To the Graduate Council:

I am submitting herewith a thesis written by Ray Allen Maynard II entitled "Transient Responses of Three Direct Formulation Injection Systems for Agricultural Sprayers." I have examined the final 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 in Agricultural Engineering.

Alvin R. Womac, Major Professor

We have read this thesis
and recommend its acceptance:

William E Hart

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

Transient Responses of Three Direct Formulation Injection Systems for Agricultural Sprayers

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

Ray Allen Maynard II
May 1997

ACKNOWLEDGMENTS

The author wishes to express his gratitude and appreciation to the following:

Former Agricultural Engineering Department head Dr. Fred D. Tompkins and current head Dr. C. Roland Mote for providing the opportunity to participate in the graduate program.

Dr. Alvin R. Womac for his instruction, guidance, and support while serving as major professor.

Dr. Fred D. Tompkins and Dr. William E. Hart, committee members, for their advice and support throughout the graduate program.

The Department of Agricultural Engineering faculty and staff for their assistance throughout my stay at The University of Tennessee.

Dr. Allen Straw for rating field tests.

Mr. Paul Elliot, Mr. Walker Garner, and Mr. Craig Wagoner for sharing their technical expertise, providing assistance in laboratory equipment construction, and constructing laboratory equipment.

Mr. David Russell for his guidance and supervision on electrical wiring of the laboratory equipment.

Ms. Tracey Odum for her assistance in collecting samples, entering data, and cleaning laboratory.

Fellow Graduate Students of the Department of Agricultural Engineering for their support and assistance.

Mr. and Mrs. Ray A. Maynard, the author's parents, for their support, both moral and financial.

ABSTRACT

Formulation injection into the spray diluent has many potential advantages, such as, less applicator exposure and improved application efficacy. However, there are some disadvantages associated with this technology that include formulation delivery delay time, inability to precisely deliver small amounts of formulation, and inadequate mixing of formulation into diluent.

Three types of formulation injection systems were observed to determine the transient performance of each system. An orifice-regulated system was designed and installed on a conventional sprayer. The orifice was calibrated under laboratory conditions before field efficacy tests were conducted. The efficacy of "before pump" and "after pump" injection sites were compared with a conventional tank-mix application at the same formulation rates.

Commercially available, water-driven, piston-type injection unit(s) were tested in a three-branch system that provided variable system dilution rates using the fixed-rate injection units. Two branches each contained an single water-driven injection unit while the third branch contained a throttling valve. Pressure transients from the pulsating units were of particular importance. Collected samples of nozzle discharge were measured for KBr concentration versus time. Flowrate through each branch was also measured.

An experimental, variable-speed, diaphragm unit was designed and operated for at-the-nozzle injection. The unit's flow was determined at different unit speeds and system pressures provided by an air back pressure arrangement. The unit also injected a KBr solution into an individual boom nozzle. The KBr solution was used as a tracer to determine the effects of diaphragm pulsation on nozzle discharge concentration uniformity versus time.

The orifice-regulated system delay time and nozzle-to-nozzle variation were measured using a manual method of KBr sample collection. The water-driven units' and the experimental unit's injection performance was measured using a rotary sampler of nozzle discharge that increased sample frequency compared to the manual method. The rotary method collected 103 samples per one minute test duration.

In the laboratory setup using a 5000 ppm KBr solution, the orifice-regulated system produced the desired formulation rate at the selected differential pressure [68.9 kPa (10 psi)] across the orifice for "after pump" injection. The differential pressure across the orifice for the "before pump" injection was affected by diluent pump suction, such that pressure supplied to the orifice had to be reduced by approximately 14-kPa (2-psi) to maintain the desired rate.

In the field study applying Gramoxone Extra (paraquat dichloride) and Latron AG-98 spreader activator, the orifice-regulated direct injection system provided broadleaf and grass control ratings that ranged from 26 to 90 percent, as compared to the tank-mix system ratings that ranged from 82 to 90 percent. The lowest rating (26 percent) was possibly caused by an orifice that plugged after calibration, or due to incorrect pressure differential across the orifice. The orifice-regulated system provided direct injection capability with efficacy comparable to conventional application, especially at higher formulation rates, i.e. larger orifice size. No significant difference (α=0.05) in control ratings were observed between "before pump" and "after pump" injection sites and conventional tank-mix applications for the 2.43 L/ha (0.25 gal/ac) formulation application rate.

The performance of the water-driven, piston pump unit varied based upon system branch selection, hose length configuration, and flowrate. The concept of using a bypass branch provided a potential method of varying KBr concentration by modulating flows through the bypass and the fixed-rate injection units. However, flow through the water-driven unit(s) was sensitive to adjustment of the bypass throttling valve due to the pressure loss [103 kPa (15 psi)] in the water-driven units. Dually-operated units did not generally lessen the intensity of the pressure pulse output, but rather tended to pulse simultaneously. The pressure measurements indicated this trend with individual water-driven unit operation variances that ranged from 71 kPa^2 (1.5 psi^2) to 361 kPa^2 (7.6 psi^2) compared to the range of dual unit variation from 532 kPa^2 (11.2 psi^2) to 4150 kPa^2 (87.3 psi^2). Pressure measurements showed no clear trend in variances between high and low system flowrates. Errors in KBr metering ranged from -57 to 26 percent and were attributed to KBr measurement accuracy, flowmeter accuracy, and the pumping efficiency of the water-driven unit at different flowrates. At higher flow rates, the water-driven units produced generally lower concentration variation (16 - 92 ppm^2) and generally improved KBr metering errors (-14 to 22.7%) compared to low flow KBr concentration variation (35 - 2037 ppm^2) and metering error (-57 - 26%).

