# PERFORMANCE OF A CHEMICAL INJECTION SPRAYER SYSTEM

K. A. Sudduth, S. C. Borgelt, J. Hou

**ABSTRACT.** *The dynamic and steady state performance of a commercial chemical injection system was evaluated to determine if the system could be modified for variable-rate herbicide application. A helium-neon (He-Ne) laser system was used to quantify concentration uniformity across the spray pattern, along with the response characteristics of the system controller, the injection pump module, and the overall system. A range of operating conditions were created by changing system pressure and simulated sprayer travel speed. There was little variation in nozzle output distribution (CV < 10.5%) and chemical concentration (CV < 7.0%) across the spray path. The delay of the injection controller was slightly more than 1 s and injection pump delay was approximately 4 s. Controller and pump responses were rapid enough to qualify these components for use in a variable-rate application system. The long delay time (14 to 21 s) for chemical concentration response after a step change in travel speed was attributed to transport delays in the mixing chamber and spray boom. Accurate variable-rate application will require reduction of this delay and/or development of control algorithms to compensate for the delay.* ***Keywords.*** *Direct injection, Chemical control, Control performance, Controller response, Nozzles.*

Chemical sprayers are used for production agriculture worldwide. In a traditional system, the concentrated chemical and the carrier, usually water, are mixed together and carried in one tank. The mixture is pumped from the tank and sprayed out the nozzles. In a chemical injection sprayer, the undiluted chemical and carrier are contained in separate tanks. The carrier is pumped to the nozzles at a constant rate per unit time, while chemical is metered and injected into the carrier on the basis of desired chemical application rate. A mixing device may be used to insure that the chemical and carrier are mixed before being discharged through the nozzles.

Compared to conventional sprayers, injection sprayer systems can reduce applicator exposure to chemicals during the mixing and loading process. Disposing of unused chemical is less of a problem, since the chemical is undiluted and can be returned to the original container for later use or disposal. Also, injection technology may be more easily adaptable to the variable-rate applicators which will be needed to apply varying amounts of pesticide at different locations within a field for site-specific crop management.

In this project, the steady state and dynamic performance characteristics of a commercial chemical injection sprayer system, the Raven SCS-700, were evaluated to determine the feasibility of modifying the system for variable-rate herbicide application. It was imperative to understand the operational characteristics and limitations of the chemical injection sprayer system available, before a successful variable-rate system could be developed. Tests of a similar system by Budwig et al. (1988) provided a basis for the investigation, but their work only reported on overall system response, and did not include the required information on controller and injection pump response characteristics.

## LITERATURE REVIEW

Reports of systems to meter, or inject, concentrated pesticides into the diluent stream began to appear in the research literature in the mid 1970s (Hughes and Frost, 1985). Vidrine et al. (1975) developed and tested a laboratory system which demonstrated the feasibility of injecting concentrated pesticides. Problems noted with this system included nonuniform pesticide application and transient application errors resulting from changes in operating speed. Reichard and Ladd (1983) developed a field sprayer which included injection of pesticides at the proper rate for variations in travel speed. The unit was reported to work well in field tests. Chi et al. (1988) developed an electronic flow rate control system for metering concentrated pesticides. Ghate and Phatak (1991) developed and tested a field sprayer which used compressed air to inject concentrated chemical into the carrier stream.

Koo et al. (1987) found the time delay of concentrated pesticides through injection sprayers to be significant, and

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The authors are **Kenneth A. Sudduth**, ***ASAE Member Engineer***, Agricultural Engineer, Cropping Systems and Water Quality Research Unit, USDA-Agricultural Research Service, **Steven C. Borgelt**, ***ASAE Member Engineer,*** Assistant Professor, **Jian-xun Hou**, former Graduate Research Assistant, Agricultural Engineering Dept., University of Missouri, Columbia.

proposed injection at the individual nozzles as a possible solution to shorten delays. Tompkins et al. (1990) injected a tracer chemical into the diluent stream at three points on a boom sprayer—immediately before and after the diluent pump, and at the individual nozzles. They found that as the injection point was moved downstream, transient time was reduced, but variations in chemical concentration between nozzles were greater. Miller and Smith (1992) reported on development of a direct nozzle injection system that overcame the concentration variation problems reported by previous researchers. Way et al. (1992) used simulation to compare chemical application accuracies for various designs of injection sprayers. They found that reducing the diameter of the fluid lines near the end of the spray booms improved overall application accuracy.

