical) at a planter speed of 4 mph, as a function of seeding rate and target seed coverage. Both seeding rate and target coverage are included because coverage is more important at lower seeding rates. While 85% coverage may be acceptable at 5 seeds/ft, a producer who plants at 2 seeds/ft may demand a higher coverage. Only the 4 mph data is included, because it is the only speed at which the planter is optimized to reduce variability. Redesigning the seed tube to eliminate the resultant horizontal velocity of the seed could optimize required band

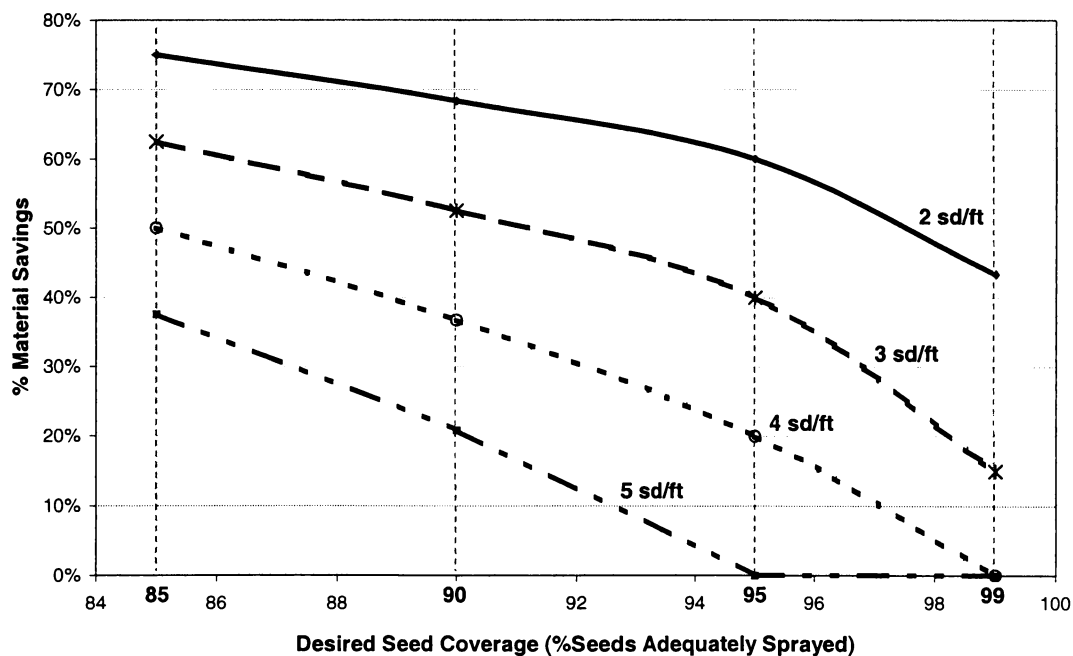


Figure 36. Relationship between target seed coverage (%) and resultant chemical savings (%) at 4 mph.

lengths at 2 or 6 mph. Figure 36 suggests that producers planting at 2 to 4 seeds/ft could realize chemical savings of 68% to 37%, while achieving 90% seed coverage.

Conclusions

The prototype seed-specific applicator met all design criteria relevant to its performance, as listed in the Design Overview. The valve/nozzle assembly provided near instantaneous response, while applying fungicides in an acceptable pattern (see Figure 28). Additionally, the seed tracking circuitry performed as designed, tracking multiple seeds between the seed sensor and high-speed valve without error. Applicator accuracy was impressive, especially at 2 and 4 mph. Field calibration of the delay times produced values within 3.5 ms of the correct value, on average.

Most of the missed seeds resulted from seed drop time variability or seed-to-soil interactions, instead of applicator design flaws. Moving the seed sensor closer to the seed tube outlet should reduce the drop time variability, and new seed tubes designed to minimize the horizontal component of seed velocity should reduce the effects of seed-to-soil interactions. As designed and implemented, a 2-in. spray band would adequately cover 85% of planted seeds at 2 to 6 mph.

Summary of Conclusions

Seed-specific application of liquid fungicide in plots inoculated with *Pythium* and *Rhizoctonia* provided seedling disease protection equivalent to the conventional application method, while reducing fungicide inputs by 50%. At this reduction, the cost of liquid fungicide application would approach that of hopper box treatments, which provided only minimal protection against disease in this test. These results, coupled with those of

Roberts et al. (1998) concerning the seed-specific application of in-furrow insecticides, suggest that seed-specific chemical application has the potential to reduce in-furrow chemical inputs significantly, with little reduction in efficacy.

In testing performance, the seed specific applicator met all objectives relevant to its design. Accuracy was best at 2 and 4 mph, although it also acceptable at 6 mph, provided a ≥ 2.0 -in. spray band was used. Increasing band length resulted in increased accuracy, as expected. Variability in seed drop-times and seed-to-soil interactions occurring as seeds landed in the furrow were the primary causes of missed seeds. Repositioning the seed sensor or redesigning the seed tube could improve performance; however, using the existing design, a properly calibrated system delivering a 2-in. spray band would adequately cover 85% of all seeds over the range of tested speeds and seeding rates.

CHAPTER VI. MULTI-ROW EMBODIMENT OF SYSTEM DESIGN

In field tests, seed-specific application of in-furrow fungicides significantly reduced the amount of chemical required to deliver adequate disease protection. Additionally, the prototype applicator and control system functioned as designed, accurately targeting over 80% of seeds (bands ≥ 2 in.), with most misses resulting from variability introduced by planter components. These results supported both the concept and current implementation of seed-specific application; however, a multi-row control strategy is needed to implement this concept in a production environment. One possible embodiment of a multi-row seed-specific chemical applicator is described below.

Overview of Multi-Row Design

To aid in the development of a multi-row control strategy, several design criteria were identified. First, the system must allow for simple retrofit installation on existing planters, while minimizing the number of required wires and connectors. Next, a new, low-cost user interface is needed for inputting calibration information and providing feedback about the system's status. Additionally, the calibration process (determining delay times) must be automated to eliminate guesswork. Finally, all electronic data communication should be implemented using the agricultural equipment industry's communication standard, as defined by ISO 11783 and SAE J1939.

A block diagram of the proposed multi-row implementation is illustrated in Figure 37. System components include individual row controllers, a mathematical calibration model, a simplified user interface, and a CAN (controller area network) communication bus. A row controller is located on each planter row-unit to implement the seed-tracking and valve actuation functions for that row. The new user interface consists of an LCD screen for user feedback and three selection buttons for entering calibration information. User inputs regarding installation geometry and planting parameters are used in the mathematical model to calculate system delay time. This information is then transmitted to all row controllers via the CAN bus. The high-speed valve, nozzle, and valve mounting are not discussed here, because they remain the same as described in Chapter IV. The other multi-row components are described in detail below.

Row Controller

As described in the Design Overview and as illustrated in Figure 37, row controllers are responsible for implementing all seed-specific functions at the row-level. Each planter row-unit is equipped with one row controller. The device obtains calibration information from the user interface, acquires seed detection signals from the seed sensor, tracks seeds in the tube, and controls the high-speed valve. External electrical connections include the seed sensor, spray valve, CAN bus, and tractor battery (power for all functions).

A variety of electronic devices were required to implement the myriad functions performed within the row controller. These devices are illustrated in electrical schematic shown in Figure 38. Sub-circuits within the row controller include a power supply module, an MCU circuit, a peak-and-hold valve firing circuit, and a CAN communications module.

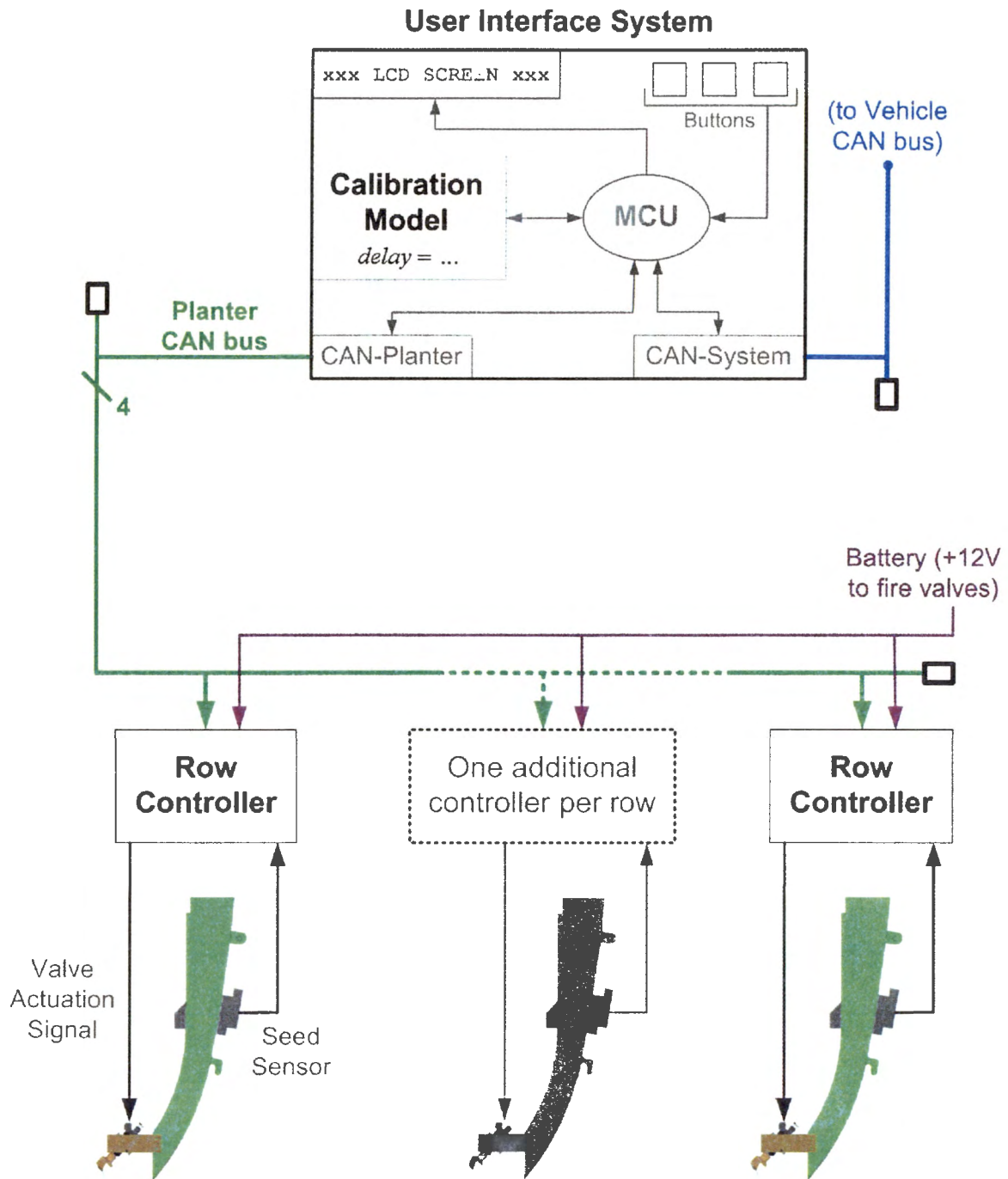


Figure 37. Block diagram of proposed multi-row implementation of the seed-specific applicator concept.

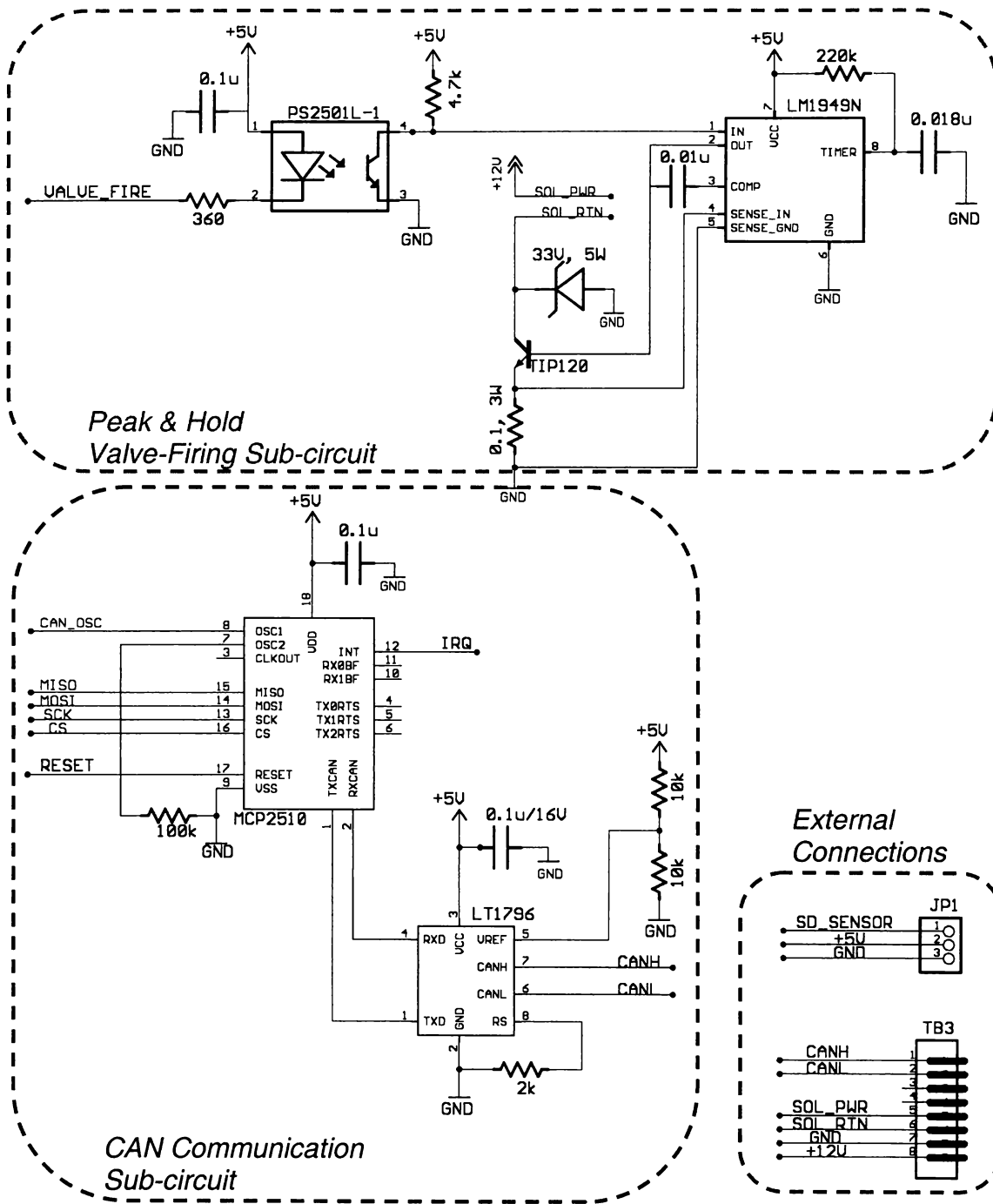


Figure 38. (CONTINUED)

The power supply module regulates battery voltage to +5VDC, which powers all digital components. This circuit consists of a 7805 voltage regulator and several filtering capacitors to smooth the transient voltage spikes caused by the tractor alternator. Additional filtering may be necessary to provide a clean +5VDC voltage supply.

Time-stamping of detected seeds, seed-tracking, valve actuation, and processing of received commands are all functions of the MCU sub-circuit. The central component is a Motorola MC68HC711E9 microcontroller, operating in single-chip mode. An 8-MHz clock (CTX, Part# MX045HS) and low-voltage inhibit circuit (Motorola, Part# MC34064) are also required. The algorithms for seed detection, seed tracking, and valve actuation are the same as previously described; refer to Figure 21 for flowcharts of these algorithms. Communication between the CAN controller and MCU is accomplished via the MCU's 4-wire, serial peripheral interface (SPI) at 500 kHz. MCU interrupts are generated when the CAN controller receives messages requiring action by the MCU (i.e., adjust delay time, adjust pulse width, power off, etc.).

The peak-and-hold valve firing circuit controls the high currents required to actuate the high-speed valve. An optoisolator (NEC, Part# PS2501) provides electrical isolation between the digital and high voltage components, while an injector driver chip (National Semiconductor, Part# LM1949) and power Darlington transistor (Fairchild Semiconductor, Part# TIP120) actually control the current to the valve. This sub-circuit is identical to the one described in Chapter 4.