The additional hose length downstream from the combining cross increased the upstream pressure variance range [436 - 2001 kPa^2 (9.2 - 42.1 psi^2)] as compared to upstream pressure variance range [266 - 766 kPa^2 (5.6 - 16.1 psi^2)] without the additional hose length. In contrast, the downstream pressure variance range [5 - 1635 kPa^2 (0.1 - 34.4 psi^2)] with the additional hose length was less than the downstream pressure variance range [361 - 4474 kPa^2 (7.6 - 94.1 psi^2)] without the additional hose length. Thus, the water-driven unit needs the additional hose length to smooth the pressure spikes that are inherent to its operation. The asymmetrical setup of the branches had no smoothing effect upon system operating characteristics.

The experimental-unit provided flowrates comparable to the rates required for injection at an individual nozzle. Specifically, the experimental unit produced flowrates for formulation application rates from 1.17 L/ha (0.125 gal/ac) to 4.68 L/ha (0.50 gal/ac) using a 6.4 km/h (4 mi/h) sprayer speed and 0.5 m (20 in) nozzle spacing. The experimental unit's flowrate range was provided by a twelve-fold increase in unit speed. Operating speeds greater than 10 rpm are required to increase the uniformity of nozzle discharge concentration versus time.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

CHAPTER I

INTRODUCTION

Background and Statement of Problem

There are three problems associated with metering and handling agricultural chemical formulations using conventional, tank-mix sprayer systems: calibration, exposure, and disposal. Conventional hydraulic sprayer systems must be calibrated for spray rate through operating pressure adjustments to achieve an accurate spray application rate. Results from a 1979 survey of 152 private and commercial applicators in Nebraska and western Iowa indicated that only one out of four operators applied pesticide formulations within a five percent tolerance of the desired spray application rate (Rider and Dickey, 1982). Incorrect calibrations accounted for the greatest number of application errors which ranged from 60 percent under-application to 190 percent over-application (Rider and Dickey, 1982). However, even if the sprayer was calibrated correctly, deviation in ground speed from the spray-calibrated speed caused an application error.

The second problem occurred after the operator calibrated the spray rate. The operator risked exposure to concentrated formulation during the measurement and pouring process required to correctly mix the specified formulation amount into the diluent tank. As an example, applicator over-exposure to pesticide formulations led to 8,241 hospitalized industrial and agricultural workers from 1971 to 1973 (Akesson et al., 1978). Kansas farmers who applied herbicide formulations more than 20 days per year had a sixfold-increase in risk of non-Hodgkin's lymphomas disease than the non-farming population (Doherty 1986). In response to over-exposure to pesticides, the Environmental Protection Agency (EPA) passed the 1992 Worker Protection Standard (WPS) for Agricultural Pesticides regulating workers' contact and interaction with crop protection formulations.

The third problem associated with conventional spray systems involves disposal of excess spray mixture. Disposal methods typically employ the application of diluted spray and wash water from the sprayer onto the crop (Akesson, 1987). This method increases the formulation application rate such that the formulation label rate may be exceeded, which is an illegal application. Besides the legal ramifications, formulation over-application may be potentially harmful to the crop and the environment.

In light of the problems associated with conventional spraying systems, alternative spraying systems were investigated. Considerable effort has been made by many researchers to develop a direct formulation injection system (Gephardt et al., 1984; Tompkins et al., 1990; Ghate and Phatak, 1990; and Ghate and Perry, 1993). Research indicates that direct formulation injection systems may offer (1) accurate formulation dispensing, (2) reduced operator exposure, as it pertains to the EPA WPS, and (3) reduced waste disposal.

One additional advantage that formulation injection systems may have over conventional spray systems is ease of adaptability to variable-rate formulation application for site-specific crop management. Site-specific, or prescription, farming requires a sprayer that can modify formulation application rates to match crop, field, or pest conditions. Accurate formulation application rates require an injection unit capable of precise metering with rapid rate adjustment.

Previous research has found that direct formulation injection systems have impediments. These shortcomings include (1) metering small rates of formulation at individual nozzles, (2) spraying uniformly due to inadequate mixing of formulation with diluent, and (3) transient errors due to changing sprayer ground speed (Vidrine et al., 1975).

Objectives

The project herein evaluates the suitability of three direct injection systems for use in agricultural production. The following formulation injection systems were examined; (1) a simple, orifice-flow-regulator-based system, (2) a commercial in-line, water-driven, positive displacement piston pump, and (3) an experimental low discharge-rate positive displacement diaphragm pump.

Specific objectives were:

(1) to determine the response time required for formulation output, the variation in formulation output among nozzles, and the effectiveness of herbicides for a steady-flow orifice-regulator-based system injecting upstream and downstream from the spray system pump,

(2) to characterize the steady-state transients of KBr solution metering, system pressures, and individual branch flow rate during single and multiple parallel branch service of water-driven units between the pressure-regulated system pump and the spray boom, and

(3) to determine the feasibility and operating characteristics of an experimental, low discharge-rate, positive displacement diaphragm pump injecting into an individual nozzle body.

CHAPTER II

REVIEW OF LITERATURE

Sprayer Importance

Effective agricultural production requires the accurate application of agricultural chemical formulations. Ksiazek (1985) stated that chemical formulations were being used to control agricultural pests on 95 percent of all corn and soybeans in the United States. If only one segment of agricultural formulations, herbicides, were not used, annual loss due to weeds would be as much as $19.6 billion (Bridges, 1992).

Using current control strategies, annual crop losses due to weeds were estimated at $4.1 billion (Bridges, 1992). Reichenberger (1986) estimated that misapplication costs ranged from $5.00 - $30.00 per ha ($2.00 - $12.00 per ac). Grisso et al. (1987) concluded from a 1986 survey of 103 private herbicide applicators in Nebraska, that $4.26 million was overspent on herbicides alone due to improper application.