Budwig et al. (1988) analyzed the Raven SCS-700 commercial chemical injection system. A helium-neon laser was used to optically measure the concentration variations of potassium permanganate injected into the sprayer boom. Tests revealed consistent chemical concentrations among the sprayer nozzles, satisfactory mixing of the diluent and chemical streams, and large delay times when chemical rates (or simulated travel speeds) were changed.

### OBJECTIVES

The objectives of this research were to:

- Measure spray distribution, uniformity of chemical and diluent mixing, and time delay at different nozzles along the boom at various pressures and simulated travel speeds.
- Determine the influence of the chemical injection controller and the injection pump on system response at various simulated travel speeds.

## EQUIPMENT AND PROCEDURES

### SYSTEM TESTED

The system tested was a Raven SCS-700 chemical injection spray system (fig. 1). The SCS-700 consisted of a control console, a radar speed sensor, two injection modules with metering pumps, and an in-line mixer.

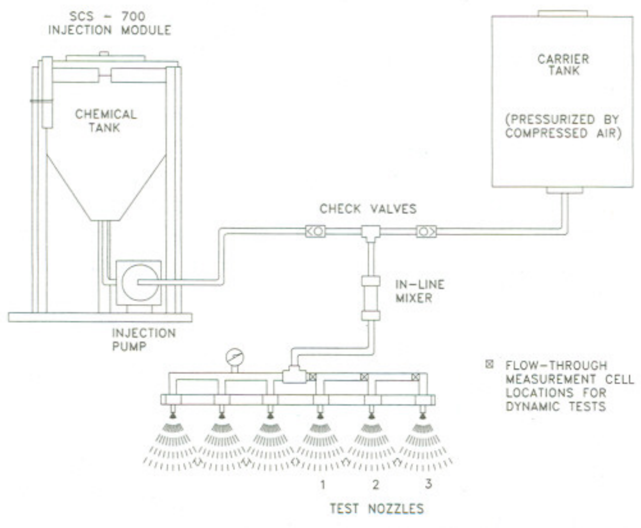


**Figure 1–Chemical injection sprayer system as configured for laboratory dynamic response tests.**

The chemical metering pumps were positive displacement piston pumps, and operated with submerged inlets due to the position of the chemical tanks above the pumps. A variable speed DC motor drove each injection pump at the proper speed based on travel speed and the desired theoretical application rate. The control console, mounted at the operator's station, contained a microprocessor and associated circuitry to monitor the radar ground speed sensor and to control the speed of the injection pump motors as required. The console allowed the operator to select sprayer boom widths, pump response parameters, and desired chemical application rates. It also calculated and displayed application rate, ground speed, area sprayed, and volume of chemical used.

In normal field operation, a power take-off- (pto-) driven or engine-driven pump would be used in conjunction with a pressure regulator to maintain a constant pressure in the spray boom, and therefore a constant flow rate of the carrier. However, in these tests it was desirable to reduce pressure variations that might be encountered with this type of system and to provide easy and repeatable pressure adjustments. This was accomplished by pressurizing the carrier (water) tank through an adjustable air regulator.

### CHEMICAL CONCENTRATION MEASUREMENT

Potassium permanganate ($KMnO_4$) at a concentration of 2.5 g/L was used as the tracer to represent concentrated chemical. Tap water was used as the carrier. As an increased volume of the $KMnO_4$ solution was injected into the carrier fluid, the optical density or opacity of the spray solution changed accordingly. The relationship between opacity of the solution and chemical concentration was established and used to calibrate the sprayer performance tests.