Communication between the user interface and the row controllers is accomplished using a CAN bus, as described by SAE J1939. The CAN communication sub-circuit consists of a CAN controller (Microchip Technology, Part# MCP2510), interfaced to the

MCU via SPI, and a CAN transceiver (Linear Technology, Part# LT1796), which serves as the interface between each row node and the CAN bus. These components are discussed more fully in the “CAN Communication Bus” section of this chapter.

A prototype row controller was fabricated in the UT Sensors and Controls Lab. Row controller components were split between two small boards (1.75 in. x 2.25 in.), such that all high voltage components (power supply and valve-actuation circuits) were located on one board, with all digital components located on the other board. Both boards are shown in Figure 39, along with a photo of what the finished row controller might resemble

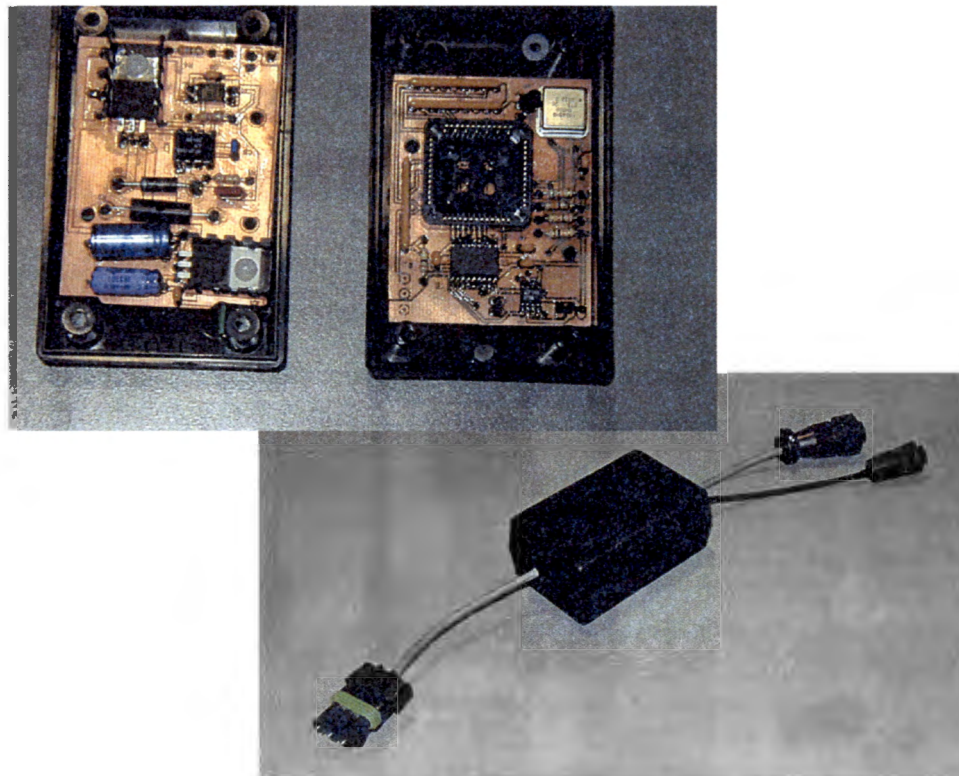


Figure 39. Fabricated row controller boards, and a pictorial representation of a finished row controller assembly.

User Interface

The primary design goal for this subsystem was to eliminate the laptop that served as a user interface in the prototype seed-specific applicator. The new interface consists of a 2-line by 20-character LCD screen and three push-buttons for entering calibration information. Two buttons function as UP/DOWN selectors, while the third button 'enters' information, or cycles thru the different calibration/feedback screens. Although this method of entering information is more cumbersome than the laptop-based system, cost-savings are significant.

Several additional functions are implemented within the user interface system, as shown in Figure 37. Similar to the row controller, a Motorola MC68HC711E9 microcontroller serves as the brains of the user interface. However, this MCU operates in expanded mode, with calibration information for different planter models stored in an external 8-kB EEPROM memory chip. The user interface MCU will interface with both the planter CAN bus and the vehicle CAN bus so that it can obtain real-time speed information from other sensors within the vehicle.

The calibration model (discussed later) is also programmed within the MCU. This allows the user to enter calibration information, such as planter make/model, speed, seed type, seed variety, etc. With this information entered, the calibration model can look up appropriate model coefficients or values, such that the system delay time (time between seed detection and valve actuation) can be accurately calculated. Correct delay times are then sent to the row controllers via the planter CAN bus.

The user interface should also provide feedback to the operator about the applicator's status. Specifically, it should notify the operator if any row controller is

malfunctioning, or if the sprayer runs out of chemical. This is a particular problem because dry-firing the valves repeatedly at high speeds could result in overheating and failure.

System Calibration Model

Accuracy of the seed-specific sprayer depends largely upon proper calibration, which involves determining system delay time (time from seed detection to valve actuation) and spray pulse width values (length of the spray pulse, in time units). Ideally, the system delay time should be set such that spray bands are centered about the seeds, on average. In the prototype one-row sprayer, these values were determined by trial and error. While this method of calibration produced reasonable values, determining the optimum value was virtually impossible, because delay time is a function of many variables. Planter speed, spray band length, seed drop time, and installation geometry of the spray valve are but a few of the variables that influence delay. To eliminate the guesswork associated with delay time calibration, a theoretical model was developed to predict system delay as a function of planter operating characteristics and valve installation geometry.

Development

The delay calibration model was developed using a kinematic analysis of the seed drop event. A cross-section of a seed tube is shown in Figure 40, with variables relevant to the delay time calculation labeled in yellow. Several assumptions were made to simplify the analysis. First, instantaneous valve response is assumed, meaning the valve instantly opens to full flow when the actuation signal is received. Literature suggests this valve is actually 1 to 3 ms for the selected injector. Next, the time required for the liquid spray to reach the ground is also assumed to be zero. Additionally, the seed is assumed to fall along

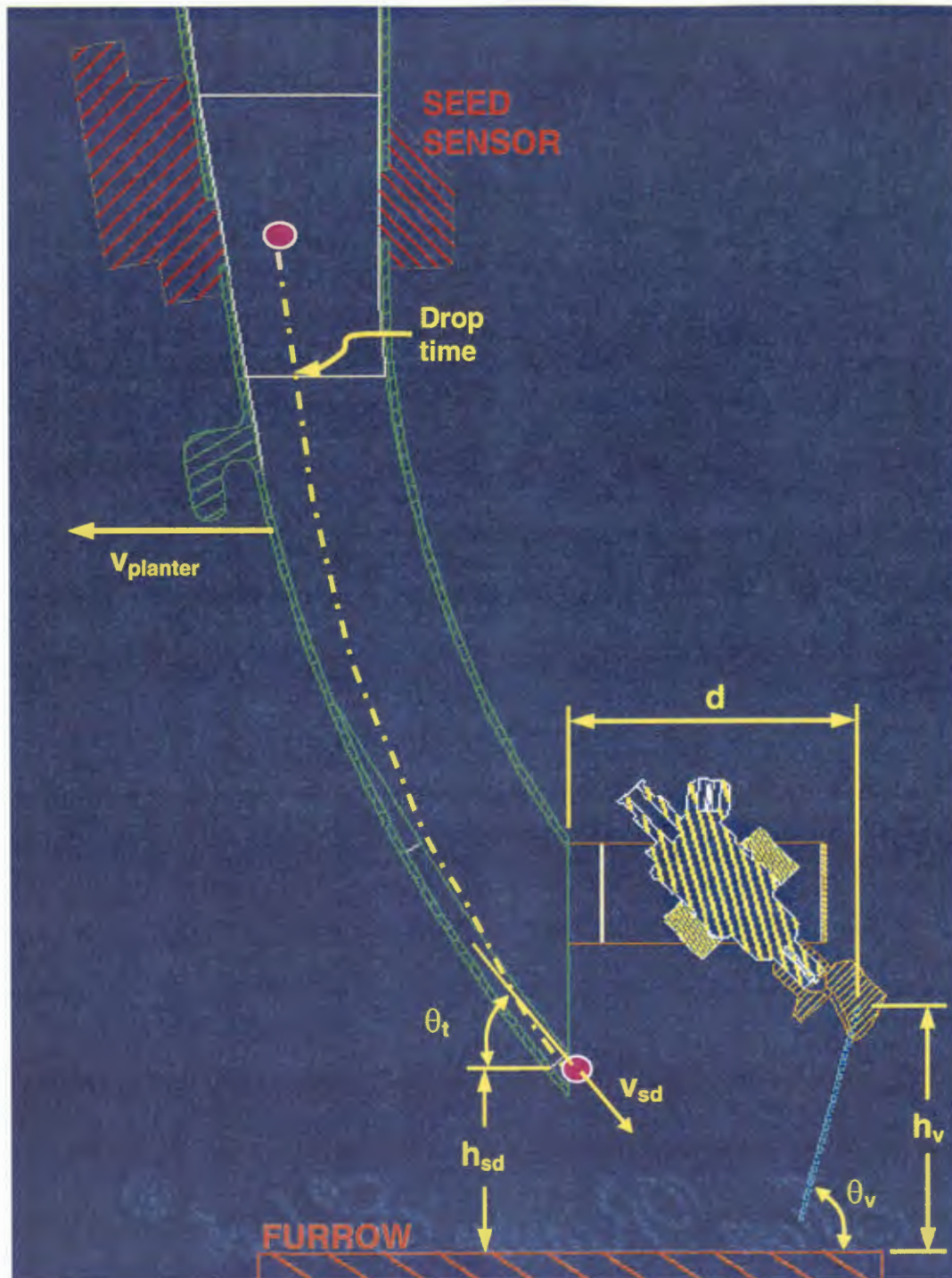


Figure 40. Model variables defining valve installation geometry and planter operating characteristics.

the bottom of the seed tube, such that the direction of the seed's velocity on exiting the tube is tangential to the seed tube bottom (θ_t).

The model was developed by mathematically describing the horizontal (x-direction, measured along the furrow, where $x=0$ at the tube outlet when the seed exits the tube) positions of the seed tube outlet, the seed, and the spray valve at three points in time: (1) seed passes sensor, (2) seed exits the tube, and (3) seed lands in the furrow. Positions are described in terms of the Figure 40 variables using the equations of projectile motion.

Between events (1) and (2), the seed moves as part of the seed tube, so projectile motion theory does not apply. Instead, the *time* between events 1 and 2 is described by the seed dwell time, as previously measured in Chapter 3. This value is assumed constant for a particular seed tube and seed type/variety (i.e., DP409-BGRR cotton). Standard drop times for all seed tubes and seed types of interest would be measured in the laboratory, and programmed into the MCU's calibration routine as a lookup routine (i.e., 'lookup' seed drop time as $f(\text{seed tube, seed type})$).

Event 2 is the position reference for all location calculations. At this instant, the seed tube and seed are both located at $x=0$. The time between events 2 and 3 is calculated using projectile equations as shown in Equation 6-1, assuming that the seed has initial velocity, v_{sd} , in direction, θ_t , and that gravity is the only external force affecting the seed.

$$t_{fall} = \frac{v_{sd} * \sin \theta_t - \sqrt{(v_{sd} * \sin \theta_t)^2 + 2 * a_g * h_{sd}}}{-a_g} \quad (6-1)$$

Next, the x-coordinate where the seed will impact the furrow is calculated, as shown in Equation 6-2. The x-coordinate where the spray band hits the furrow at any time, t , is

calculated as shown in Equation 6-3. The spray valve should start delivering fluid one-half of the desired spray band length in front of where the seed will actually land. Therefore, delay time is calculated by substituting Equations 6-2 and 6-3 into Equation 6-4, and solving for time, t . The resulting mathematical model for predicting delay time is labeled Equation 6-5 below.

$$x_{SD_LANDS} = (v_p - v_{sd} * \cos \theta_t) * t_{fall} \quad (6-2)$$

$$x_{SPRAY} = v_p * t - d + \frac{h_v}{\tan \theta_v} \quad (6-3)$$

$$x_{SPRAY_DESIRED} = x_{SD_LANDS} - \frac{1}{2} * band \quad (6-4)$$

$$Delay = t_{dwell} + t_{fall} - \frac{v_{sd} * \cos \theta_t * t_{fall}}{v_p} + \frac{d}{v_p} - \frac{band}{2 * v_p} - \frac{h_v}{v_p * \tan \theta_v} \quad (6-5)$$

Model Validation

The theoretical calibration model was validated using optimized delay times from the tests evaluating seed-specific applicator accuracy. Optimized delay times were calculated as described in “Chapter V, Evaluation of Applicator Performance – Test Procedures.” Table 7 contains the optimized delay times as a function of planter speed and spray band length. The calibration model shown in Equation 6-5 was used to calculate predicted delay times based on the valve installation geometry used in the field tests. These values are summarized as follows: $v_{sd} = 102.8$ in./s (measured in the lab), $\theta_t = 52.5^\circ$, $\theta_v = 80.0^\circ$, $d = 4.35$ in., $h_v = 2.2$ in., $h_{sd} = 2.0$ in., and $t_{drop} = 98$ ms.

In general, the predicted delay times were very close to the optimized values. However, predicted values were consistently 3.5 ms larger than optimized values at all

speeds and band lengths. The consistency associated with the error suggests some variable may have been inadvertently omitted from the model. Specifically, instantaneous valve response and instantaneous fluid delivery were assumed in developing the model. Literature (SAE, 1989) suggests that injector response ranges from 1 to 3 ms. Neglecting valve response would tend to inflate predicted delay times, because it assumes the fluid is delivered exactly when the actuation signal is emitted. A constant offset of -3.5 ms was added to the calibration model shown in Equation 6-5 to adjust for the model assumptions. Model-predicted delay times are included in Table 7, and Figure 41 graphically illustrates the predicted and observed delay times.

The adjusted calibration model accurately predicted delay times over the range of operating planter speeds and spray bands. Error between the observed and predicted values ranged from -3.8 ms to 1.9 ms, with an average error of -0.2 ms. For example, at 4 mph the positional error would be -0.02 to 0.04 in. The model accurately captures the

Table 7. Optimized and model-predicted delay times.

v_{planter} (mph)	Spray Band (in.)	Optimized Delay (ms)	Model-predicted Delay (ms)	Timing Error (ms)	Positional Error (in.)
2	1.00	173.7	172.8	0.9	0.032
2	1.50	164.5	165.7	-1.2	-0.042
2	2.00	155.7	158.6	-2.9	-0.102
2	2.64	145.7	149.5	-3.8	-0.134
4	1.00	144.8	144.3	0.5	0.035
4	1.50	140.4	140.7	-0.3	-0.021
4	2.00	137.6	137.2	0.4	0.028
4	2.64	133.0	132.6	0.4	0.028
6	1.00	136.7	134.8	1.9	0.201
6	1.50	132.8	132.4	0.4	0.042
6	2.00	129.9	130.0	-0.1	-0.011
6	2.64	127.8	127.0	0.8	0.084

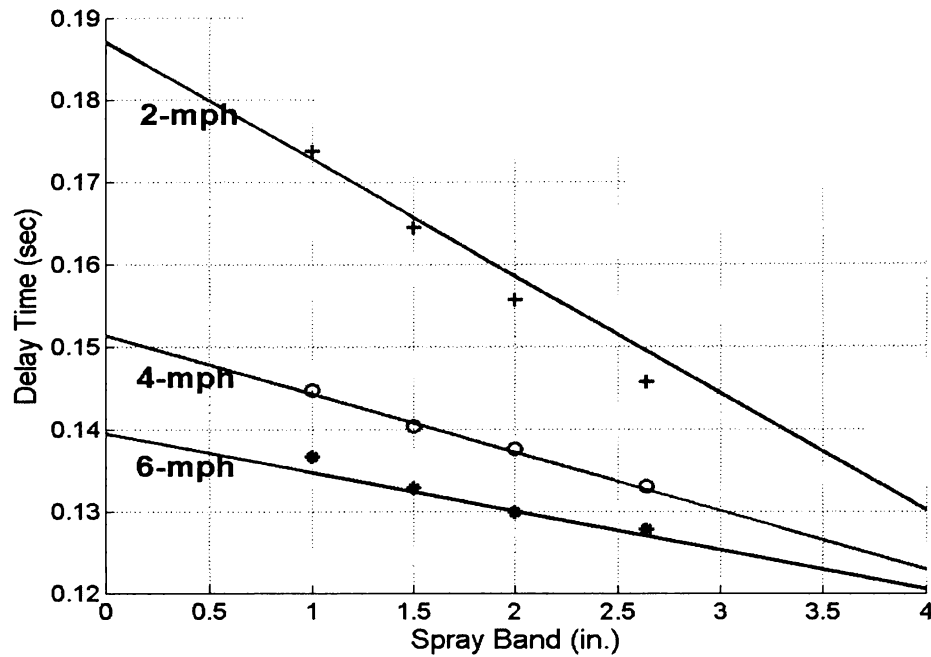


Figure 41. Accuracy of the calibration model in predicting delay time at 2, 4, and 6 mph, with theoretical model predictions shown as lines.

relationship between valve installation geometry and delay time; however, additional testing is needed with other valve installation geometries (i.e., change the variables d , h_v , and θ_v) to verify that the model is accurate across the range of possible valve installations.