Spray Metering and Application Systems

Conventional Sprayer Systems

Standard hydraulic systems mix chemical formulations and diluent, usually water, in the same tank. The sprayer pump moves the mixture from the tank to the sprayer boom. A pressure relief valve maintains a nearly constant pressure at the boom and the bypass flow from the relief valve is usually recirculated into the sprayer tank. Recirculation ensures formulation-diluent mixing by providing turbulence in the sprayer tank.

Direct Injection Systems

A sprayer using a formulation injection system contains undiluted formulation and diluent in separate tanks. The sprayer diluent pump moves diluent from the tank to the sprayer boom, usually at a constant rate. The injection system meters and pumps undiluted formulation into the diluent stream. The three sprayer injection sites are (1) preceding the diluent pump, (2) after the diluent pump and preceding the boom, or (3) at the hydraulic nozzles.

Formulation and diluent mixing depends on flow turbulence between the point of injection and the hydraulic nozzle exit. Injection upstream from the diluent pump allows turbulence within the pump to mix the formulation and diluent (Tompkins et al., 1990). Some systems employ an in-line mixer to introduce turbulence between the injection point and nozzles (Brown and Bennett, 1995, and Wolf, 1996). However, the delay required for the injected formulation to move from the injection point to the nozzle increases due to the added liquid volume of the mixer.

Spray Rate

Total spray rate is the amount of spray volume applied per unit area of field. Total spray rate from a hydraulic sprayer depends on the (1) nozzle flow rate, (2) ground speed of the sprayer, and (3) the sprayed width per nozzle. The spray rate remains constant unless ground speed or flow rate is changed. Spray width is usually considered constant for a fixed spacing of nozzles. Nozzle operating pressure affects flow rate and should be constant for a uniform application rate from hydraulic nozzles.

Chancellor et al. (1994) and Brown et al. (1995) demonstrated that variable-rate formulation applications may reduce total herbicide usage by 40 percent without reducing weed control or crop yield. Therefore, the ability to vary formulation rates during spraying may be desirable to optimize the use of often expensive chemicals. However, conventional sprayer systems cannot vary formulation rates without reducing the spray rate and altering spray particle dynamics. It has been noted that reducing the hydraulic nozzle flowrate below one-sixth of the rated rate caused a loss in nozzle spray pattern and poor crop coverage by droplets (Bode et al., 1979).

Formulation Rate

Common agricultural formulation rates of herbicides used in wheat, soybeans, corn, and cotton vary from 0.468 - 11.69 L/ha (0.005 - 1.25 gal/ac) (Rhodes, 1994). Common travel speeds for sprayers range from 4.8 - 24.1 km/h (3 - 15 mi/h). The following equation determines formulation injection rate per nozzle:

$$Q = \frac{RSV}{K} \tag{1}$$

where,

Q = output per nozzle(s), L/min (gal/min),

R = spray application rate, L/ha (gal/ac),

S = spray width, m (in),

V = sprayer ground speed, km/h (mi/h),

K = constant, 600 (m km)/ ha, (5940 (in mi)/ ac).

Applications using a variable-rate injection unit can control the formulation rate independent of the spray rate that may remain constant. Assuming a 140 L/ha (15 gal/ac) spray rate, the formulation volume is approximately 3.3×10^{-2} - 8.3 percent of the diluent volume. Formulation rate can be changed during the spraying operation without significantly affecting the spray rate and the resulting nozzle spray pattern.

During broadcast spraying with variable formulation rates, the injection system must change the formulation rate due to (1) the sprayer travel speed and (2) the desired formulation rate per unit of field area. Direct injection systems for variable formulation rates should have a larger range of injection rates than direct injection systems designed to only adjust the formulation rate based on changing sprayer speed.

The lowest formulation flow rate through the injection unit was determined based on (1) the narrowest common nozzle spacing of 0.50 m (20 in.), (2) the lowest common formulation rate of 0.0468 L/ha (0.005 gal/acre), and (3) the lowest common sprayer ground speed of 4.8 km/hr (3.0 mi/h). Inputting the lowest rate condition into Equation 1 resulted in a flowrate of 1.87×10^{-4} L/min (5.05×10^{-5} gal/min). The highest flowrate required through the injection unit was determined using (1) a nozzle spacing of 1.02 m (40 in.), (2) a formulation rate of 11.69 L/ha (1.25 gal/acre), and (3) a sprayer ground speed of 24.1 km/hr (15 mi/hr). Thus, the highest rate was 0.478 L/min (0.126 gal/min).

Turndown ratio indicates the ratio of an injection unit's metering range and is defined as:

$$TD = \frac{Q_h}{Q_l} \qquad (2)$$

where,

TD = Turndown ratio,

Q_h = highest formulation flowrate, L/min (gal/min),

Q_l = lowest formulation flowrate, L/min (gal/min).

A turndown ratio of 2500 is required for the highest and lowest chemical flowrates of 0.478 L/min (0.126 gal/min) and 1.87 x 10^{-4} L/min (5.05 x 10^{-5} gal/min), respectively.

Previous Direct Injection Research

System Studies

Vidrine et al. (1975) used a positive displacement pump to introduce pesticide formulations into a sprayer line upstream of the boom. Through testing in the laboratory, they concluded that the system could satisfactorily apply formulations for pest control. The system did not vary formulation flow rate to maintain a uniform application rate during conditions of changing sprayer speeds. Vidrine et al. recognized two problems with this system: (1) poor formulation deposition uniformity as compared to conventional systems, and (2) a slow response time to formulation injection rate change. They defined response times as the time from formulation injection to attaining 90 percent of the desired concentration at the nozzle. These response times ranged from 5 to 16 s.

Reichard et al. (1983) modified a Model 100 TMG sprayer (F. E. Myers Co., Ashland, OH) to inject pesticide formulation into the sprayer lines. Water diluent and formulation were contained in separate tanks. The formulation was pumped using a Hydracone Pulsafeeder metering pump (Interpace, Muskogee, OK). Diameter of the pump piston, length of stroke, and rate of stroke determined the formulation flow rate delivered by the metering pump. When set at the maximum stroke length, the metering pump delivered approximately 2.9 mL/stroke (0.098 oz/stroke). The formulation was injected into the sprayer line directly upstream from a Tee Valve boom selector valve (Spraying Systems, Wheaton, IL) which controlled the flow to three boom sections.