The concentration of $KMnO_4$ in the spray solution was measured using an Aerotech LSR5P He-Ne laser and a United Detector Technology UDT-455 photodetector. The laser beam was oriented to pass through a known thickness of solution held in a cuvette or a flow-through sample cell. The photodetector was positioned to measure that portion of the laser output transmitted through the solution. A 100 Hz low-pass filter was implemented to attenuate high-frequency electrical noise from the photodetector signal. All electrical grounds, including the AC power supply earth ground, were connected together. Shielded wires were used, and the measurement system was powered by a separate DC supply.

The spray solution was collected in small square glass cuvettes (10 × 10 × 44 mm) during steady state tests. Initial tests using conventional test tubes were unsuccessful, due to the difficulty of maintaining alignment of the laser beam on the diametral axis of the tube. The data recorded from identical concentration solutions showed a coefficient of variation (CV) of 1.5% with the square cuvette compared to 8% with a round test tube. For dynamic tests, a sample cell was constructed and mounted in the spray boom hose. Parallel optical glass windows on two sides of the sample cell provided the optical pathway for laser optical density measurements.

A voltage-to-frequency converter circuit was built to simulate the output of the radar speed sensor. Changes in the simulated travel speed of the sprayer, and therefore the injected chemical flow rate, could then be made by adjusting the voltage input to the circuit.

Data were collected with a Metrabyte DAS-16 plug-in data acquisition board in an IBM XT computer. A program written in QuickBasic recorded the photodetector output and injection pump control signals. This program also controlled the voltage-to-frequency circuit used to simulate travel speed.

### Steady State Tests

A 9.5 mm (0.375 in.) diameter test boom with two Teejet 8003 nozzles (Spraying Systems Co., Wheaton, Ill.) spaced 510 mm (20 in.) apart was used for the steady state tests. The two nozzles were installed 460 mm (18 in.) above a spray table with 32 mm (1.25 in.) wide channels. The output from the nozzles was collected for 60 s on the spray table and pattern uniformity was evaluated for the portion of the spray pattern between the two nozzles.

To measure chemical concentration uniformity, a small amount of solution from each tube on the spray table was transferred to a square cuvette. The cuvette was then placed in a holder installed between the laser and the photodetector. The mean output voltage from the photodetector for each sample was obtained as the average of 500 individual readings (10 s at a 50 Hz sampling rate).

Six operating conditions were used in the steady state measurements. Three system pressure settings, 207, 276, and 345 kPa (30, 40, and 50 psi) were combined with two simulated travel speeds, 1.8 and 2.7 m/s (4 and 6 mile/h). Using a target application rate of 5.2 L/ha (0.5 gal/A), these speeds corresponded to chemical flow rates of 3.4 and 5.1 mL/s (6.9 and 10.3 oz/min), respectively.

### Dynamic Response Tests

The dynamic response of the system was quantified by the standard approach of imposing a step change in the command input, which in this case was simulated travel speed. It was recognized that this was a more severe test of system response than would be expected in field operation of a sprayer, where changes in travel speed would not be instantaneous. However, the goal of these tests was not to simulate normal field operation, but rather to measure response parameters which could then be used to evaluate the applicability of the tested system for variable-rate chemical application. In this regard, the step change test did simulate the response which might be required in a map-based approach to variable-rate chemical application. The input to the injection controller would exhibit a step change as the sprayer traversed from an area mapped with one application rate to an adjacent area mapped with a different rate.

A symmetrical spray boom with six Teejet 8002 nozzles spaced 510 mm (20 in.) apart in a 9.5 mm (0.375 in.) diameter line was used for the dynamic tests. Data were collected with the test cell installed at three locations on one side of the boom, adjacent to each nozzle (fig. 1).

Data collection for the dynamic tests began with the system in steady state. After 1500 data points were collected (30 s), the data acquisition system simulated a step change in sprayer travel speed. Another 3000 data points were collected after the change in simulated speed, allowing the system to come to steady state at the new operating level. Four channels of analog data were recorded during the dynamic tests—photodetector output voltage, injection pump speed, and the two control signals from the system controller to the injection pump drive motor. Controller response could then be determined by measuring the time from input command change to controller output change. Similarly, pump response was quantified by measuring the time from controller output change to pump speed change.