This calibration model is implemented in the user interface MCU. During calibration, the planter operator is prompted for information about 1) planter make, 2) planter model, 3) seed tube type, 4) seed type, 5) seed variety, 6) planting speed, etc. The menus are organized such that each subsequent menu is adjusted based on the previous answer. For example, under the ‘Planter Make’ menu, options would include <Case IH>, <Great Plains>, <John Deere>, <Kinze>, and <Monosem>. Selecting <John Deere> would result in a ‘Planter Model’ menu with the following options: <7100>, <7200>, <1700>, etc. Based on the operator’s selections, the MCU looks up the proper parameter values and

solves the calibration model. This delay is then communicated to all row controllers via the CAN communication bus.

CAN Communication Bus

A CAN (Controller Area Network) data communication bus was implemented in the multi-row seed-specific applicator to facilitate data exchanges between the user interface and row controllers. This communication protocol is recognized as the industry standard for agricultural equipment, as defined by SAE J1939 (2000). The J1939/12 physical layer (Baker et al., 1994) is a 250kbps serial bus consisting of a twisted quad (four conductors twisted together) transmission line. Only two of the lines (CANH and CANL) make connections along the bus, with the other two included for shielding and network termination at the bus ends. Each ECU (electronic control unit) on the CAN network has a unique identifier, which determines the priority of messages transmitted by that ECU. The format of a standard CAN message is as follows: identifier (11 or 29 bit), data length code (# bytes in the data field), data field (0 to 8 bytes), CRC field, and End-of-Frame field, with various other control bits scattered throughout.

SAE J1939 (2000), based on CAN 2.0b (Bosch, 1991), utilizes Extended Data Frames (29-bit identifier) and assigns a 64-bit NAME that allows each ECU node to be uniquely identified. While this complexity is necessary within the context of a complete vehicle, a much simpler naming scheme is sufficient and desirable within the planter subnetwork. To minimize the processing load on the row controller MCUs, a non-J1939 CAN, utilizing Standard Data Frames (11-bit identifiers) was implemented on the planter. The user interface MCU functions as a bridge node between the J1939 vehicle CAN and

the non-J1939 planter CAN. Using this network topology, the user interface can capture relevant information (such as speed) on the vehicle bus, calculate an updated delay time using the calibration model, and transmit this value to row controllers on the planter CAN.

All nodes within the planter bus include an identical CAN communication sub-circuit, as shown in Figure 38. The primary components of this circuit are the CAN controller (Microchip Technology, Part# MCP2510) and the CAN transceiver (Linear Technology, Part# LT1796). Messages, consisting of the node identifier, data length code (# data bytes to be sent) and data bytes, are constructed in the MCU, and then serially transferred to the CAN controller via Motorola's SPI interface. Once the message is loaded in the controller, it translates the message into the proper CAN format. The CAN transceiver serves as the physical connection between the CAN bus and the CAN controller, providing the high currents necessary to drive signals on the bus.

The primary factor influencing CAN controller selection was the availability of an SPI interface. This 4-line interface – master-in-slave-out (MISO), master-out-slave-in (MOSI), serial clock, and chip select (CS) – significantly reduced the number of connections between the MCU and CAN controller. A parallel CAN controller has 44-pins, where the Microchip device only has 18-pins. More importantly, using a parallel chip would have required operating the MCU in expanded-mode (ports B and C become multiplexed address/data bus), which would have added even more chips and complexity to the row controller design.

As previously stated, the planter CAN does not adhere to J1939 standards regarding node addressing and naming. Instead, the 11-bit identifier is used to uniquely identify each row controller, such that the user interface node can determine which node is transmitting

based on the message identifier. The left-most row-unit (looking in the direction of travel) is assigned 'Row #1', with the right-most row-unit named 'Row #N', where N=the number of planter row-units. The five, least significant bits of the row controller identifier (ID bits [4:0]) correspond to the number of the row-unit on which it is installed. Identifier bit5 designates each node as either a user interface (0) or a row controller (1). Identifier bits[11:6] are the same for all nodes within the planter CAN bus (11011).

Row controller identifiers are dynamically configurable, so that each row controller can be assigned an identifier that corresponds to its position along the planter. When each row controller is first powered up, it dynamically claims the first available unused identifier, starting at [xxxxxx00000]. Installing the row controllers in order ensures that the captured ID will correspond to the row position.

Relatively few messages are needed on the planter CAN. Six messages are defined from the user interface, with the first byte of new serving as the 'command' byte. These message are summarized in Table 8. Messages from the row controller would consist a single byte. Only one message is defined for the row controller. It consists of a single data

Table 8. CAN message transmitted by user interface to row controllers.

Message	DLC	Data1	Data2	Data3	Data4	Data5
Turn off valve	2	0x00	Row Controller ID, or 0xFF for all			
Turn on valve	2	0x01	Row Controller ID, or 0xFF for all			
Update PW	3	0x02	PulseH	PulseL	-	-
Update Delay	3	0x04	DelayH	DelayL	-	-
Set spray parameters	5	0x06	DelayH	DelayL	PulseH	PulseL
Reset Row IDs	1	0xF0	-	-	-	-

byte, with each bit corresponding to a status flag, such as 'row controller state' (on/off), 'fluid flowing in valve?' (yes/no), 'valve opening correctly?' (yes/no), etc.

Summary of Multi-Row Embodiment of Seed-Specific Applicator

A conceptual design for a multi-row seed-specific applicator has been developed. Shortcomings associated with the prototype one-row applicator have been addressed. Design improvements included in the multi-row design include the following: a row controller that tracks seeds and actuates the high-speed valve; a simplified, low-cost user interface, providing feedback about system status and an interface for calibrating the system; a mathematical model to calculate system delay time based on planter speed, spray band length, and planter specific variables; and a robust CAN bus facilitating communications between the row controllers and user interface.

No improvements were made to either the valve/nozzle assembly or its mounting at the seed tube outlet. Ideally, the nozzle holder will be incorporated into the design of a new, injection-molded seed tube to rigidly fix valve placement and simplify installation. Additional MCU programming is required to fully implement the CAN and user interface routines. The multi-row design will be tested in Spring 2003 to evaluate the performance of system components.

CHAPTER VII. SUMMARY AND CONCLUSIONS

Summary

A seed-specific applicator that applies pulses of liquid chemical spray to individual seeds at planting has been developed, prototyped, and tested. This system utilized an opto-electronic seed sensor, MCU-based seed tracking algorithm, and high-speed fluid valve. Seeds were detected in the seed tube, tracked from the point of detection to the point of chemical application, and then sprayed with a pulse of liquid chemical as they landed in the furrow.

The tracking algorithm assumed that seed drop-times (time between the points of detection and chemical application) were consistent from seed to seed. Variability in these times was evaluated in both laboratory and field environments to determine the effect on tracking accuracy. In the laboratory, cotton variety influenced drop-time, with observed times for 16 varieties ranging from 104 to 108 ms ($\sigma = 2.7$ to 4.4 ms). Planter speed influenced drop-time variability in field evaluations, with standard deviations increasing from 3.8 to 5.4 ms with increasing speed. These results suggest that the spray pulse width must be set to some minimal length to ensure that drop time variability would not affect seed coverage.

Field evaluation of the prototype seed-specific applicator included both biological and accuracy components. The biological concept of seed-specific fungicide application was evaluated in field tests conducted at a producer's farm in Jackson, TN. Eight fungicidal treatments were tested to determine whether fungicides applied seed-specifically

provided equivalent protection to those applied in a continuous band. The seed-specific treatments consisted of liquid fungicides applied in two-inch bands, centered about each seed, with two inches of untreated soil (on average) between the bands. Plots were inoculated with *Rhizoctonia* and *Pythium* to ensure disease pressure. Stands averaged less than one viable cotton plant per five row-feet in the untreated check. Statistically, there was no difference between conventional and seed-specific application. At 41 DAP, seed-specific treatments averaged 10.7 and 13.4 plants per 10 ft, while conventional treatments averaged 13.0 and 10.2 plants per 10 ft (TSX at 48 and 64 oz/ac, respectively).

Applicator accuracy was evaluated over a range of planting speeds, seeding rates, and spray band lengths to assess how it might perform under actual planting conditions. Accuracy increased with spray band length, and ranged from 71-98%, 70-96%, and 55-90%, at 2, 4, and 6 mph, respectively. By adjusting the applicator's calibration to the correct value, it was found that a spray band length of 2-in. would adequately cover over 85% of planted seeds, over the range of test conditions. Most missed seeds resulted from seed drop-time variability or seed-to-soil interactions.

Testing results supported both the concept and current implementation of seed-specific application. To proceed with testing on a larger scale, a conceptual design for a multi-row seed-specific applicator has been developed. The multi-row design addressed shortcomings of the prototype unit, adding a mathematical model to automatically calculate system delay time and a simplified, cost-efficient user interface for user feedback and calibration. All seed-tracking and valve actuation functions were incorporated into a row controller. Each planter row unit will be equipped with a row controller, with a CAN bus facilitating communications between the row controllers and user interface.

Conclusions

Testing performed during this study included laboratory and field evaluations of seed fall time variability, an evaluation of the concept of seed-specific application, and an evaluation of the prototype applicator's accuracy. Results of these tests led to the following conclusions:

- Seed-specific placement of in-furrow fungicides (placing the chemical in a small zone around the seed) reduced chemical inputs by 50% while providing protection equivalent to the conventional application method.
- The MCU-based seed tracking algorithm successfully tracked multiple, irregularly-spaced seeds.
- Based on standard seed sensor placement, sufficient time exists for a control system to actuate a solenoid valve after acquiring a pulse from the sensor.
- Variability in seed drop-times was small, but it did affect the accuracy of the seed-specific applicator, particularly at faster planting speeds.
- Field calibration of the system delay times was accurate within 3.5 ms on average, and the theoretical calibration model will automate this process.
- The prototype seed-specific applicator could adequately cover over 85% of planted seeds with a 2-in. spray band, over the range of test conditions.
- A multi-row seed-specific applicator has been designed with few modifications to the prototype single row unit.

Recommendations

System Refinements

The prototype seed-specific applicator functioned as designed, accurately spraying a large percentage of planted seeds. Still, there is considerable room for improvement.

System refinements to improve performance and function are discussed below.

The major causes of missed seeds were seed drop-time variability and seed-to-soil interactions occurring as the seed landed in the furrow (i.e., bounce). To reduce drop-time variability, the seed sensor should be moved closer to the seed tube outlet, such that there is less time for seed-to-tube interactions. Minimizing seed bounce as the seed lands in the furrow is a more complicated problem. As discussed in “Chapter V, Evaluation of Applicator Accuracy – Results,” seed bounce is caused by the horizontal component of the seed’s velocity with respect to ground. Since most producers operate at a constant speed, new seed tubes could be designed for a specific speed, such that the horizontal component of seed velocity is minimized. For example the ‘6-mph seed tube’ would have an outlet angle that produces a horizontal seed velocity of 6 mph. Both of these changes – repositioning the seed sensor and new, speed-specific seed tubes – would require a new, injection mold for the tube, but could be incorporated at the same time. A valve holder should also be incorporated into the seed tube design to ensure proper valve placement.

A new, corrosion-resistant valve is also needed to replace the fuel injectors that are currently used to deliver chemicals. While the fuel injector’s response time is exceptional, the wettable components of the valve are mild steel. Nightly valve cleanup and lubrication was required to keep the fuel injector from rusting shut. Additionally, the injector’s rubber

seals were non-compatible with xylene, a carrier often present in EC (emulsifiable concentrate) agricultural chemicals. A new valve that combines fast response and corrosion resistance with xylene-compatibility is needed to improve valve life.

Additional error-checking should be implemented in the row controllers so that the operator is alerted when a valve malfunctions. Specifically, the following conditions should produce an operator warning: (1) valve fails to open when actuation pulse is delivered; (2) valve is clogged; and (3) fluid lines are empty, causing valves to dry fire. All three conditions require operator attention to correct or prevent problems. Possible solutions could include flow sensors, temperature sensors on the valves (temperature increases when fired dry), or signal processing of the electrical power signal to the valve.

The final design refinement relates to the row controller MCU and CAN communications sub-circuit. A new microcontroller should be selected that includes a CAN module as an on-chip peripheral. Possible Motorola MCUs include the MC68HC908AZ32A, the MC68HC908AZ60A and the MC68HC912D60A. Significant cost savings should be realized due to reduce number of components, reduced number of electrical connections, and simplified board design. Savings of four dollars per row controller would be realized in chips alone (an integrated MCU/CAN for \$6 versus an \$8 MCU and \$2 CAN chip). Additionally, the CPU burden to maintain the on-chip CAN would be much less than that to maintain a stand-alone CAN chip via SPI.

Additional Testing

Additional testing is necessary to further validate the seed-specific concept. The biological evaluation was limited to a single year, single location, and single seed type.

Additional fungicide tests are needed to validate the initial results. Tests should also be expanded to include in-furrow cotton and corn insecticides. The potential for chemical savings is much higher in corn because the seeds are placed much further apart. Extensive testing with all in-furrow inputs (fungicides, insecticides, starter fertilizers) is needed to determine the potential benefits of seed-specific application in other areas.

Future testing with the seed-specific applicator should utilize the calibration model discussed in Chapter VI. This theoretical model was adjusted based on one year's data (determination of the 3.5 ms offset), and must be validated in an actual planting environment to assess system accuracy.

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APPENDICES

Appendix A. Mechanical Drawings

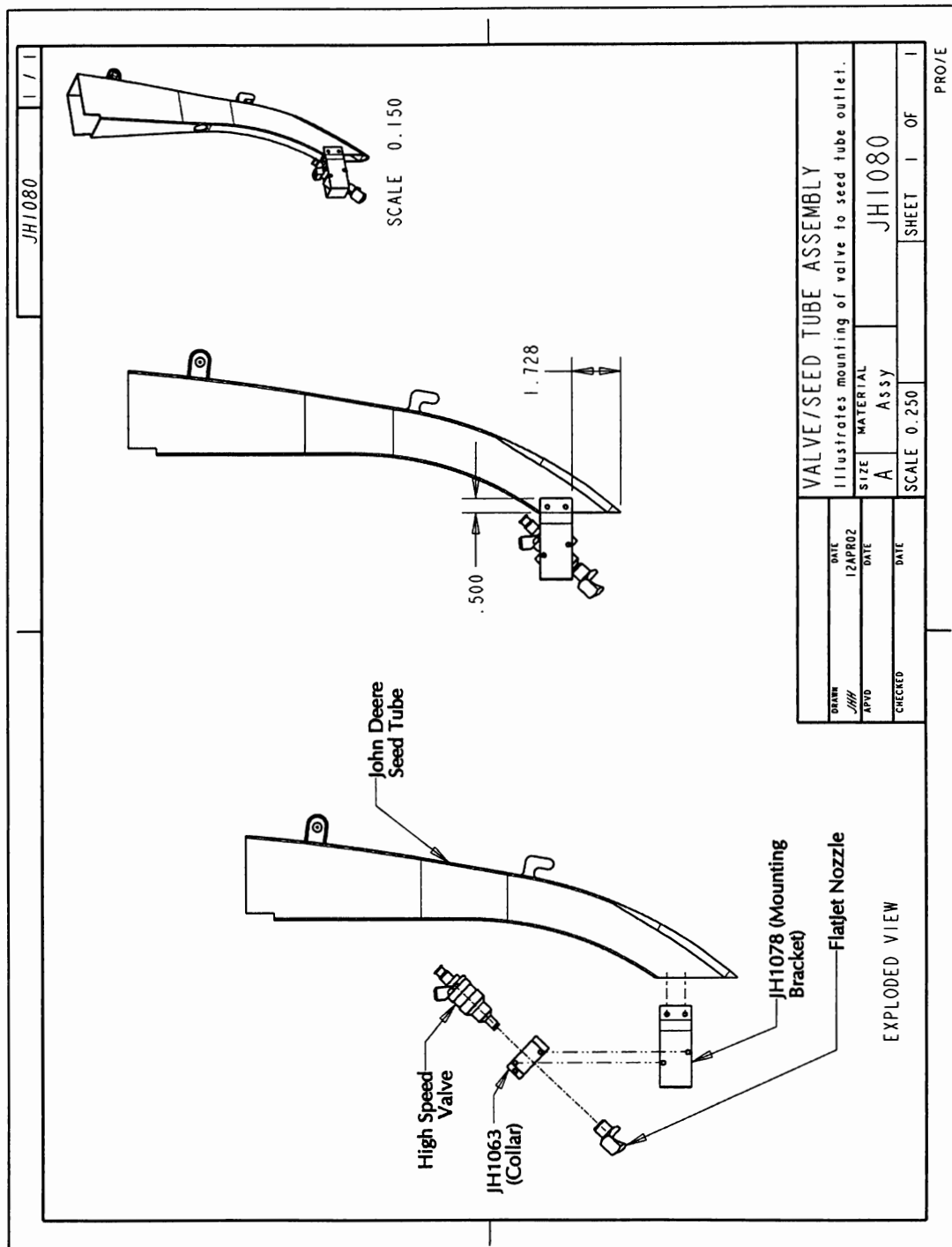


Figure A1. Valve Mounting, Assembly Drawing.