Reichard addressed concerns of formulation flow rate pulsation, as introduced by the pump, by investigating a pulsation dampener installed between the metering pump and the sprayer line. Water was treated with a fluorescent tracer and pumped through the metering pump into the sprayer line. Ten samples with durations no greater than 0.25 s were obtained from a nozzle on the boom. The coefficient of variations among samples with and without the pulsation dampener were 11 and 6 percent, respectively. Reichard concluded that natural line turbulence sufficiently mixed the tracer and water.

Reichard used the formulation injection unit to apply pesticide formulations to a potato crop and found no significant difference (P=0.95) between the insect control for the plots sprayed with formulation injection versus a conventional sprayer. Despite delay time problems, the injection system satisfactorily metered formulation at the proper rates when slow changes of travel speeds occurred. However, injection at the nozzle may be needed to apply proper rates when quick changes in travel speed or application rates are needed.

Koo et al. (1987) developed and verified a simulation model for calculating delay time in a formulation injection system. They used an actual boom sprayer to verify the results of the simulation model. The system injected a dye through a metering orifice into the sprayer line. A fluorometer indicated the concentration at a nozzle location with respect to time. Two pressure transducers measured the boom and injection pressures. A microcomputer-based data acquisition system interfaced the fluorometer and pressure transducers to monitor the fluorescence and pressure data.

The fluorescent tracing technique by Koo et al. evaluated delay times for step inputs. Results showed sizeable time delays associated with spray equipment injecting formulation directly into the sprayer lines. Delay times of up to 20 s were measured for the experimental setup. Koo et al. simulated various formulation applications with the effects of delay times. In a hypothetical 16.2 ha (40 ac) field with three terraces, the system misapplied formulation to 41 percent of the field area. Even though 51 percent of the area had been sprayed correctly, the system produced an absolute application error of at least 10 percent for the entire area. Koo et al. concluded that application errors were large enough that time delays should be minimized. Steps to minimize delay times include smaller sprayer lines and increased boom flow rates. Koo et al. stated that the best way to minimize delay time is to inject the chemical formulations at each nozzle body using a low volume metering device.

Tompkins et al. (1990) tested three types of injection systems for (1) uniformity of formulation concentration at the nozzles and (2) transient time to reach desired formulation concentration. Injection systems tested included (1) low-pressure injection upstream from the system diluent pump, (2) high-pressure injection downstream from the system diluent pump, and (3) injection into individual nozzles. Delay times from formulation injection to nozzle equilibrium were found to be 24 and 12 s for low pressure and high pressure line injections, respectively. The delay times for the individual nozzles were found to be negligible. Variation of the mean bromide concentrations among nozzles were 2 to 3, 5 to 11, and 19 to 37 percent for low pressure injection, high pressure injection and individual nozzle injection, respectively. Also, uniformity depended on system configuration changes that included the use of three different injection pumps. Pump types used included (1) a peristaltic pump for low pressure side only, (2) a Scienco fabricated piston pump, and (3) a Fluid Metering Inc. (Oyster Bay, NY) piston pump.

Tompkins et al. (1990) concluded that formulation injection directly into the individual nozzles effectively eliminated delay times. However, a consistent nozzle-to-nozzle formulation concentration was difficult to obtain using a pump with manifold assembly. The nozzle injection site reduced the time allowed for fluid turbulence within the system, and hence, a reduced mixing effect.

Miller and Smith (1989) reported that direct formulation injection at the spray nozzles was feasible. In Miller and Smith's injection system, the diluent flowed through a 90 degree turn before entering the nozzle body that was positioned vertically. The system injected formulation into the diluent stream while the diluent stream was in the process of changing directions. This injection orientation provided mixing of diluent and formulation across nozzle pattern and time.

The limitation of Miller and Smith's system was reliable metering of formulation. The system varied differential pressure across an orifice. The pressure differential change was based on the change of sprayer ground speed to achieve a constant formulation application rate. To operate the sprayer over a six-fold speed range, the differential pressure across the orifice plate at top speed was 36 times that at the lowest speed. For this reason, orifice selection limited the formulation flow rate.

Ollila et al. (1990) integrated a field grid sense system with direct injection technology. Using a positive-displacement, variable-stroke piston pump, formulation injection rate was altered from 0.059 - 1.48 L/min (0.016 - 0.391 gal/min). The system injected upstream of a 0.40 m (16 in.) in-line mixer before supplying the sprayer boom. The lag time for the system was reported to be 40 s at a sprayer speed of 8 km/h (5 mi/h). This translates into a sprayer-travel distance of 100-110 m (327-362 ft) of misapplied formulation.

Hou et al. (1993) tested a Raven (Sioux Falls, SD) SCS-700 formulation injection system for use in variable rate application. The study concluded that the Raven system controller could be used, although a delay in formulation transport through the sprayer boom resulted in misapplication to a significant area of the field. In terms of sprayer-travel distance, this delay exceeded 50 m (164 ft). Hou et al. noted that use of direct nozzle injection may reduce the delays in delivery of the formulation.

Shearer et al. (1995) evaluated a direct injection unit for use in variable application of herbicide formulations based on soil texture, organic matter content, and yield potential. The direct injection system injected the formulation upstream of the spray boom (Shearer et al. 1992). Application errors for the direct injection system were as high as 40 percent based on misapplied areas of the field. These application errors, caused by the delay in formulation concentration changes at the boom nozzles, occurred for a distance as much as 80 m (262 ft) from the location of the rate change initiation.