The response parameters quantified from these data included delay time, dead time, and rise time (fig. 2). Delay time was defined as the time required for the output response to a step input to reach 50% of its final value. Dead time was defined as the time required for the output response to a step input to reach 10% of its final value. Rise time was defined as the time required for the output response to a step input to rise from 10 to 90% of its final value (DiStefano et al., 1967). All three response parameters were measured for chemical concentration and injection pump speed. The delay time between the simulated speed input signal to the controller and the output from the controller to the injection pump motor was also measured.

Four operating conditions were tested, with the simulated travel speed of the sprayer changing stepwise from 1.8 to 2.7 m/s (4 to 6 mile/h, 3.4 to 5.1 mL/s), from 2.7 to 1.8 m/s, from 1.8 to 3.1 m/s (4 to 7 mile/h, 3.4 to 6.0 mL/s), and from 3.1 to 1.8 m/s. The wider speed range approached the maximum dynamic range available with a single manual setting of the Raven injection pump. Use of the second, narrower speed range allowed for testing of the linearity of the system response with inputs of various magnitudes, information which would would be important for detailed control system design. System pressure was maintained at 207 kPa (30 psi) for the dynamic response tests. Three replications of data were obtained for each operating condition.

## Results and Discussion

### Concentration Calibration Curve

Calibration curves for the relationship between photodetector output voltage and $KMnO_4$ concentration were obtained experimentally. In order to stabilize output voltages from the photodetector, the laser and photodetector instrumentation were preheated for at least

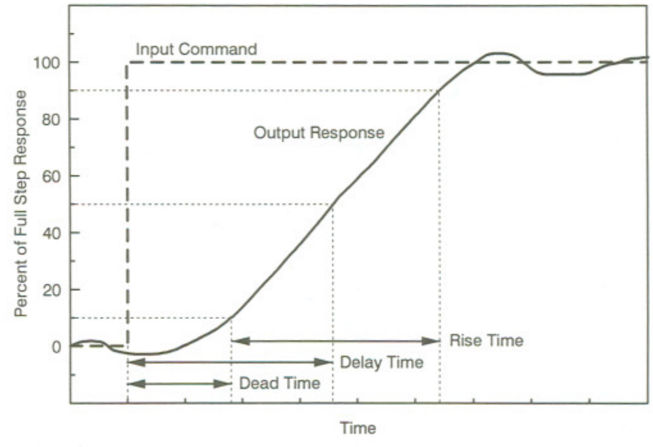


**Figure 2–Definitions of delay time, dead time, and rise time.**

2 h before calibration tests and the subsequent response tests.

The calibration equation was assumed to follow Lambert's Law for the absorbance of light by a medium with negligible fluorescence and light scattering (Freeman, 1990). Experimental data obtained at a number of concentrations were fit to the following equation:

$$V = Be^{-aC} \qquad (1)$$

where

**V** = photodetector output (V)

**C** = concentration of $KMnO_4$ (g/L)

**a, B** = experimental coefficients

Good calibrations were obtained both for the steady state test configuration with the glass cuvettes (fig. 3) and for the dynamic test configuration using the flow-through sample cell ($R^2 > 0.995$ in all cases). Although the value of the coefficient **a** remained constant over multiple calibration tests, the value of **B** varied considerably over a number of hours or days. As shown by equation 1, **B** was the photodetector output at zero concentration, a parameter which could be expected to change due to drift in the measurement system. However, tests showed the drift of **B** within 1 h was less than 1%. Therefore, the value of **B** was redetermined every 60 min or sooner by calibrating the system with tap water. For future use of the measurement system, it would be desirable to include additional signal conditioning circuitry to stabilize photodetector output over longer time periods.