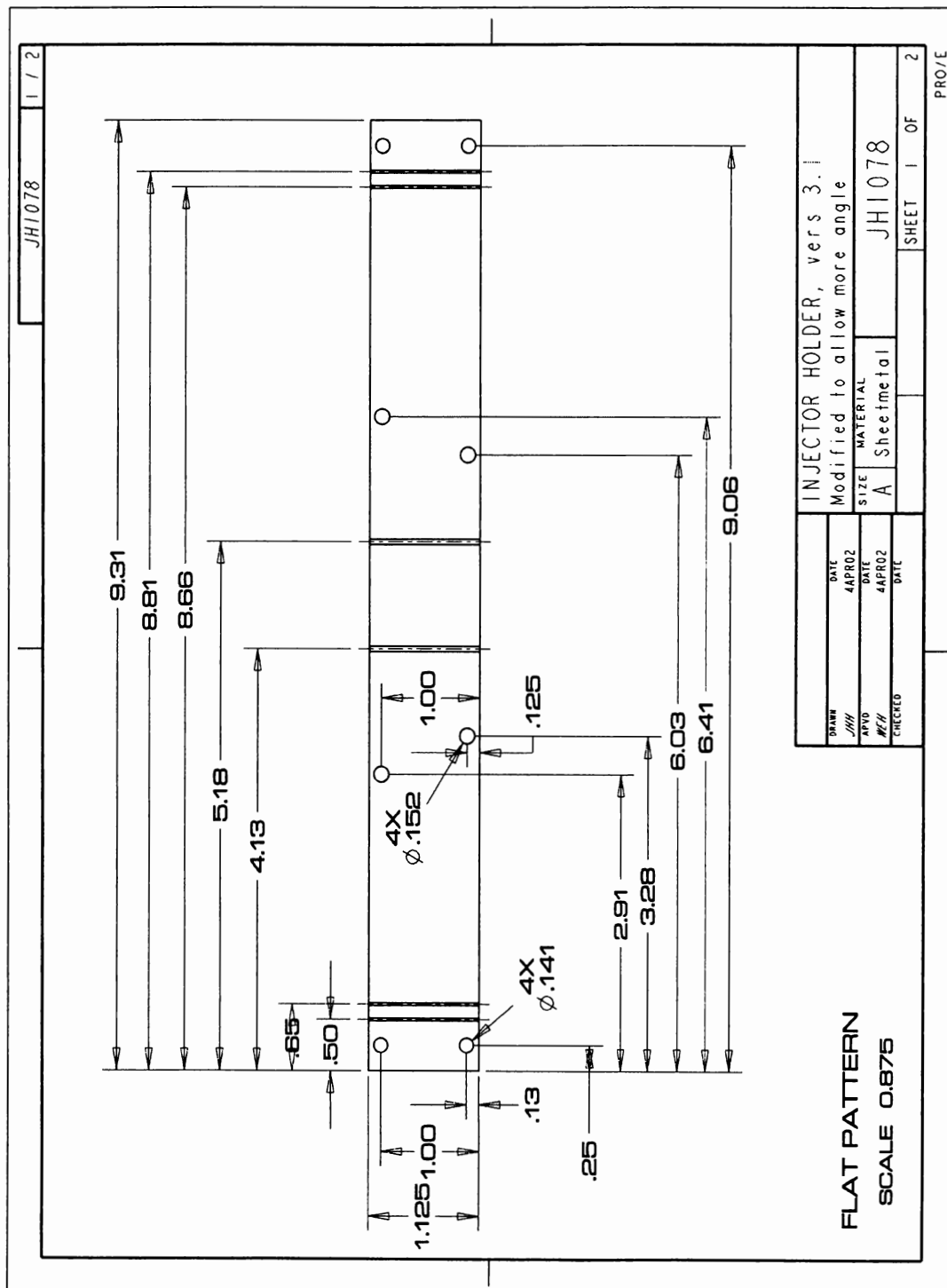


Figure A2. Valve Mounting Bracket Drawing (FLAT Pattern).

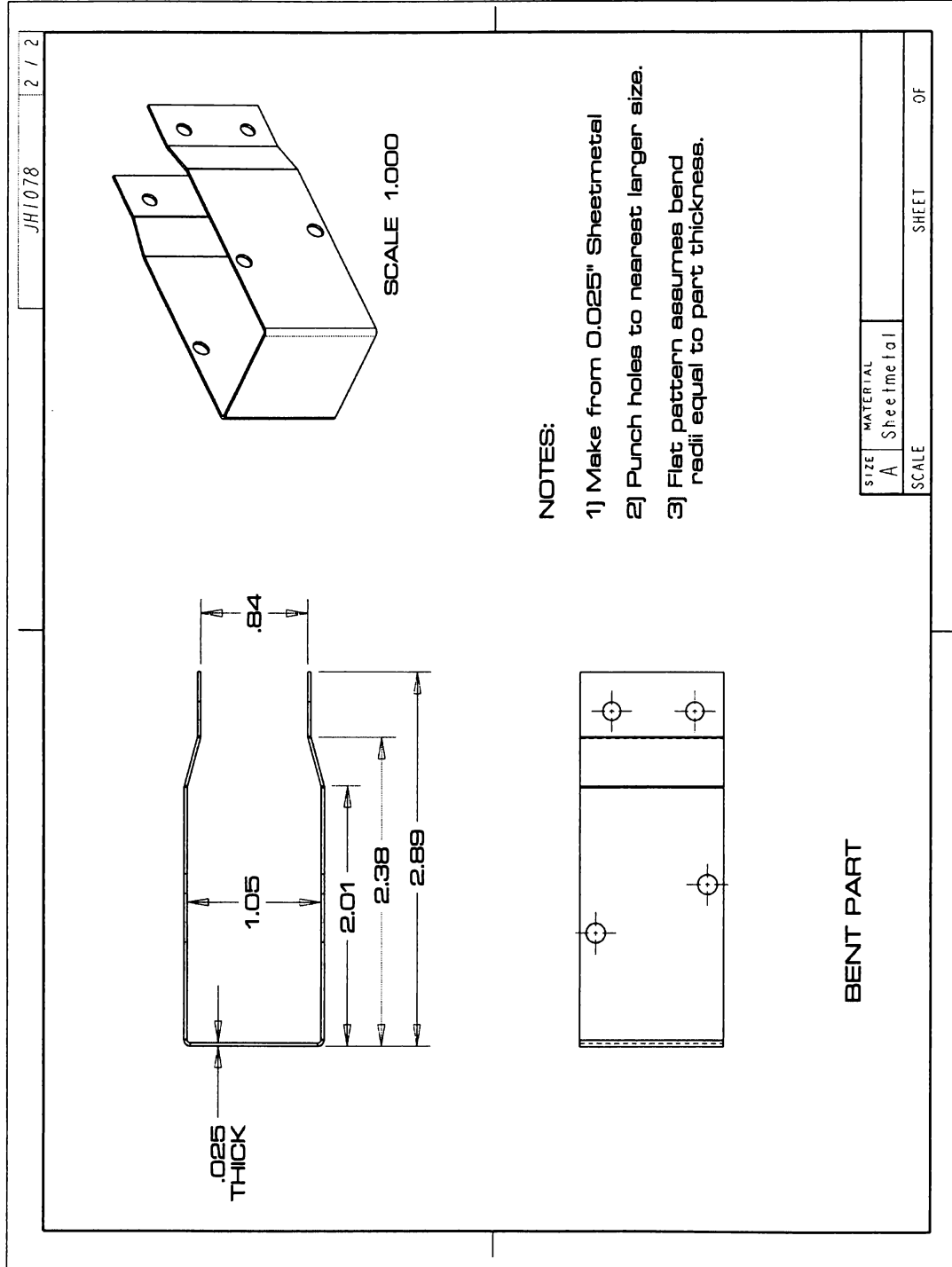
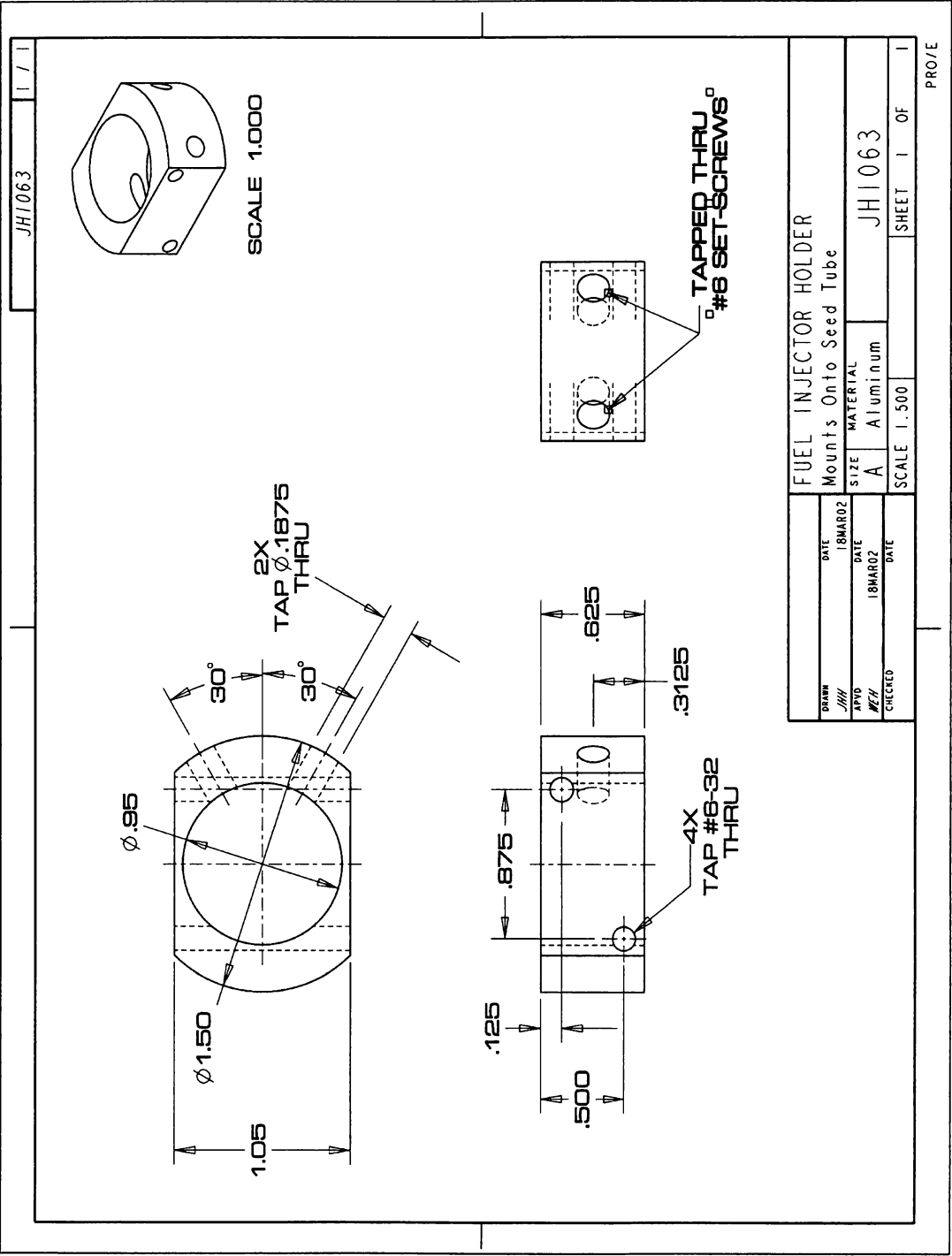


Figure A3. Valve Mounting Bracket Drawing (BENT Part, JH1078).



Microcontroller Specifications (Motorola, MC68HC11E9)

SECTION 1 INTRODUCTION

This document contains a detailed description of the M68HC11 E series of 8-bit microcontroller units (MCUs). These MCUs all combine the M68HC11 CPU with high-performance, on-chip peripherals. The E series is comprised of many devices with various configurations of RAM, ROM or EPROM, and EEPROM. Several low-voltage devices are also available. With the exception of a few minor differences, the operation of all E-series MCUs is identical. A fully static design and high-density complementary metal-oxide semiconductor (HCMOS) fabrication process allow E-series devices to operate at frequencies from 3 MHz to dc, with very low power consumption.

1.1 Features

- M68HC11 CPU
- Power Saving STOP and WAIT Modes
- Low-Voltage Devices Available (3.0 – 5.5 Vdc or 2.7 – 5.5 Vdc)
- 0, 256, 512, or 768 Bytes of On-Chip RAM, Data Retained During Standby
- 0, 12, or 20 Kbytes of On-Chip ROM or EPROM
- 0, 512, or 2048 Bytes of On-Chip EEPROM with Block Protect for Security
 - 2048 bytes of EEPROM with selectable base address in MC68HC811E2
- Asynchronous Nonreturn to Zero (NRZ) Serial Communications Interface (SCI)
 - Additional Baud Rates Available on MC68HC(7)11E20
- Synchronous Serial Peripheral Interface (SPI)
- 8-Channel 8-Bit Analog-to-Digital (A/D) Converter
- 16-Bit Timer System
 - Three Input Capture (IC) Channels
 - Four Output Compare (OC) Channels
 - One Additional Channel, Selectable as Fourth IC or Fifth OC
- 8-Bit Pulse Accumulator
- Real-Time Interrupt Circuit
- Computer Operating Properly (COP) Watchdog System
- 38 General-Purpose Input/Output (I/O) Pins
 - 16 Bidirectional I/O Pins
 - 11 Input-Only Pins
 - 11 Output-Only Pins
- Several Packaging Options
 - 52-Pin Plastic Leaded Chip Carrier (PLCC)
 - 52-Pin Windowed Ceramic Leaded Chip Carrier (CLCC)
 - 52-Pin Plastic Thin Quad Flat Pack, 10 mm X 10 mm (TQFP)
 - 64-Pin Plastic Quad Flat Pack (QFP)
 - 48-Pin Plastic Dual In-Line Package (DIP), MC68HC811E2 only
 - 56-Pin Plastic Dual In-Line Package, .070" Lead Spacing (SDIP)

1

Microcontroller Specifications (continued):

1.2 Structure

Below is the functional diagram of the E-series MCUs. Differences among devices are noted in the table.