Miller and Stafford (1995) patented a direct injection sprayer suitable for spatially-variable spraying. The injection system incorporates ideas to lesson the response time for the injected chemical formulation to move to the nozzle. A response time of 0.2 s is reported. The metering device is a water-driven cylinder with one end containing water and the other end containing concentrated formulation.

Brown and Bennett (1995) also investigated an injection system improvement for injecting herbicide formulations based upon spatial variability. A prototype direct injection system was developed to deliver formulation directly upstream of the nozzle tips. This design reduced transient lag time to approximately 0.1 s. The system used independent metering pumps for each nozzle to assure precise flow injection. Evaluation of injection system performance pertaining to formulation and diluent mixing throughout the nozzle pattern, concentration versus time, and uniformity between nozzles has not been reported.

Chemical Concentration Measurements

Several methods have been used by researchers to measure chemical concentration of the solution produced by direct injection. Cho et al. (1985) injected a salt solution, collected samples from the nozzle effluent, dried the samples, and then weighed the dried samples. Weights of the sample were related to chemical concentration in the sprays; the heavier the residue sample, the higher the concentration. Chemical concentration measurements by this method took more than a day to complete because of the drying process.

Koo et al. (1987) and Vidrine et al. (1975) used flourometric analysis of direct injection produced solution. Koo injected a fluorescent dye (Rhodamine B) and connected a fluorometer to the boom. The fluorometer measured the intensity of the emitted light from the effluent. Light intensity increased as concentration increased and was related to concentration through a calibration curve.

Tompkins et al. (1990) used potassium bromide (KBr) to represent the simulated chemical formulation to be injected into the sprayer lines. Tompkins et al. (1990) used a solution of 28.3 grams (1 oz) of KBr per liter (0.25 gal) of distilled water. After injecting the KBr solution into a sprayer line, the resulting solution had an approximate concentration of 0.6 g/L (8.4×10^{-2} oz/gal). A field conductivity meter (Cole-Palmer, Niles, IL.) was used to measure samples over a range of 0.05 to 1.0 g/L (7.1×10^{-3} - 0.14 oz/gal). The injection tracer of KBr was chosen for its relatively linear response over a range of concentrations.

Hart et al. (1991) used a KBr solution to test spray tank rinsing procedures. Hart concluded that an Orion 290A meter and bromide specific probes proved to be a reliable device for detecting bromide concentration in samples. Bromide concentration measurements ranged from 1 to 10 000 ppm.

The Orion 290A pH/ISE meter specifications state that direct electrode measurements are reproducible to 2% with hourly calibration (Analytical Technology, 1995). The bromide sensor can be used in temperatures from 0° to 80° C (32° to 176° F) (Analytical Technology, 1995). However, bromide sensor detection sensitivity was 2% for every 1° C (2° F) difference from measured solution temperature to calibration solution temperature (Analytical Technology, 1995).

CHAPTER III

PROCEDURES AND EXPERIMENTAL METHODS

Introduction

Evaluations of three injection systems were conducted. First, an orifice-based injection system was installed on a conventional hydraulic sprayer. The sprayer was replumbed to allow formulation injection into the diluent line upstream and downstream from the sprayer diluent pump. The formulation injection rate was regulated by orifices. The orifice-based system was tested for response time, uniformity of KBr concentration in nozzle discharge across boom, and biological efficacy.

Second, a commercial in-line, water-driven injection unit was installed on a hydraulic spray boom in a laboratory setting. The water-driven unit supplied a constant injection ratio of KBr solution to diluent. The resulting solution was collected from an individual nozzle on the boom and measured for KBr concentration during selected tests. The water-driven unit(s) was tested in varied piping configurations to allow use of the injection units during variable-rate formulation application and to detect any configuration effect on system pressure and flow transients. The flowrate and pressure measurements were recorded for each test.

Third, an experimental, low discharge-rate, diaphragm pump supplied a KBr solution to an individual nozzle on a spray boom. The experimental unit was evaluated for water flowrate under various pressure and speed conditions before installation into the spray boom system. During spray boom system testing, the flowrate, pressure, and KBr concentration were recorded versus time. From recorded data, the uniformity of KBr concentration versus time was examined for the effect of unit pulsations.

Formulation Substitute

Solutions of potassium bromide (KBr) were used to simulate formulation during orifice-regulated system, water-driven unit, and experimental unit testing. Tompkins et al. (1990) described KBr as being readily available, relatively inexpensive, and safe to handle. Windholtz et al. (1983) indicated that large ingested doses of KBr could cause central nervous system depression and prolonged intake may cause mental deterioration and acne-like skin blemishes. KBr has therapeutic applications as a sedative and anticonvulsant and manufacturing applications in photographic paper and plate production (Windholtz et al., 1983). KBr is a white granular material with a specific gravity of 2.75. One gram readily dissolves into 1.5 mL of water with the resulting aqueous solution pH neutral (Windholtz et al., 1983).

Analytical reagent grade KBr crystals were used to formulate calibration standards and injection solutions. KBr crystals weighing 14.89 g (3.53×10^{-2} oz) are collected and mixed into solution to yield the specific 10 000 ppm bromide concentration. The 10 000 ppm KBr solution was serially diluted to produce 1000, 100, 10 and 1 ppm KBr solution standards.

The Orion (Boston, MA) 290A portable pH/ISE meter and model 9435 bromide half-cell sensor (ion selective electrode) were calibrated hourly to check instrument straying from calibration standards. A measurement error could be introduced from the sensor's sensitivity to temperature change. Temperature compensation was included in the ion selective probe, provided the calibration and test solutions were at nearly the same temperature. However, the tests were conducted with no temperature control between calibrations. Overall error in bromide measurement was assessed at +/- 10 percent for the overall range of conditions encountered in the study.

Orifice-Regulated Injection System

Design

An orifice-regulated injection system was developed to apply varied formulation rates into the diluent line upstream from the system pump (Figure 1) and downstream from the system pump (Figure 2). The design allowed use of the conventional hydraulic system either as a conventional "tank-mix" spray system or as a direct injection system.