### Steady State Results

Spray pattern and concentration distribution uniformity were quite good (table 1, fig. 4). The largest coefficient of variation (CV) value was 10.4% for pattern uniformity, with the rest of the CV values less than or equal to 6.6%. Values of CV up to 15% have been reported as acceptable, with values of 10% or less called desirable (Bode and Butler, 1983). Therefore, spray pattern uniformity was at an acceptable level. The maximum CV value for concentration distribution across the spray pattern was 7.0%. Chemical concentration increased propor-tionally as the simulated travel speed of the sprayer increased. Over the range tested, system pressure had little influence on the concentration of the output. These data showed that the chemical and carrier were well-mixed by the Raven SCS-700 system.

**Table 1. Steady state test results for spray pattern and chemical concentration uniformity**

| | Operating Pressure and Travel Speed | | | | | |
|---|---|---|---|---|---|---|
| | 207 kPa (30 psi) | | 276 kPa (40 psi) | | 345 kPa (50 psi) | |
| | 1.8 m/s (4 mile/h) | 2.7 m/s (6 mile/h) | 1.8 m/s (4 mile/h) | 2.7 m/s (6 mile/h) | 1.8 m/s (4 mile/h) | 2.7 m/s (6 mile/h) |
| **Volume/Spray Table Channel** | | | | | | |
| Mean (mL) | 42.3 | 42.4 | 49.3 | 49.1 | 51.9 | 55.5 |
| CV (%) | 10.4 | 6.6 | 6.0 | 5.8 | 6.1 | 4.0 |
| **Chemical Concentration** | | | | | | |
| Mean (g/L) | 0.08 | 0.11 | 0.08 | 0.11 | 0.07 | 0.10 |
| CV (%) | 3.9 | 4.1 | 4.1 | 0.0 | 7.0 | 5.0 |

### Dynamic Response Results

Response parameters for chemical concentration at each nozzle were tabulated (table 2). Delay time measurements were quite repeatable, with the largest CV being 3% for the three replications of data collected. The mean concentration delay times did not depend on the size of the step input given to the controller. This indicated that the nonlinearities present in the dynamic system were small enough that it could be successfully modeled as a linear system.

At the first nozzle, the average delay time was 15.0 s for all four operating conditions tested, while at the third nozzle there was an average 19.8 s delay time. It would obviously take more than 20 s for nozzle concentration to respond with wider nozzle spacings or more than three nozzles on one side of the boom, a situation which would be typical with field sprayers. These delays were similar to those reported by Budwig et al. (1988) in their tests of an SCS-700 system.

Concentration dead time was somewhat less repeatable than delay time (table 2), with the largest CV being 7%. As expected, the nozzles closer to the pump exhibited smaller dead times. Concentration rise time was even less repeatable (table 2), with a maximum CV of 34%. The higher CVs in the dead time and rise time measurements may have been due to the dynamic variations the system