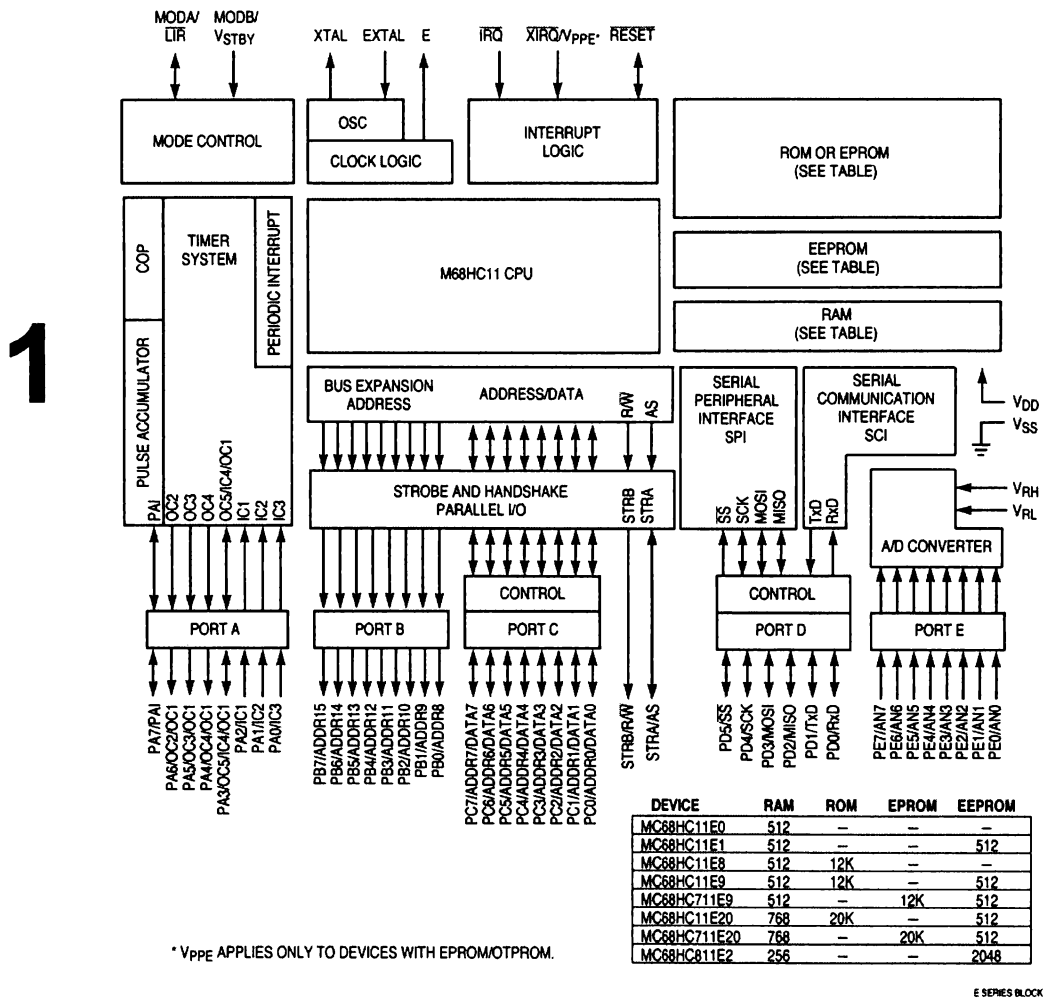


Figure 1-1 M68HC11 E-Series Block Diagram

SECTION 2 PIN DESCRIPTIONS

M68HC11 E-series MCUs are available packaged in 52-pin PLCC, 52-pin windowed CLCC, 64-pin QFP, 52-pin thin QFP, 56-pin SDIP, and 48-pin DIP (MC68HC811E2 only). Most pins on these MCUs serve two or more functions, as described in the following paragraphs. Refer to **Figure 2-1**, **Figure 2-2**, **Figure 2-3**, **Figure 2-4**, and **Figure 2-5**, which show the M68HC11 E-series pin assignments for the PLCC/CLCC, QFP, and DIP packages.

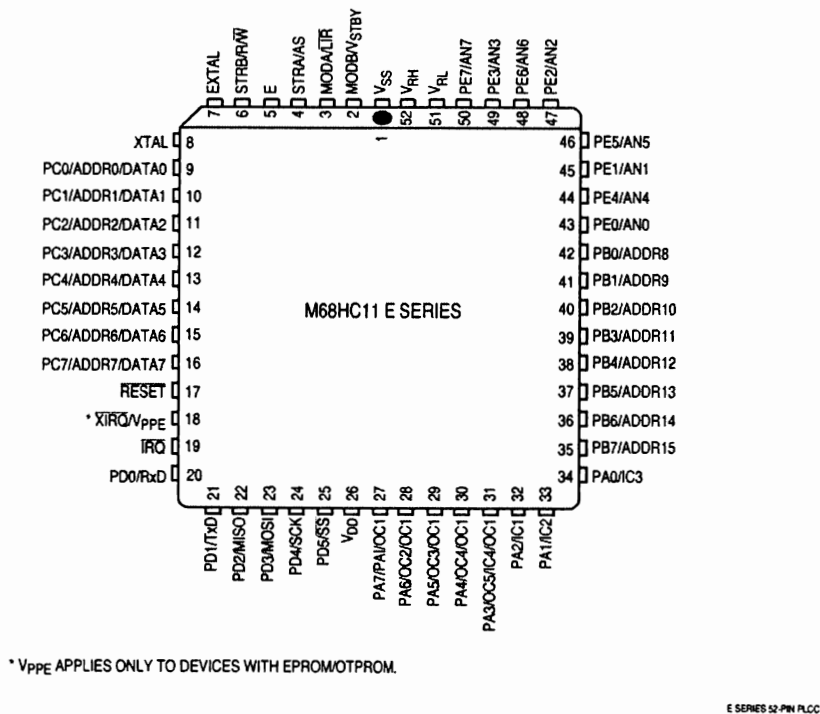


Figure 2-1 Pin Assignments for 52-Pin PLCC and CLCC

Peak-and-Hold Driver Specifications (National Semiconductor, LM1949)



February 1995

LM1949 Injector Drive Controller

LM1949 Injector Drive Controller

General Description

The LM1949 linear integrated circuit serves as an excellent control of fuel injector drive circuitry in modern automotive systems. The IC is designed to control an external power NPN Darlington transistor that drives the high current injector solenoid. The current required to open a solenoid is several times greater than the current necessary to merely hold it open; therefore, the LM1949, by directly sensing the actual solenoid current, initially saturates the driver until the "peak" injector current is four times that of the idle or "holding" current (Figure 3-*Figure 7*). This guarantees opening of the injector. The current is then automatically reduced to the sufficient holding level for the duration of the input pulse. In this way, the total power consumed by the system is dramatically reduced. Also, a higher degree of correlation of fuel to the input voltage pulse (or duty cycle) is achieved, since opening and closing delays of the solenoid will be reduced.

Normally powered from a $5V \pm 10\%$ supply, the IC is typically operable over the entire temperature range (-55°C to $+125^{\circ}\text{C}$ ambient) with supplies as low as 3 volts. This is particularly useful under "cold crank" conditions when the battery voltage may drop low enough to deregulate the 5-volt power supply.

The LM1949 is available in the plastic miniDIP, (contact factory for other package options).

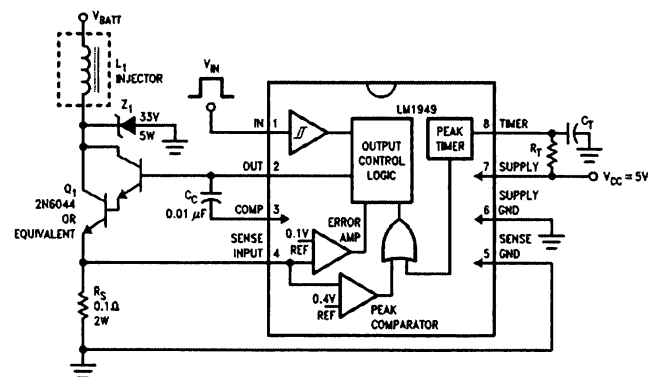
Features

- Low voltage supply (3V–5.5V)
- 22 mA output drive current
- No RFI radiation
- Adaptable to all injector current levels
- Highly accurate operation
- TTL/CMOS compatible input logic levels
- Short circuit protection
- High impedance input
- Externally set holding current, I_H
- Internally set peak current ($4 \times I_H$)
- Externally set time-out
- Can be modified for full switching operation
- Available in plastic 8-pin minDIP

Applications

- Fuel injection
- Throttle body injection
- Solenoid controls
- Air and fluid valves
- DC motor drives

Typical Application Circuit



Order Number LM1949M or LM1949N
See NS Package Number M08A or N08E

FIGURE 1. Typical Application and Test Circuit

Peak-and-Hold Injector Driver Specifications (continued):

LM1949

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

Supply Voltage	8V
Power Dissipation (Note 2)	1235 mW

Input Voltage Range	-0.3V to V_{CC}
Operating Temperature Range	-40°C to +125°C
Storage Temperature Range	-65°C to +150°C
Junction Temperature	150°C
Lead Temp. (Soldering 10 sec.)	260°C

Electrical Characteristics

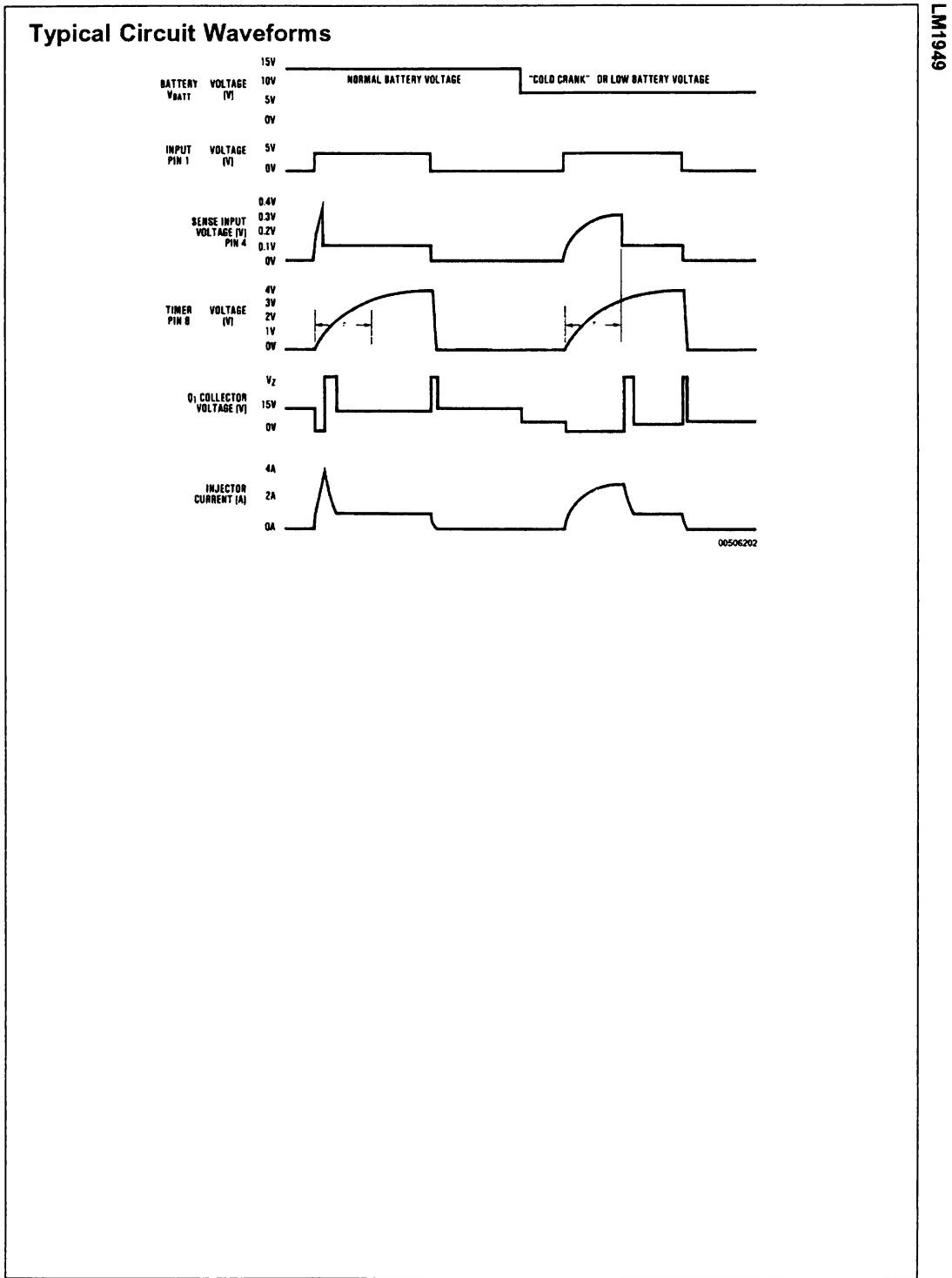
($V_{CC} = 5.5V$, $V_{IN} = 2.4V$, $T_J = 25^\circ C$, Figure 1, unless otherwise specified.)

Symbol	Parameter	Conditions	Min	Typ	Max	Units
I_{CC}	Supply Current					
	Off	$V_{IN} = 0V$		11	23	mA
	Peak	Pin 8 = 0V		28	54	mA
	Hold	Pin 8 Open		16	26	mA
V_{OH}	Input On Level	$V_{CC} = 5.5V$		1.4	2.4	V
		$V_{CC} = 3.0V$		1.2	1.6	V
V_{OL}	Input Off Level	$V_{CC} = 5.5V$	1.0	1.35		V
		$V_{CC} = 3.0V$	0.7	1.15		V
I_B	Input Current		-25	3	+25	μA
I_{OP}	Output Current					
	Peak	Pin 8 = 0V	-10	-22		mA
	Hold	Pin 8 Open	-1.5	-5		mA
V_S	Output Saturation Voltage	10 mA, $V_{IN} = 0V$		0.2	0.4	V
V_P	Sense Input					
	Peak Threshold	$V_{CC} = 4.75V$	350	386	415	mV
V_H	Hold Reference		88	94	102	mV
t	Time-out, t	$t + R_T C_T$	90	100	110	%

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur.

Note 2: For operation in ambient temperatures above 25°C, the device must be derated based on a 150°C maximum junction temperature and a thermal resistance of 100°C/W junction to ambient.

Peak-and-Hold Injector Driver Specifications (continued):



CAN Controller Chip Specifications (Microchip, MCP2510)



MCP2510

Stand-Alone CAN Controller with SPI® Interface

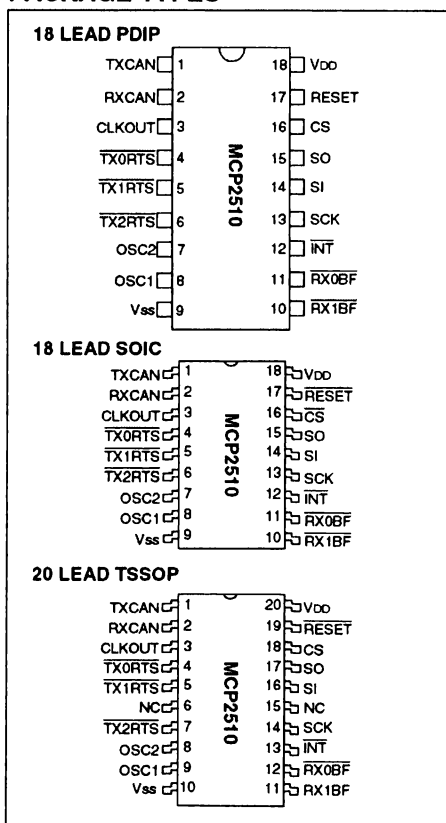
FEATURES

- Implements Full CAN V2.0A and V2.0B at 1 Mb/s
 - 0 - 8 byte message length
 - Standard and extended data frames
 - Programmable bit rate up to 1 Mb/s
 - Support for remote frames
 - Two receive buffers with prioritized message storage
 - Six full acceptance filters
 - Two full acceptance filter masks
 - Three transmit buffers with prioritization and abort features
 - Loop-back mode for self test operation
- Hardware Features
 - High Speed SPI Interface (5 MHz at 4.5V I temp)
 - Supports SPI modes 0,0 and 1,1
 - Clock out pin with programmable prescaler
 - Interrupt output pin with selectable enables
 - 'Buffer full' output pins configureable as interrupt pins for each receive buffer or as general purpose digital outputs
 - 'Request to Send' input pins configureable as control pins to request immediate message transmission for each transmit buffer or as general purpose digital inputs
 - Low Power Sleep mode
- Low power CMOS technology
 - Operates from 3.0V to 5.5V
 - 5 mA active current typical
 - 10 μ A standby current typical at 5.5V
- 18-pin PDIP/SOIC and 20-pin TSSOP packages
- Temperature ranges supported:
 - Industrial (I): -40°C to +85°C
 - Extended (E): -40°C to +125°C

DESCRIPTION

The Microchip Technology Inc. MCP2510 is a Full Controller Area Network (CAN) protocol controller implementing CAN specification V2.0 A/B. It supports CAN 1.2, CAN 2.0A, CAN 2.0B Passive, and CAN 2.0B Active versions of the protocol, and is capable of transmitting and receiving standard and extended messages. It is also capable of both acceptance filtering and message management. It includes three transmit buffers and two receive buffers that reduce the amount of microcontroller (MCU) management required. The MCU communication is implemented via an industry standard Serial Peripheral Interface (SPI) with data rates up to 5Mb/s.