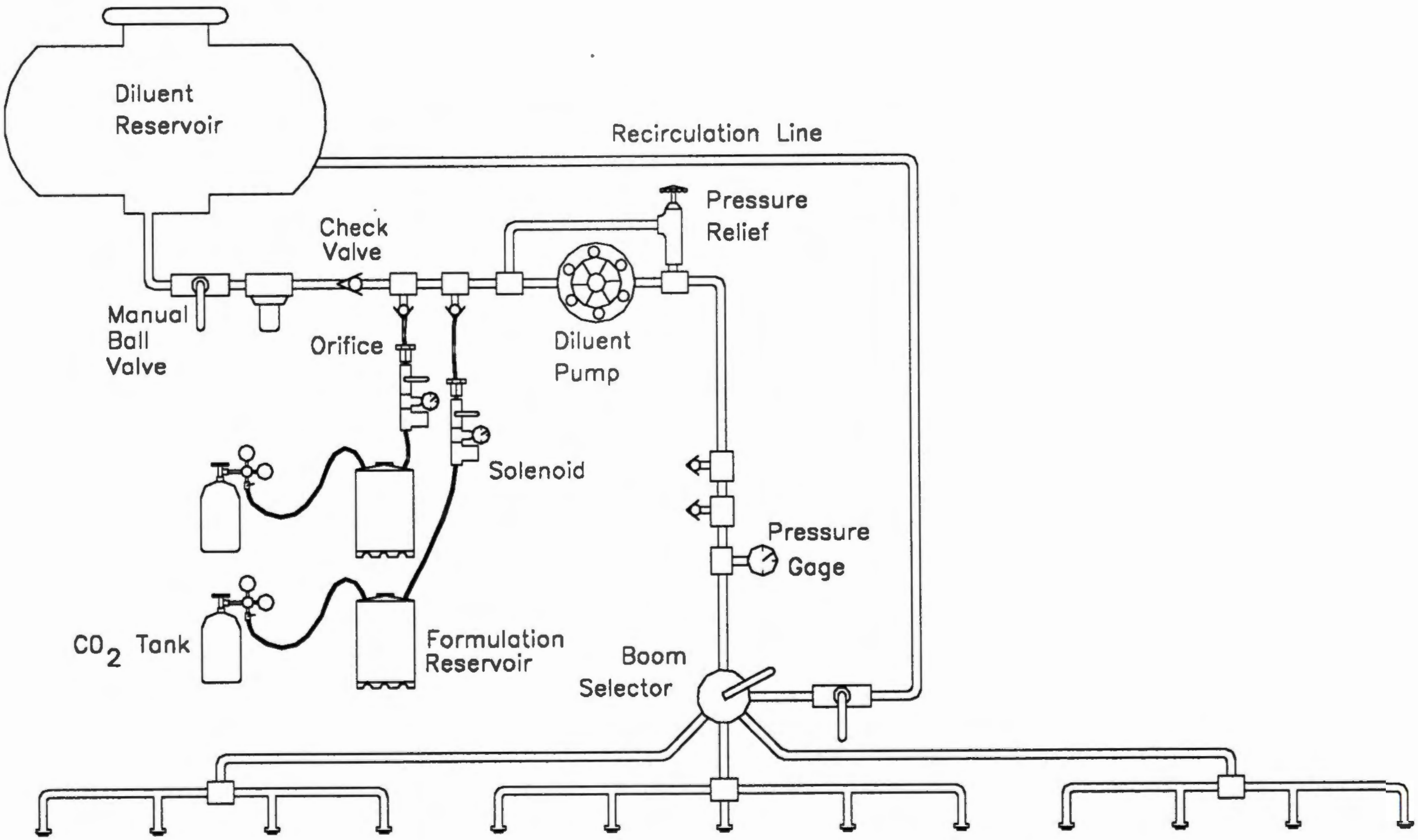


Figure 1. Orifice-based injection system with injection location preceding diluent pump.