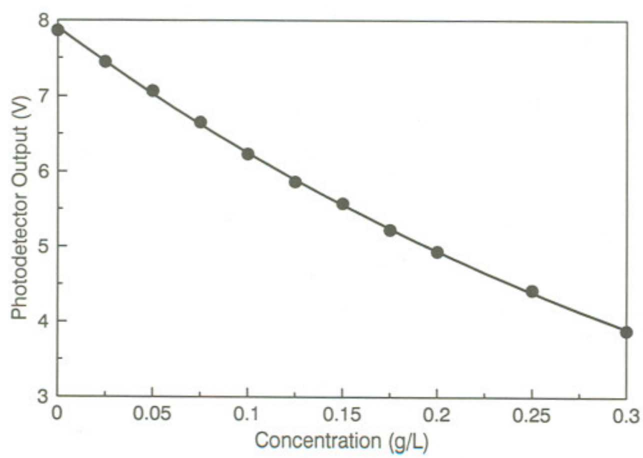


**Figure 3–Chemical concentration calibration curve used for steady state measurements.**

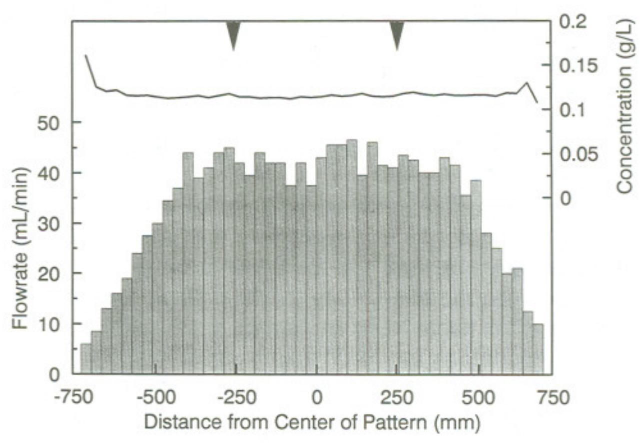


**Figure 4–Nozzle flowrate and chemical concentration distribution across the spray pattern for 207 kPa (30 psi) system pressure and 2.7 m/s (6 mile/h) simulated travel speed. Arrows indicate nozzle positions.**

Table 2. Chemical concentration response times obtained at each of the three nozzle positions

| Response Parameters | Nozzle Position | Travel Speed Step Change 1.8-2.7 m/s (4-6 mile/h) Mean | SD* | 2.7-1.8 m/s (6-4 mile/h) Mean | SD | 1.8-3.1 m/s (4-7 mile/h) Mean | SD | 3.1-1.8 m/s (7-4 mile/h) Mean | SD |
|---|---|---|---|---|---|---|---|---|---|
| Delay Time (s) | 1 | 14.5 | 0.5 | 15.1 | 0.2 | 15.1 | 0.3 | 15.4 | 0.5 |
| | 2 | 16.6 | 0.4 | 16.5 | 0.4 | 16.7 | 0.5 | 17.1 | 0.5 |
| | 3 | 20.8 | 0.5 | 19.7 | 0.1 | 19.6 | 0.3 | 19.9 | 0.2 |
| Dead Time (s) | 1 | 11.3 | 0.1 | 12.1 | 0.8 | 12.6 | 0.5 | 12.2 | 0.3 |
| | 2 | 12.6 | 0.5 | 12.9 | 0.4 | 13.9 | 0.6 | 14.0 | 0.3 |
| | 3 | 16.4 | 1.2 | 15.6 | 1.0 | 15.6 | 0.8 | 16.7 | 0.3 |
| Rise Time (s) | 1 | 10.4 | 3.6 | 8.2 | 2.3 | 8.1 | 0.9 | 10.0 | 2.5 |
| | 2 | 12.5 | 1.8 | 10.8 | 2.4 | 9.6 | 2.2 | 9.2 | 0.2 |
| | 3 | 10.4 | 1.4 | 10.8 | 0.4 | 13.2 | 1.3 | 8.7 | 0.7 |

* SD = standard deviation.

exhibited about its steady state operating points, as seen at the beginning and end of the test run (fig. 5). The low magnitude periodic oscillation about the operating point sometimes made it difficult to determine the 10% and/or 90% response points required for dead time and rise time measurements. As delay time was quantified at the 50% response point, the uncertainties present in that measurement were much lower.

The standard deviations of pump dead time and rise time (table 3) were smaller than those for the corresponding concentration measurements (table 2). A t-test with a 95% confidence interval showed that pump delay time was consistent for speed changes of the same magnitude, and independent of the direction of speed change (from low to high or high to low). However, pump response was dependent on the size of the step change in simulated speed, with smaller speed changes providing faster responses (table 3). This result indicated observable nonlinearities in the controller-injection pump dynamic system. However, these nonlinearities were small enough in magnitude that they became insignificant when considering the complete sprayer system.

Measured controller delay times ranged from 1.0 to 1.6 s (table 3). This was the time required for the chemical injection controller to give the injection pump/motor assembly the command to change pump speed after the step function input to the controller was given. Response of the SCS-700 injection controller would not be a limiting factor in the design of a variable-rate injection sprayer. At a field travel speed of 3 m/s (6.7 mile/h), a maximum of 4.8 m (16 ft) would be required for the controller to respond. With the same travel speed, a maximum of 14 m (46 ft) would be traversed during injection pump delay time. This distance approaches the minimum size which might be considered for a management cell in site-specific crop management; making the pump response marginal for variable-rate control based on real-time sensing. If, however, applications were based on premapped data, a predictive control algorithm could be used to accurately control pump output flow rates based on the calculated future position of the sprayer.