PACKAGE TYPES



SPI is a registered trademark of Motorola Inc.

MCP2510

1.0 DEVICE FUNCTIONALITY

1.1 Overview

The MCP2510 is a stand-alone CAN controller developed to simplify applications that require interfacing with a CAN bus. A simple block diagram of the MCP2510 is shown in Figure 1-1. The device consists of three main blocks:

1. the CAN protocol engine,
2. the control logic and SRAM registers that are used to configure the device and its operation, and
3. the SPI protocol block.

A typical system implementation using the device is shown in Figure 1-2.

The CAN protocol engine handles all functions for receiving and transmitting messages on the bus. Messages are transmitted by first loading the appropriate message buffer and control registers. Transmission is initiated by using control register bits, via the SPI interface, or by using the transmit enable pins. Status and errors can be checked by reading the appropriate registers. Any message detected on the CAN bus is

checked for errors and then matched against the user defined filters to see if it should be moved into one of the two receive buffers.

The MCU interfaces to the device via the SPI interface. Writing to and reading from all registers is done using standard SPI read and write commands.

Interrupt pins are provided to allow greater system flexibility. There is one multi-purpose interrupt pin as well as specific interrupt pins for each of the receive registers that can be used to indicate when a valid message has been received and loaded into one of the receive buffers. Use of the specific interrupt pins is optional, and the general purpose interrupt pin as well as status registers (accessed via the SPI interface) can also be used to determine when a valid message has been received.

There are also three pins available to initiate immediate transmission of a message that has been loaded into one of the three transmit registers. Use of these pins is optional and initiating message transmission can also be done by utilizing control registers accessed via the SPI interface.

Table 1-1 gives a complete list of all of the pins on the MCP2510.

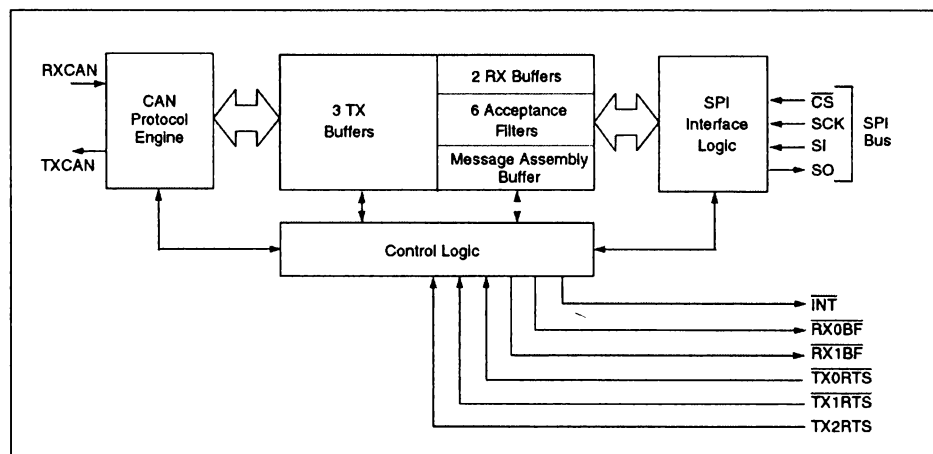


FIGURE 1-1: Block Diagram

CAN Controller Chip Specifications (continued):

MCP2510

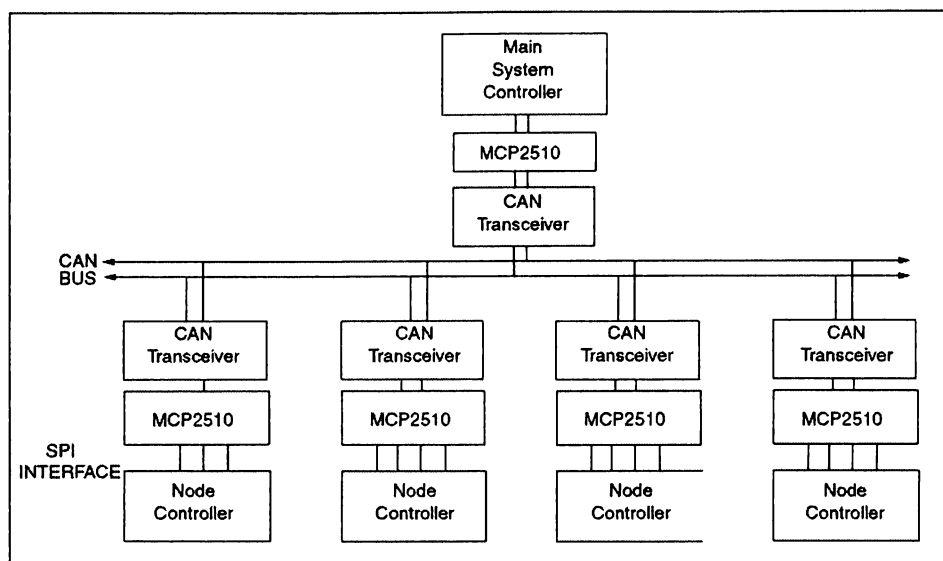


FIGURE 1-2: Typical System Implementation

Name	DIP/ SOIC Pin #	TSSOP Pin #	I/O/P Type	Description
TXCAN	1	1	O	Transmit output pin to CAN bus
RXCAN	2	2	I	Receive input pin from CAN bus
CLKOUT	3	3	O	Clock output pin with programmable prescaler
TX0RTS	4	4	I	Transmit buffer TXB0 request to send or general purpose digital input. -100K
TX1RTS	5	5	I	Transmit buffer TXB1 request to send or general purpose digital input. -100K
TX2RTS	6	7	I	Transmit buffer TXB2 request to send or general purpose digital input. -100K
OSC2	7	8	O	Oscillator output
OSC1	8	9	I	Oscillator input
V _{SS}	9	10	P	Ground reference for logic and I/O pins
RX1BF	10	11	O	Receive buffer RXB1 interrupt pin or general purpose digital output
RX0BF	11	12	O	Receive buffer RXB0 interrupt pin or general purpose digital output
INT	12	13	O	Interrupt output pin
SCK	13	14	I	Clock input pin for SPI interface
SI	14	16	I	Data input pin for SPI interface
SO	15	17	O	Data output pin for SPI interface
CS	16	18	I	Chip select input pin for SPI interface
RESET	17	19	I	Active low device reset input
V _{DD}	18	20	P	Positive supply for logic and I/O pins
NC	—	6,15	—	No internal connection

Note: Type Identification: I=Input; O=Output; P=Power

TABLE 1-1: Pin Descriptions

Appendix C. Microcontroller Programs

EXHIBIT E

Assembly Program for Prototype Seed-Specific Applicator

```

*-----
*UT Agricultural Engineering:  Sensors & Controls Lab
*Written by:  John Hancock
*SECOND MODIFICATION:  29 August 2002
*FIRST MODIFCATION:  8 August 2002;
*ORGINALLY WRITTEN: 28 February 2002
*
*This third version functions identical to v2.0, with one exception - instead of
*the main routine determining which TCNT to load into OC1, this function is
*integrated into the OC1 service routine so that it automatically loads the next
*buffer value into TOC1... if the buffer is currently empty (i.e., no seed waiting
*to be sprayed), the OC1_ISR set the BufEmptyF flag and loads TOC1 with a value of
*'current 'TCNT+10-ms' so that in 10-ms the program will check to see if anything
*has appeared in the buffer.
*
*This is the second version of the MCU implementation of the precision
*fungicide placement program. The main revision is that this version replaces
*the continuous testing of values in the main routine of the initial version;
*an additional OC channel implements this functionality in this version. Like
*the original version, this program interfaces with a laptop for initialization on
*RESET, provided that a switch connected to pin PE1 is on. Otherwise, the program
*uses the information from the last calibration, and starts looking for seeds to
*spray. CPU registers are mapped to 0x0000, as is the system RAM. The TCNT pre-
*scalar is set to 16, providing a rollover period of 524-ms.
*
*Pin connections for this program are as follows:
*   PA1 - IC2 (Seed sensor signal)
*   PA6 - OC2 (Opto-iosolator output)
*   PE1 - Calibration request (on RESET only)
*
*-----
***** Define Registers in memory
BASE    EQU    $1000 ;Register Base address immmed. after RESET; changed to $0000 by INIT
reg.
PRTA    EQU    $00   ;Port A data register
PIOC    EQU    $02   ;Parallel I/O control register
PRTC    EQU    $03   ;Port C data register
PRTB    EQU    $04   ;Port B data register
PRTD    EQU    $08   ;Port D data register
DDRD    EQU    $09   ;Port D data direction register
PRTE    EQU    $0A   ;Port E data register
OC1M    EQU    $0C   ;Output compare #1 mask register
OC1D    EQU    $0D   ;Output compare #1 data register
TCNT    EQU    $0E   ;Free running counter (16-bit)
TIC1    EQU    $10   ;latches TCNT on IC1 interrupt
TIC2    EQU    $12
TIC3    EQU    $14
TOC1    EQU    $16   ;interrupt will occur when TCNT = TOC1
TOC2    EQU    $18
TOC3    EQU    $1A
TOC4    EQU    $1C
TIC4    EQU    $1E   ;latches TCNT on IC4 interrupt
TCTL1   EQU    $20   ;output capture functions
TCTL2   EQU    $21   ;input capture functions
TMSK1   EQU    $22   ;Timer interrupt masks (OC's amd IC's)
TFLG1   EQU    $23   ;Timer flags (IC's and OC's)
TMSK2   EQU    $24   ;Timer interrupt masks (RTI & overflows)
TFLG2   EQU    $25   ;Timer flags (RTI, accumulator, & overflows)
PACTL   EQU    $26   ;Pulse Accumulator control register
PACNT   EQU    $27   ;Pulse Accumulator count register
SPCR    EQU    $28   ;Serial peripheral control register
SPSR    EQU    $29   ;Serial peripheral status register
SPDR    EQU    $2A   ;Serial peripheral data register

```

```

BAUD    EQU    $2B    ;Baud rate register
SCCR1   EQU    $2C    ;Serial comm. control register 1
SCCR2   EQU    $2D    ;Serial comm. control register 2
SCSR    EQU    $2E    ;Serial comm. status register
SCDR    EQU    $2F    ;Serial comm. data register
BPROT   EQU    $35    ;Block Protect register
OPTION  EQU    $39    ;System configuration register
PPROG   EQU    $3B    ;EEPROM Programming Control Register
INIT    EQU    $3D    ;RAM and I/O mapping register (high nib = RAM)

```

```

***** IC/OC Pins, flags, & mask bits
OC1     EQU    $80    ;mask for bit7 (OC1) of PORTA, TFLG1, & TMSK1
OC2     EQU    $40    ;mask for bit6 (OC2) of PORTA
OC3     EQU    $20    ;mask for bit5 (OC3) of PORTA
OC4     EQU    $10    ;mask for bit4 (OC4) of PORTA
IC1     EQU    $04    ;mask for bit2 (IC1) of PORTA
IC2     EQU    $02    ;mask for bit1 (IC2) of PORTA
IC3     EQU    $01    ;mask for bit0 (IC3) of PORTA
IC4     EQU    $08    ;mask for bit3 (IC4) of PORTA

```

* _____ Key ASCII characters _____

```

RETRN   EQU    $0D
LF       EQU    $0A
NULL    EQU    $00

```

* _____ Definition of RAM variables: _____

```

                ORG    $0040
CRLPF   RMB     1      ;CRLLOOP flag, 0=do not send, 1=send
charctr RMB     1      ;counter to see how many characters are entered at prompt
charexp RMB     1      ;indicates number of expected characters for any message
ErrrF   RMB     1      ;Error capturing incoming text flag
Interm  RMB     2      ;intermediate result for math ops
FailF   RMB     1      ;Failed First Test flag (0 = passed, 1 = failed)
MemNxt  RMB     2      ;address of where to store TCNT on next IC2 interrupt
offset  RMB     2      ; TCNT +/- offset to create comparison window
SeedBuf RMB     48     ;allocate 24, 2-byte spots to seed tracking
SeedEnd RMB     2      ;last seed tracking location, TOTAL of 20 seeds

PWans   RMB     3      ;Pulse Width answer from user (3-digit decimal expected)
        FCB     $00    ;ASCII nullspace
TbDans  RMB     3      ;Tube Delay answer from user (3-digit decimal expected)
        FCB     $00    ;ASCII nullspace
VlPans  RMB     3      ;Valve Placement answer from user (3-digit decimal expected)
        FCB     $00    ;ASCII nullspace
SpdAns  RMB     1      ;Answer to speed in MPH
        FCB     $00

NextOne RMB     2      ;holds the value of when valve should come on the next time
BufEmpF RMB     1      ;flag (0= on last OC1 interrupt, TOC loaded w/ value from buffer;
                        ;      1 = buffer empty on last interrupt, so TOC loaded w/ x-ms)
TOCRpt  RMB     2      ;TOC repeat interval when mem. buf empty (no seeds awaiting spray)
                        ;      TOCRpt = AdjDel / 2
OC1_Bld RMB     2      ;buffer address that 'OC-on loop' is currently looking at <if
                        ;      OC1_Bld ~= MemNxt (where next seed sensor TCNT is latched),
                        ;      then load buffer value @ 0,Y into TOC1

PW       RMB     2      ;pulse width (ms) -- Calculated from PWans
TbDel   RMB     2      ;tube delay time (ms) -- Calculated from TbDans
ValPlc  RMB     2      ;distance behind valve and tube outlet (t-in)
PlacDel RMB     2      ;calculated placement delay (ValPlc * 100 / speed in ips --> ms)
SPDips  RMB     2      ;calculated speed from SpdAns (ips)
TotDel  RMB     2      ;calculated total delay (TbDel+PlacDel) (ms)
AdjDel  RMB     2      ;adjusted total delay (in TCNT cts)
PWadj   RMB     2      ;adjusted PW (in TCNT cts)

```

```

* _____ Definition of Calibration Questions _____
*Requires 0x01A6 of EEPROM space for these questions
    ORG    $E400
CAL_STR FCC    "Prepare to Calibrate System:"
    FCB    $00
PW_STR  FCC    "Enter pulse width in msec (3-digits).\"
    FCB    $00          ;ASCII nullspace
OLD_VA1 FCC    \" (saved value is \"
    FCB    $00          ;ASCII nullspace
OLD_VA2 FCC    \"-ms) ----> \"
    FCB    $00          ;ASCII nullspace
TubeSTR FCC    "Enter in-tube delay in msec (3-digits).\"
    FCB    $00          ;ASCII nullspace
ValvSTR FCC    "Dist. from tube to valve in tenth inches (3-dig):\"
    FCB    $00          ;ASCII nullspace
OLD_V12 FCC    \"-mm) ---> \"
    FCB    $00          ;ASCII nullspace
OLD_Ra2 FCC    \") ---> \"
    FCB    $00          ;ASCII nullspace
SPD_STR FCC    "Enter usual planting speed in MPH (one-digit):\"
    FCB    $00
ERR_STR FCC    "Entry not recognized. Please try again ---> \"
    FCB    $00          ;ASCII nullspace

* _____ Definition of EEPROM variables: _____
    ORG    $B600
AdjDels RMB    2          ;adjusted total delay (in TCNT cts)
PWadjS  RMB    2          ;adjusted PW (in TCNT cts)
PWansS  RMB    4          ;Stored Pulse Width answer from user (3-digit + $00 stored)
TbDansS RMB    4          ;Stored Tube Delay answer from user (3-digit + $00 stored)
VlPansS RMB    4          ;Stored Valve Placement answer from user (3-digit + $00 stored)
SpdAnsS RMB    2          ;Stored Answer to speed in MPH

    ORG    $FFFE
    FDB    START          ;define RESET vector location
    ORG    $FFEC
    FDB    IC2_ISR        ;define IC2 interrupt location (captures seed sensor pulse)
    ORG    $FFE8
    FDB    OC1_ISR        ;define OC1 interrupt location (turns valve ON)
    ORG    $FFE6
    FDB    OC2_ISR        ;define OC2 interrupt location (turns valve OFF)

* _____ MAIN PROGRAM _____
    ORG    $E000
***** MCU System initialization:
START  LDX    #BASE
    LDAA    #$03
    STAA    TMSK2,X        ;set TCNT prescaler=16 (524-ms rollover @ 8MHz)
    LDAA    #$00
    STAA    INIT,X        ;map I/O and RAM to $0000
    BCLR    BPROT,$01      ;clear protection of $b600-$b61f
    LDS     #$1FFF          ;load Stack pointer... omit when running in BUFFALO
    LDAA    #$14
    STAA    PACTL          ;enable PA3 as 4th IC, set PA3 & 7 to be inputs,
                        ; set RTI period = 32.768-ms, and PulseAc counts on rising

    LDAA    #$80
    STAA    OC1M           ;set OC1 to only control OC1
    BCLR    PRTA,OC2       ;be sure OC2 on PORTA is off
    BCLR    PRTA,OC1       ;be sure OC1 on PORTA is off

***** SCI Communications initialization:
    LDAA    #$30
    STAA    BAUD           ;select 9600 baud
    LDAA    #00
    STAA    SCCR1          ;select 8 bits of data
    LDAA    #$0C
    STAA    SCCR2          ;Rx and Tx are enabled