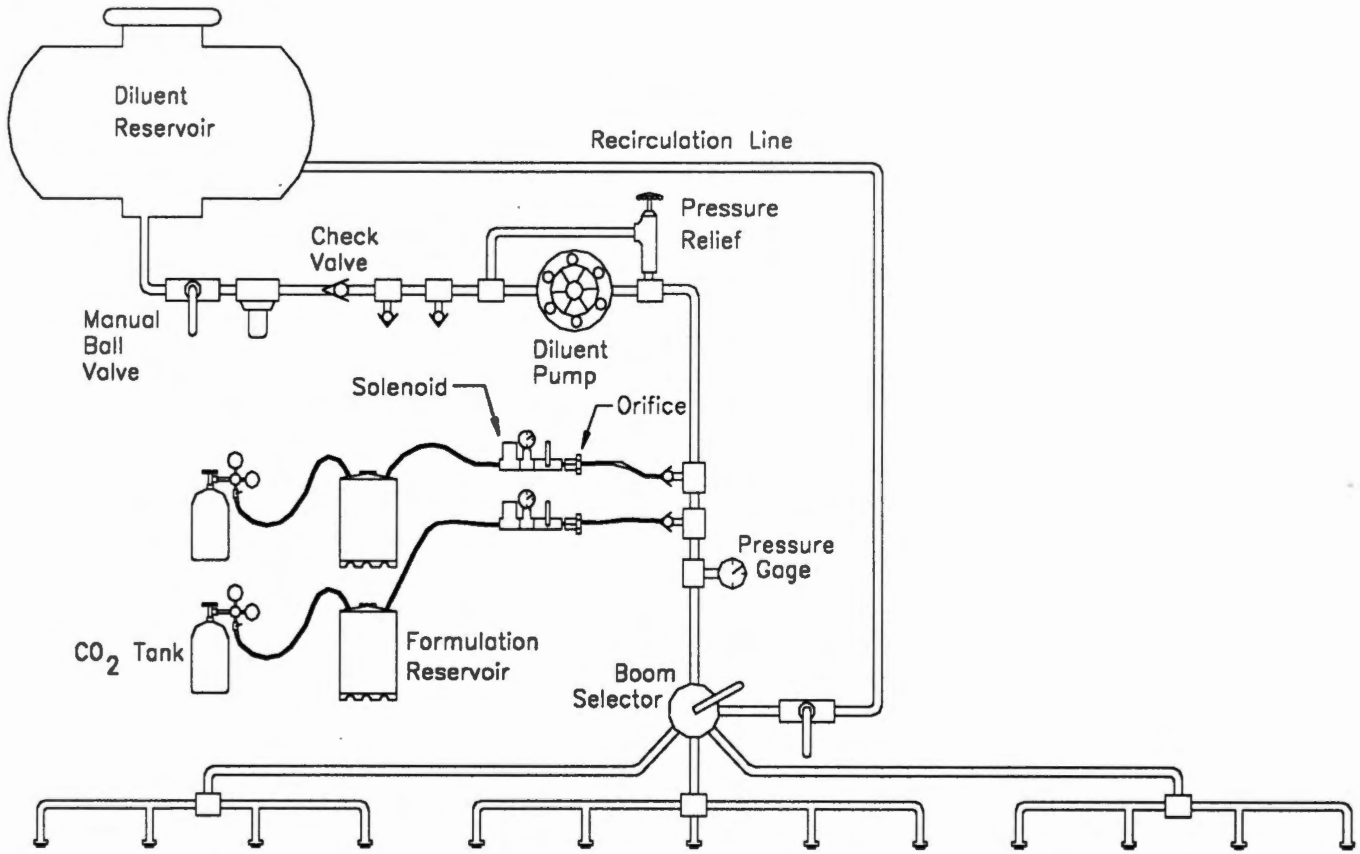


Figure 2. Orifice-based injection system with injection location after diluent pump.

The system had three possible formulation application configurations; (1) "before pump" injection, (2) "after pump" injection, and (3) "tank-mix".

The orifice-regulated injection system required two functions: (1) formulation storage and (2) formulation flow. Stainless steel beverage containers equipped with industrial-type disconnects (R&D Sprayers, Opelousas, LA) provided formulation storage. High pressure carbon dioxide (CO_2) tanks (R&D Sprayers, Opelousas, LA) provided pressure to cause formulation flow. A pressure regulator and shutoff valve on the CO_2 tank controlled the CO_2 flow to the formulation storage reservoir. From the formulation storage reservoir, the formulation entered a 6.35 mm (0.25 in) diameter polytetrafluoroethylene (PTFE) transport line (Cole Palmer, Niles, IL). The line carried the formulation to a 12-volt, model 2203 solenoid control valves (Texas Industrial Rencor, Temple, TX). The solenoid control valve allowed the sprayer operator to remotely permit or prohibit formulation flow. A normally closed type solenoid valve was used such that loss of power closed the valve to prevent unwanted formulation flow.

Immediately following the solenoid valve was a 5-cm (2-in) diameter pressure gage with 13.8-kPa (2-psi) divisions. The pressure gage preceded the orifice to accommodate pressure reading directly upstream from the orifice. A manual shutoff valve located between the pressure gage and the orifice prevented formulation flow during accidental switching "on" of the solenoid valves during transport or conventional spraying.

The orifice body, orifice plates, hose shank, and cap (Spraying Systems, Wheaton, IL) were attached to the manual shutoff valve. The orifice plates were selected based on the desired formulation rate at a constant sprayer speed of 6.4 km/h (4 mi/h) and a spray width of 0.5 m (20 in) (Equation 1). Correct orifice sizes for the six desired formulation rates were selected using the orifice selection chart located in Spraying System's catalog. Orifice sizes were selected according to flowrates at a 68.9 kPa (10 psi) pressure difference across the orifices. Five orifice sizes were selected with one orifice size (orifice # 32) serving two flowrates with an increased differential pressure [96 kPa (14 psi)] for the larger flowrate (Table 1). The orifices provided formulation metering into the formulation line.

The formulation line was equipped with a one-way shut-off coupling (R&D Sprayers, Opelousas, LA) immediately preceding the injection point. The quick coupler allowed easy manual changes of injection location. The male coupler was internally checked to prevent formulation leakage at disconnect. A brass poppet check valve (Specialty MFG., St. Paul, MN.) installed after the female coupler prevented system diluent from entering formulation lines during system use and prevented the diluent from leaving an inactive injection site.

Three modifications were made to the conventional sprayer provided by the University of Tennessee Plateau Experiment Station to allow the system to operate safely with the injection system attached. First, a 19 mm (0.75 in) swing check valve (Cole Palmer, Niles, IL.) was installed between the diluent reservoir and the diluent

Table 1. Orifice selection chart based upon manufacturer data for a 690 kPa (10 psi) pressure difference across orifice.