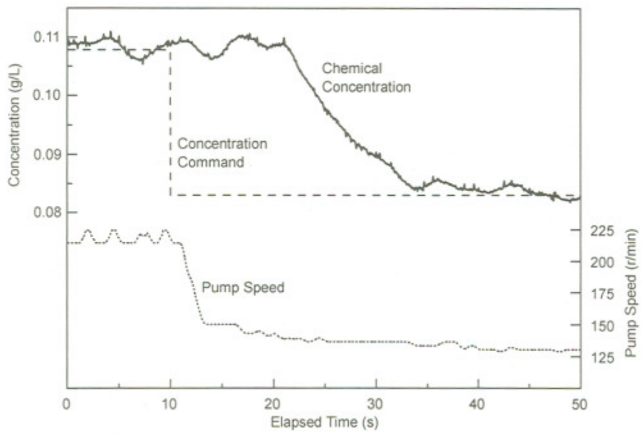


**Figure 5–Desired and actual chemical concentration (top) and injection pump speed (bottom) for simulated step change in travel speed from 3.1 to 1.8 m/s (7 to 4 mile/h). Chemical concentration measured at nozzle position 2.**

These measured response data were obtained with the pump control parameters in the SCS-700 system set to default values. The system controller allowed the user to vary several of these parameters, including backlash, response speed, and deadband of the pump controller. Changes in these control settings might decrease pump response time, but additional research would be required to determine the optimum values which would minimize response times while maintaining stable operation of the control system.

The major impediment to using direct injection technology for variable-rate application is the time lag encountered as the injected chemical moves through the spray boom and out the nozzles. In terms of travel distance, this delay could easily exceed 50 m. The transport delay could be reduced by the use of smaller diameter lines, but this would then increase the pressure drop in the system. Direct injection of the concentrated chemical at the spray nozzles, as reported by Miller and Smith (1992) and others, may provide a way to greatly reduce the transport delays associated with injection systems, provided that acceptable mixing of chemical and carrier for uniform concentration across the spray pattern can be maintained.

## Conclusions

The steady state and dynamic response of a Raven SCS-700 chemical injection system was evaluated. The following results were obtained:

**Table 3. Pump and controller response times**

| | Travel Speed Step Change | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.8-2.7 m/s (4-6 mile/h) | | 2.7-1.8 m/s (6-4 mile/h) | | 1.8-3.1 m/s (4-7 mile/h) | | 3.1-1.8 m/s (7-4 mile/h) | |
| Response Parameter | Mean | SD* | Mean | SD | Mean | SD | Mean | SD |
| Pump Delay Time (s) | 4.2 | 0.7 | 4.2 | 0.4 | 4.4 | 0.5 | 4.7 | 0.1 |
| Pump Dead Time (s) | 2.8 | 0.6 | 2.6 | 0.3 | 2.6 | 0.5 | 4.7 | 0.2 |
| Pump Rise Time (s) | 2.7 | 0.3 | 3.2 | 0.8 | 3.4 | 0.2 | 2.9 | 0.3 |
| Controller Delay Time (s) | 1.6 | 0.9 | 1.1 | 0.4 | 1.6 | 0.4 | 1.2 | 0.2 |

* SD = standard deviation.

- Chemical and diluent were mixed well in the system, with little variation in chemical concentration across the spray pattern.
- A large delay time was observed in chemical concentration after a step change in simulated travel speed. The majority of this delay was due to the transport delays associated with movement of the injected chemical through the mixing chamber and spray boom.
- Delay time for response of the injection pump speed was approximately 4 s, while the delay time associated with the injection controller was slightly more than 1 s.
- The controller and injection modules of the Raven SCS-700 system responded quickly enough that they would be usable for variable-rate chemical application.
- Chemical transport delays through the sprayer boom, inherent with any injection system, may cause significant areas of misapplication. The use of direct nozzle injection, where the raw chemical is injected into the carrier at the nozzle body, should be considered to reduce the magnitude of these transport delays.

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