```

```

***** Timers Function initialization:
        LDAA    #$08
        STAA    TCTL2           ;set IC2 to interrupt on falling edges
        LDAA    #$02
        STAA    TMSK1           ;enable IC2 interrupts
        LDAA    #$00
        STAA    TCTL1           ;set no action on successful TCNT =? TOCX comparisons

***** Calibration Routine, when PE0 = HIGH:
        BRSET   PRTE,$02,Calib ;if PE1 = 1, then calibrate
        JMP     MAINpre         ;otherwise, jump to main routine
Calib    CLRA
        STAA    CRLPF           ;clear CRLoop flag (0 = do not send CR)
        JSR     CRLPF           ;send CR & LF at start of program
        LDX     #CAL_STR        ;loads starting address of calibration string
        BSET    CRLPF,$01       ;set bit to output CR & LF
        JSR     MessOut         ;send message to screen
        JSR     CRLPF           ;send extra CR & LF

        JSR     GetPW           ;Get pulse width value
        JSR     GetTube         ;Get tube delay value
        JSR     GetPlac         ;Get valve placement info
        JSR     GetSpd          ;Get average speed info

        JSR     CalcDel         ;Calc sys. & PW delays, converted to TCNT units from time
        JSR     EEProg          ;Store calculated delays to EEPROM for future retrieval
        JSR     EEProg3         ;Store user's answers to all questions to EEPROM
        JMP     MAIN

MAINpre  LDD     PWadjS          ;load stored value from EEPROM from last calibration
        STD     PWadj           ;store to RAM value, called in program
        LDD     AdjDelS         ;load stored value from EEPROM from last calibration
        STD     AdjDel          ;store to RAM value, called in program

MAIN     LDD     AdjDel          ;load delay time (TCNT units)
        LSRD                    ;divide by 2 to get repeat int. for OC1 when buf. empty
        STD     TOCRpt          ; store to 'OC1 Repeat Interval'
        JSR     ClrMem          ;jump to subroutine to clear mem. buffer locations
        LDD     #SeedBuf        ;load starting address of mem. buffer
        STD     MemNxt          ;initialize so IC2 knows where in mem buf. to store values
        STD     OC1_Bld         ;initialize OC1 exam address so OC1_ISR knows where
        ; 1st Valve ON time will be stored in Buffer

        LDAA    #$01
        STAA    BufEmpF        ;set 'Buf Empty Flag' so Valve doesn't fire 1st OC1_ISR
        LDD     TCNT            ;load TCNT
        ADDD    TOCRpt          ;calculate <TCNT + TOC_Repeat_Interval>
        STD     TOC1           ;set OC1_ISR to occur in TOCRpt-ms
        BSET    TMSK1,OC1       ;enable OC1 interrupt when TCNT = TOC1
        LDAA    #$C2
        STAA    TFLG1          ;clear OC1F, OC2F, & IC2F before enabling interrupt
        CLI                     ;enable maskable interrupts (OC1 & IC2 only, now)

MAIN2    BRA     MAIN2

*****
*** SUBROUTINE - Fires spray valve for time stored in 'PWadj' variable, which is the
*** PW (ms) value adjusted to TCNT cts.
*
TurnON   LDD     TCNT           ;load AccD with current TCNT value
        BSET    PRTE,OC2       ;actuate the valve by setting OC2 pin (PA6)
        ADDD    PWadj          ;PWadj + TCNT = TCNT value when to turn off valve
        STD     TOC2           ;store value (PWadj + TCNT) to TOC2
        BSET    TFLG1,OC2      ;clear OC2F flag before enabling interrupts
        BSET    TMSK1,OC2      ;enable OC2 interrupt (when TCNT = TOC2)
        RTS
*****

```

```

*****
*** SUBROUTINE - Fills entire memory buffer with zeros at beginning of program, b/c
*** zero is value with represents "nothing stored here"
ClrMem LDX #SeedBuf ;load X with starting location of mem. Buffer
      LDD #0000 ;load D with zeros
ClrMem2 STD 0,X ; store zeros to first buffer location
      INX
      INX ;jump over just cleared bytes (2)
      CPX #SeedEnd ;compare X to last buffer location
      BLS ClrMem2 ;if current X <= last buf. location, then keep clearing
      RTS
*****

*****
*** SUBROUTINE - Gets pulse width information in the Calibration routine
*
GetPW LDX #PW_STR ;load pulse width message
      BSET CRLPF,$01 ;set bit to output CR & LF
      JSR MessOut ;send message to screen
      LDX #OLD_VA1 ;load "old value =" message
      BCLR CRLPF,$01 ;clear flag to prevent sending CR & LF
      JSR MessOut ;send message to screen
      LDX #PWansS ;load stored value of pulse width
      JSR MessOut ;send to screen
      LDX #OLD_VA2 ;load remainder of message
      JSR MessOut ;send message to screen
      LDAB #3
      STAB charexp ;store expected number of characters
GetPW2 LDY #PWans ;load location of where to store incoming values
      JSR INTXT ;jump to subroutine to receive input
      LDAA ErrF ;load error flag status
      BEQ GetPW3 ;if ErrF=0, then continue
      BRA GetPW2 ; otherwise, recapture message
GetPW3 LDY #PWans ;load location of first digit
      JSR ConvDec ;convert 3 dec digits to hex
      STD PW ;store to PW (ms) in hex
      JSR CRLOOP
      JSR CRLOOP
      RTS
*****

*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
*@@ SUBROUTINE - Gets information about how long the delay should be for @
* the seed to fall down the tube (ms); independent of speed @
GetTube LDX #TubeSTR ;load tube delay message @
      BSET CRLPF,$01 ;set bit to output CR & LF @
      JSR MessOut ;send message to screen @
      LDX #OLD_VA1 ;load "old value =" message @
      BCLR CRLPF,$01 ;clear flag to prevent sending CR & LF @
      JSR MessOut ;send message to screen @
      LDX #TbDansS ;load current value of tube delay @
      JSR MessOut ;send to screen @
      LDX #OLD_VA2 ;load remainder of message @
      JSR MessOut ;send message to screen @
      LDAB #3 @
      STAB charexp ;store expected number of characters @
GetTub2 LDY #TbDans ;load loc. of where to store incoming values @
      JSR INTXT ;jump to subroutine to receive input @
      LDAA ErrF ;load error flag status @
      BEQ GetTub3 ;if ErrF=0, then continue @
      BRA GetTub2 ; otherwise, recapture message @
GetTub3 LDY #TbDans ;load location of first digit @
      JSR ConvDec ;convert 3 dec digits to hex @
      STD TbDel ;store to TdDel (ms) in hex @
      JSR CRLOOP @
      JSR CRLOOP @
      RTS @
*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```



```

*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
*@@ SUBROUTINE - Gets information about where the valve is placed relative @
*      to seed tube outlet, measured in tenths of inches (i.e., @
*      3.5" = 35, 10.2" = 102, etc) @
* @
GetPlac LDX      #ValvSTR      ;load valve placement message @
      BSET      CRLPF,$01    ;set bit to output CR & LF @
      JSR       MessOut      ;send message to screen @
      LDX      #OLD_VA1      ;load "old value =" message @
      BCLR      CRLPF,$01    ;clear flag to prevent sending CR & LF @
      JSR       MessOut      ;send message to screen @
      LDX      #VlPansS      ;load current value of valve placement @
      JSR       MessOut      ;send to screen @
      LDX      #OLD_Vl2      ;load remainder of message @
      JSR       MessOut      ;send message to screen @
      LDAB     #3 @
      STAB     charexp      ;store expected number of characters @
GetPlc2 LDY      #VlPans      ;load loc. of where to store incoming values @
      JSR       INTEXT      ;jump to subroutine to receive input @
      LDAA     ErrF         ;load error flag status @
      BEQ      GetPlc3      ;if ErrF=0, then continue @
      BRA      GetPlc2      ; otherwise, recapture message @
GetPlc3 LDY      #VlPans      ;load location of first digit @
      JSR       ConvDec      ;convert 3 dec digits to hex @
      STD      ValPlc        ;store to ValPlc (mm) in hex @
      JSR       CRLOOP      @
      JSR       CRLOOP      @
      RTS @
*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

```

*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
*@@ SUBROUTINE - Gets information about the average planter planting speed.@
*      Info is enter as a SINGLE DIGIT, in MPH; is then converted @
*      to speed in inches / sec and stored to SPDips @
* @
GetSpd  LDX      #SPD_STR      ;load planting speed question @
      BSET      CRLPF,$01    ;set bit to output CR & LF @
      JSR       MessOut      ;send message to screen @
      LDX      #OLD_VA1      ;load "old value =" message @
      BCLR      CRLPF,$01    ;clear flag to prevent sending CR & LF @
      JSR       MessOut      ;send message to screen @
      LDX      #SpdAnsS      ;load current value of valve placement @
      JSR       MessOut      ;send to screen @
      LDX      #OLD_Ra2      ;load remainder of message @
      JSR       MessOut      ;send message to screen @
      LDAB     #1 @
      STAB     charexp      ;store expected number of characters @
GetSpd2 LDY      #SpdAns      ;load loc. of where to store incoming values @
      JSR       INTEXT      ;jump to subroutine to receive input @
      LDAA     ErrF         ;load error flag status @
      BEQ      GetSpd3      ;if ErrF=0, then continue @
      BRA      GetSpd2      ; otherwise, recapture message @
GetSpd3 LDAB     SpdAns      ;load AccB with speed values (MPH) @
      ANDB     #$0F         ;mask MS-nibble (ASCII component) @
      LDAA     #12          ;Load AccA with 12 @
      MUL      ;Multiply speed * 12 (max. ans = 9*12) @
      LDAA     #88          ;load A with 88 @
      MUL      ;(speed in MPH * 12 * 88) @
      LDX      #60 @
      IDIV     ;(speed in MPH * 12 * 88/60 = speed in in/s) @
      STX      SPDips      ;store result to SPDips @
      JSR       CRLOOP      @
      JSR       CRLOOP      @
      RTS @
*@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

[illegible]

```

        INX                ;increment Reg. X to starting address of next in-cmd &
        LDY    #VlPans    ;load starting address of tube delay answer &
        CLR    charctr    ;clear character counter &
        JSR    EEProg4    ;go & store current answer values in EEPROM &
        LDAA   #$00       ;load AccA with nullspace &
        JSR    EEPByte    ;store to EEProm &
        INX                ;increment Reg. X to starting address of next in-cmd &
        LDY    #SpdAns    ;load starting address of tube delay answer &
        LDAA   #01        ;store # chars expected = 1 &
        STAA   charexp    ;clear character counter &
        CLR    charctr    ;go & store current answer values in EEPROM &
        JSR    EEProg4    ;load AccA with nullspace &
        LDAA   #$00       ;store to EEProm &
        JSR    EEPByte    ;store to EEProm &
        RTS                &
*                                &
EEProg4 LDAA   0,Y        ;load byte of data to be stored &
        JSR    EEPByte    ;store byte to EEPROM address 0,X &
        INX                &
        INY                &
        INC    charctr    ;increment character counter &
        LDAA   charexp    ;load AccA with number of expected chars &
        CMPA   charctr    ;compare # expected to number stored &
        BNE    EEProg4    ;if exp ~= received, then continue storing &
        RTS                &
*                                &
*****                                &
****SUBROUTINE INFO:  RegX = EEPROM address to store to, AccA = Byte to be stored &
EEPByte LDAB   #$02      ;Set EELAT bit (EEPGM=0) &
        STAB   PPROG      &
        STAA   0,X        ;store to EEPROM address &
        LDAB   #$03      ;Set EEPGM bit (EELAT=1) &
        STAB   PPROG      &
        JSR    DLY10      ;Delay for 10-ms to burn EEPROM &
        CLR    PPROG      ;Disable high prog. voltage & set EEPROM to read &
        RTS                &
*                                &
*****                                &
** SUBROUTINE - Generates 12-ms delay for EEPROM programming *
DLY10  PSHY                ;push Reg. Y onto stack *
        LDY    #$0D7A      ;load register Y with 0x1000 *
DLY2   DEY                ;decrement Y *
        BNE    DLY2        ;if not = 0, then decrement again *
        PULY                ; when Y=0, pull Y from stack *
        RTS                *
*****                                *

Err_Mes JSR    CRLOOP      ;send CR & LF
        LDX    #ERR_STR    ;load Reg. X with starting address err message
        BCLR   CRLPF,$01    ;clear bit to prevent outputting CR & LF
        JSR    MessOut      ;send message to screen
        RTS

*****
*                                |
*          IC2 INTERRUPT ROUTINE (Capture seed sensor pulse)          |
*-----|-----|
*                                |
IC2_ISR LDD    TIC2        ;load AccD with TCNT value @ time of interrupt
        LDX    MemNxt      ;load next available mem. location
        ADDD   AdjDel      ;TCNT + number TCNT cts equivalent to delay
        BNE    IC2_2      ;if not equal to zero, then continue
        LDD    #$0001      ; if = 0, store 0x0001 b/c 0x0000 means no value
IC2_2   STD    0,X        ;store value to mem. location

```

```

        INX
        INX
        CPX    #SeedEnd      ;increment X over just saved value
        BLS    IC2_3         ;check to see if at end of buffer?
        LDX    #SeedBuf      ;if X <= SeedEnd, then done
        STX    MemNxt        ; otherwise, load X with first buffer location
        BSET   TFLG1,$02     ;store X to MemNxt variable (next avail. spot)
        RTI                 ;clear IC2F flag
*~~~~~

```

```

*-----<
*          OC1 INTERRUPT ROUTINE (Turn ON Valve) <
*-----<
*-----<
OC1_ISR LDAA  BufEmpF        ;chk 'Buf Empty flag' to check last TOC stat <
        BEQ   OC1ISR1       ; if =0, then fire valve <
        BRA   OC1ISR2       ; otherwise, check if buffer is still empty <
OC1ISR1 JSR    TurnON        ;jump to subroutine to turn on valve <
        ; and enable OC2 IRQ when time to shut off <
OC1ISR2 LDY    OC1_BLD       ;load address of current OC1 Buffer location <
        CPY    MemNxt        ;check if buffer address that OC1 loop is <
        ; looking at = address that seed sensor will <
        ; latch next seed drop event to <
        BEQ   OC1ISR5       ;if OC1_BLD = MemNxt, then awaiting seed drop<
        LDD    0,Y          ; otherwise, seed in transit; prep. to spray <
        STD    TOC1         ;store 0,Y buffer value to TOC1 <
        LDD    #$0000       ;load AccD w/ 0000's <
        STD    0,Y         ;clear just-serviced buffer location <
        INY                 <
        INY                 ;increment Y to address of next buffer value <
        CPY    #SeedEnd     ;check to see if at end of buffer? <
        BHI   OC1ISR3       ; if > end of buffer, then reload buf start <
        BRA   OC1ISR4       ; otherwise, store cur. Y as cur. buff add. <
OC1ISR3 LDY    #SeedBuf      ;load starting address of buffer <
OC1ISR4 STY    OC1_BLD       ;store new add. as curr. buf. addr. to look @<
        CLR    BufEmpF      ;clear Buf Empty Flag b/c new buf val loaded <
        BRA   OC1_END       ;jump to end of ISR to clear IC1F & RTI <
OC1ISR5 LDD    TCNT         ;load current TCNT Value <
        ADDD   TOCRpt       ;calculate <TCNT + TOC Repeat Time> <
        STD    TOC1         ; interrupt again in TOCRpt-ms to chk if any <
        ; new values were added to buffer <
        LDAA   #$01         <
        STAA   BufEmpF      ;set Buf Empty Flag b/c no new buf val loaded<
OC1_END BSET   TMSK1,OC1     ;enable OC1 interrupt when TCNT = TOC1 <
        BSET   TFLG1,OC1    ;clear OC1F flag <
        RTI                 ;return from interrupt service routine <
*-----<

```

```

*~~~~~&
*          OC2 INTERRUPT ROUTINE (Turn OFF Valve) &
*-----&
*-----&
OC2_ISR BCLR   PRTA,OC2      ;clear bits controlling OC2 action &
        BCLR   TMSK1,OC2    ;disable additional OC2 interrupts &
        ;output went LOW when TCNT=TOC2, triggering this &
        ;interrupt &
        RTI                 &
*~~~~~&

```

```

*~~~~~
*~~~~~SCI Text Capture, Echo, Save, etc. Routines~~~~~
*~~~~~
*
***SUBROUTINE - saves ASCII characters to memory locations
***          (assumes that Reg Y contains address of where to store)
CHRSVE STAA   0,Y           ;stores character just read to one of buffer locations

```

```

        INY                ;increment Y to next mem location
        RTS

*
***SUBROUTINE - checks for errors, reads the in-character, & strips parity.
*** (Reads character in Serial Comm. Data Reg. to AccA)
INCHAR  LDAA  SCDR
        ANDA  #$7F          ;mask parity (clear MS bit)
        RTS

*
*SUBROUTINE - echoes characters back to the terminal          (assumes char is in AccA)
ECHO    BRCLR  SCSR,$80,ECHO    ;wait for TDRE=1
        ANDA  #$7F          ;mask parity
        STAA  SCDR          ;send data to serial 'shift-out' register
        RTS

*
***SUBROUTINE - receives multi-char message via serial comm., terminated by <ENTER>
*** (Reg. Y should contain starting location of where to store info)
INTEXT  CLR    charctr      ;clear character counter
        CLR    ErrF        ;clear Error receiving flag
INTEXT2 BRCLR  SCSR,$20,INTEXT2 ;wait here till character received RDRF=1
        JSR    INCHAR      ;latches char from screen to AccA
        CMPA  #RETRN      ;check if "ENTER" is hit
        BNE   TEXT2       ;if no, then go save CHAR
        RTS              ;if yes, goto processing
TEXT2   INC    charctr      ;increment character counter
        LDAB  charctr      ;load number of characters received
        CMPB  charexp      ;compare #expected chars to number received
        BHI   TEXTERR     ; if #received > #expected, send error message
        JSR   CHRSAVE      ;if not return, then save character
        JSR   ECHO         ;echo character to screen
        BRA   INTEXT2      ;go wait for next character
TEXTERR JSR    Err_Mes     ;send error message
        LDAA  #01
        STAA  ErrF        ;set error flag to indicate problem receiving data
        RTS

*
*SUBROUTINE - echoes 'CR' and 'LF' to the terminal
CRLOOP  LDAA  #RETRN      ;get ASCII 'CR' value
        JSR   ECHO        ;echo to terminal
        LDAA  #LF         ;get ASCII 'LF' value
        JSR   ECHO        ;echo to terminal
        RTS

*
*SUBROUTINE - sends characters of a multi-character message to terminal screen
*** (assumes that address of message's 1st char is in Reg X)
MessOut LDAA  0,X         ;get next character of the message
        CMPA  #NULL       ;character=null?
        BEQ   OutDne      ;if yes, then done outputting characters
        JSR   ECHO        ;otherwise, echo character
        INX
        BRA   MessOut
OutDne  LDAA  CRLPF        ;flag that indicates whether to send CRLOOP
        BRCLR CRLPF,$01,OutDne2 ;if equals zero, do not send
        JSR   CRLLOOP     ;otherwise, send CR & LF as part of message
OutDne2 RTS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

*
*----- Conversion Routines (Hex2Ascii & Ascii2Hex) -----
*
*SUBROUTINE - convert hex characters to ASCII(put char to be converted in AccA)
Cv_Asci PSHA             ;store original in_value
        LSRA
        LSRA
        LSRA
        LSRA
        CMPA  #10         ;check if a letter or number
        BHS   C_Alph1     ;if letter, then diff. conversion
        ORAA  #$30        ;set hi nib to 3 & leave lo nib

```

```

        BRA      Nex_Nib
C_Alph1 SUBA     #09
        ORAA     #$40          ;set hi nib to 4 & subtract 9 from low nibble
Nex_Nib JSR      ECHO          ;echo ASCII of high nibble to screen
        PULA     ;restore original value
        ANDA     #$0F          ;clear high nibble
        CMPA     #10          ;check if a letter or number
        BHS      C_Alph2      ;if letter, then different conversion
        ORAA     #$30
        BRA      Cv_end
C_Alph2 SUBA     #09
        ORAA     #$40
Cv_end  JSR      ECHO          ;echo ASCII of low nibble to screen
        RTS

*
*SUBROUTINE - converts consecutive ASCII characters to their hex equivalent;
*** (ASSUMES X contains address of 1st Ascii; returns ans in AccA)
Asci2Hx LDAA     0,X          ;load character
        JSR      ConvA_H      ;convert 1st ascii byte to upper hex nibble
        PSHA     ;store intermediate value on stack
        LDAA     1,X          ;load 2nd Ascii char
        JSR      ConvA_L      ;convert 2nd ascii byte to lower hex nibble
        PULB     ;pull upper hex nibble from stack as AccB
        ABA      ;add AccA (lower nibble) to AccB (upper nib)
Qend    RTS
*
*SUBROUTINE - converts 1st ascii character to high nibble of hex equivalent
ConvA_H CMPA     #$40          ;ascii value > $40?
        BHS      ALPH         ;if yes, then hex equiv is a char
ConvA2  LSLA
        LSLA
        LSLA
        LSLA          ;if no, then shift left 4X to get hi nib
        BRA      Con1Dne
ALPH    ADDA     #09          ;if hex is a char, add 9 to ascii
        BRA      ConvA2       ;and shift left 4X to get hi nib
Con1Dne RTS
*
*SUBROUTINE - converts 2nd ascii character to low nibble of hex equivalent
ConvA_L CMPA     #$40          ;ascii value > $40?
        BHS      ALPH2        ;if yes, then hex is a char
        ANDA     #$0F          ;if no, then mask hi nib to get hex
        BRA      Con2Dne
ALPH2   ANDA     #$0F          ;mask hi nib and add 9 to get hex
        ADDA     #09
Con2Dne RTS
*
*SUBROUTINE - converts three digit decimal number, each in Ascii to equivalent|
*** 2-byte hex value... Y should contain address of first digit
ConvDec LDD      #$0000
        STD      Interm       ;clear intermediate math value
        LDAA     #100         ;load weight of 3rd digit in dec.
        LDAB     0,Y          ;load value of MS-digit
        ANDB     #$0F         ;clear ASCII part of digit (upper nibble)
        MUL      ;multiply digit by its decimal weight
        STD      Interm       ;store to intermediate
        LDAA     #10          ;load weight of 2nd digit in dec.
        LDAB     1,Y          ;load value of 2nd dec digit
        ANDB     #$0F         ;clear ASCII part of digit (upper nibble)
        MUL      ;multiply digit by its dec. weight
        ADDD     Interm       ;add this part to intermediate result
        STD      Interm       ;store this intermediate answer
        LDAA     #0           ;weight of 1 for last digit, so no need to MUL
        LDAB     2,Y          ;load value of last digit
        ANDB     #$0F         ;clear ASCII part of digit (upper nibble)
        ADDD     Interm       ;add to intermediate result
        STD      Interm       ;return from routine with result in AccD
        RTS
*

```

Appendix D. MATLAB® Optimization Information

Example Output from Optimization Program

```

-----
Test           =                               12-6-51480-50
Speed          =                               6-mph
Seeding Rate   =                               51480-Seeds/Ac
Required Protection Band:  Front Distance = 0.1-in.  Rear distance = 0.1-in.
-----

```

The matrix of adjusted delays & corresponding hit ratios are printed below:

```

-1.0000  42.5926
-0.9000  40.7407
-0.8000  44.4444
-0.7000  57.4074
-0.6000  56.4815
-0.5000  62.0370
-0.4000  71.2963
-0.3000  74.0741
-0.2000  75.0000
-0.1000  75.9259
  0       72.2222
 0.1000  65.7407
 0.2000  56.4815
 0.3000  50.0000
 0.4000  37.9630
 0.5000  34.2593
 0.6000  26.8519
 0.7000  22.2222
 0.8000  16.6667
 0.9000  11.1111
 1.0000  11.1111

```

Matrix below contains pct of seeds sprayed based on varying band widths:

BAND WIDTH	ADJUSTMENT	PCT. HIT	BAND WIDTH	ADJUSTMENT	PCT. HIT
0.10	0.00	0.00	2.10	-0.40	85.19
0.20	0.00	0.00	2.20	-0.10	87.96
0.30	-0.20	9.26	2.30	-0.10	89.81
0.40	-0.10	15.74	2.40	-0.10	90.74
0.50	-0.10	23.15	2.50	0.00	91.67
0.60	0.00	31.48	2.60	0.10	94.44
0.70	0.00	38.89	2.70	0.00	95.37
0.80	0.00	44.44	2.80	0.00	95.37
0.90	-0.10	50.00	2.90	0.10	96.30
1.00	-0.20	55.56	3.00	0.10	96.30
1.10	-0.20	62.96	3.10	0.00	96.30
1.20	-0.20	67.59	3.20	-0.20	96.30
1.30	-0.20	71.30	3.30	0.40	97.22
1.40	-0.10	74.07	3.40	0.40	98.15
1.50	-0.10	76.85	3.50	0.30	98.15
1.60	-0.10	78.70	3.60	0.30	98.15
1.70	-0.20	79.63	3.70	0.20	98.15
1.80	-0.30	81.48	3.80	0.20	98.15
1.90	-0.30	84.26	3.90	0.10	99.07
2.00	-0.30	85.19	4.00	0.10	99.07

Based on the theoretical coverage, the avg. pulse width should be 1.5-in., with the seeds placed 0.8-in. from the leading edge of the spray.

The average delay distance (start spray to seed) was 1.07-in. with a standard deviation = 0.738-in.

The average spray pulse width was 1.44-in. with a standard deviation = 0.087-in.

Based on this information, 72.22-percent of the planted seeds were adequately sprayed with the fungicide.

The optimal delay time (to achieve max. hit ratios) would have shifted all spray bands by 0.1-in., and delivered a coverage rate of 75.93-pct.

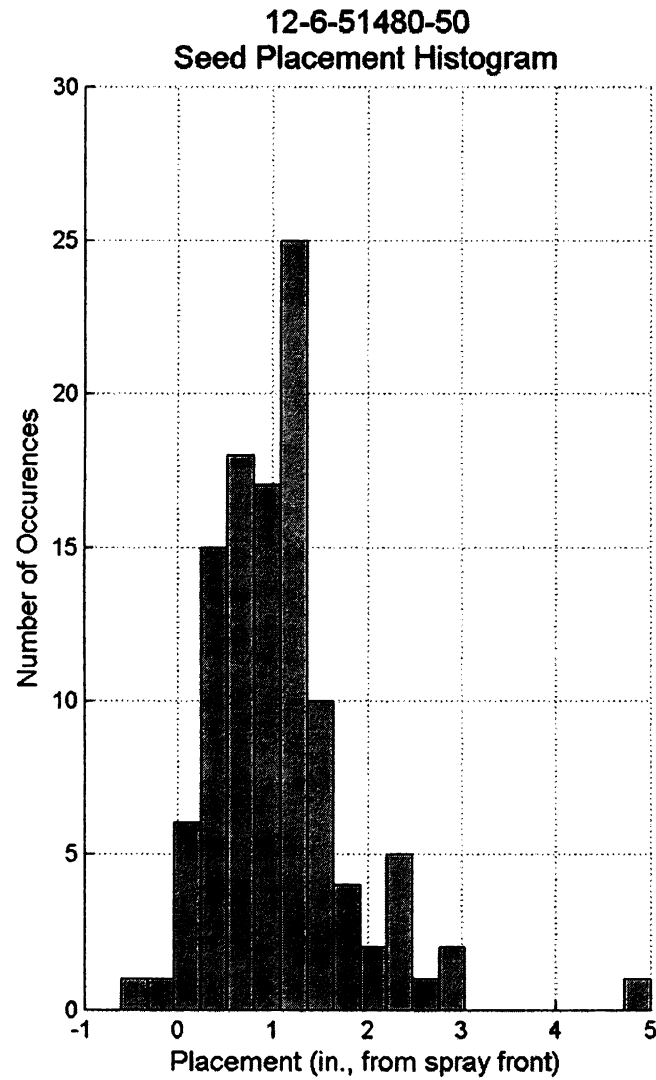
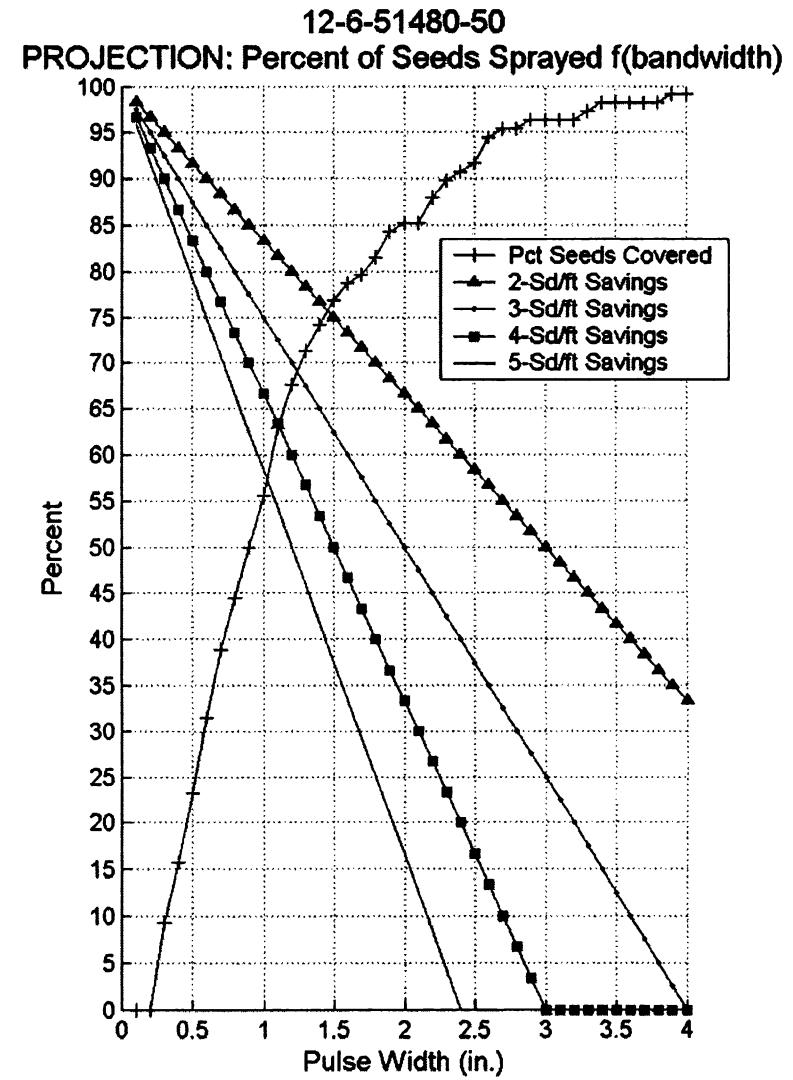


Figure D1. Example of the MATLAB figure created using the optimization program.

VITA

John Houston Hancock was born on March 3, 1977, in Murfreesboro, Tennessee. He grew up on a farm in Lebanon, TN, attending Byars Dowdy Elementary School, Walter J. Baird Middle School, and Lebanon High School. He graduated from Lebanon High in May 1995, and enrolled at The University of Tennessee, Knoxville, the following August. While at UTK, Hancock was active in the Tennessee Branch of the American Society of Agricultural Engineers and in other organizations with the College of Agricultural Sciences and Natural Resources. He graduated in December 1999 with a Bachelor of Science in Agricultural Engineering. Following graduation, he accepted a design engineering internship at John Deere Commercial Worksite Products in Loudon, TN, leaving that position after five months for a marketing internship with John Deere North American Agricultural Marketing Center in Atlanta, GA. He returned to The University of Tennessee in August 2000, as a graduate research assistant. He graduated in May 2003 with a Master of Science in Biosystems Engineering.