Sprayer Speed km/h (mi/h)	Nozzle Spacing m (ft)	Formulation Application Rate L/ha (gal/ac)	Formulation Flow Rate for a Nozzle L/min (gal/min)	Formulation Flow Rate for Boom[a] L/min (gal/min)	Orifice Number
6.4 (4)	0.5 (20)	1.17 (0.125)	6.35×10^{-3} (1.68×10^{-3})	0.0825 (0.0219)	# 18
		1.76 (0.188)	9.54×10^{-3} (2.52×10^{-3})	0.1240 (0.0328)	# 22
		2.34 (0.250)	1.27×10^{-2} (3.37×10^{-3})	0.1651 (0.0438)	# 26
		3.51 (0.375)	1.91×10^{-2} (5.05×10^{-3})	0.2483 (0.0656)	# 32
		4.10 (0.438)	2.23×10^{-2} (5.89×10^{-3})	0.2899 (0.0766)	# 32[b]
		4.68 (0.500)	2.56×10^{-2} (6.77×10^{-3})	0.3328 (0.0875)	# 37

[a] Thirteen nozzle boom

[b] Operated at 83 kPa (14 psi) pressure difference

pump suction-side injection point to prevent inadvertent contamination of the reservoir through possible backflow of the injected formulation. Second, a manual shutoff valve was installed on the hose from the boom selector valve to the diluent reservoir. This shutoff valve prevented diluent flow into the diluent reservoir during injection applications. With this shutoff valve open, diluent circulation to the diluent tank could provide additional mixing during "tank-mix" applications. The third modification was the rerouting of the flow released by the pressure relief valve. Excess flow was routed to the suction side of the pump rather than to the diluent reservoir. Additional components of the spray system included a manual shutoff valve from the diluent reservoir, diluent in-line filter, and a dry boom equipped with thirteen Spraying System's 8003 nozzle tips.

Tests

The orifice-regulated system was tested under laboratory-controlled conditions for accurate metering of desired formulation rate, response time, and nozzle to nozzle uniformity. The response time and nozzle to nozzle uniformity were measured using KBr as a tracer. First, the system was calibrated for the correct spray application rate. By using Equation 1 with a 9464 L/ha (25 gal/ac) spray rate, 0.5-m (20-in) nozzle spacing, and 6.4 km/h (4 mi/h) travel speed, the desired average nozzle output was 1.27 L/min (0.3367 gal/min). New 8003 nozzles are rated at 1.14 L/min (0.30 gal/min) at 276 kPa (40 psi) (Spraying Systems, Wheaton, IL). The output from each nozzle was collected in a 2-L (0.5 gal) container for one minute. Nozzle operating pressure was adjusted until the average nozzle output across the boom was within 5 percent of the desired nozzle output.

Second, the system was checked for correct metering by each specified orifice. The orifice flowrate was calculated by measuring the water mass flow rate. The water-filled beverage container was weighed for an initial weight before operation of the system. After injection system operation, the beverage container and remaining water were weighed for a final weight. The difference between initial and final weights in kg (lb) was divided by elapsed time (min) for the mean mass flowrate kg/min (lb/min). The mass flowrate divided by the water density of 1.0 kg/L (8.3 lb/gal) gave the volumetric flowrate, L/min (gal/min), through the tested orifice.

Third, the system response time was measured. The diluent was sprayed through the boom nozzles at the desired rate. The formulation injection lines were filled with KBr solution to the quick couplers immediately preceding the diluent line injection point. With the diluent flowing at a steady rate, the solenoids were opened to allow the KBr formulation to flow.

The right boom section outside nozzle was chosen as the sampling location for the response time tests. This location was chosen because it was the "worst case" location for response time such that it should have the greatest response time. Samples from the nozzle were collected over a 10 s period with 5 s between samples for insertion of the next sample cup. Therefore, one sample was taken every 15 s with the sample representing an average bromide concentration over 10 s. The sampling lasted for 100 s from the activation of the solenoid valve. The response time for the KBr to reach equilibrium at the nozzle was calculated for two KBr formulation flowrates at the two injection locations.

The uniformity of KBr concentration output from nozzle-to-nozzle across the boom was also checked. Samples were collected by placing cups under nozzle pairs for a duration of 10 s, with 5 s allocated for cup replacement. This process began at the left boom section outside nozzle and proceeded across the boom for all thirteen nozzles. The last three nozzles were sampled simultaneously. The sample KBr concentration measurements were analyzed for variance (s^2). Sample variance is defined as the average value for the squares of the deviations of individual observations from the sample mean. Sample variance is calculated using equation 3.

$$s^2 = \frac{\sum_{i=1}^{n} X_i^2 - \frac{(\sum X_i)^2}{n}}{n-1} \qquad (3)$$

where: s^2 = Sample variance

n = number of observations

X = observation value

The percent difference of the measured mean nozzle bromide concentration from expected mean bromide concentration was calculated. A 5000 ppm KBr solution was injected into a spray rate of 234 L/ha (25 gal/ac). The ratio of formulation rate to spray rate was multiplied by the injection solution concentration to calculate the expected concentration of nozzle discharge. For the 1.17 L/ha (0.125 gal/ac) application rate, the expected concentration of nozzle discharge was 25 ppm. For the 2.34 L/ha (0.250 gal/ac) application rate, the expected concentration of nozzle discharge was 50 ppm.

Fourth, the orifice-regulated system was used in field trials applying paraquat dichloride (Gramoxone Extra, Zeneca, Wilmington, DE) and Latron AG-98 spreader activator (Rohm and Haas, Philadelphia, PA). The efficacy tests were conducted on The University of Tennessee Plateau Experiment Station. Six test combinations of the three system setups and two formulation rates were applied. The formulation application rates [2.34 L/ha (1 qt/ac), 1.17 L/ha (1 pt/ac)] correspond to injection rates using orifice 26 and orifice 18, respectively, with a 70 kPa (10 psi) differential pressure across the orifices. The paraquat dichloride and spreader activator were applied simultaneously through separate orifice-regulated lines at the specified formulation rate. The tests are: Test A, "before pump" injection, orifice 26; Test B, "before pump" injection, orifice 18; Test C, "after pump" injection, orifice 26; Test D, "after pump" injection, orifice 18; Test E, "tank-mixed", orifice 26 rate; Test E, "tank-mixed, orifice 18 rate. Four replications were conducted of each treatment.

Treatment efficacy was determined by a plant scientist experienced in chemical control ratings. Allen Straw, The University Tennessee Plateau Experiment Station research associate, visually rated the percent kill of broadleaf and grass in the sprayed area. The broadleaf and grass control ratings were statistically evaluated based upon the average control ratings of the four plots for broadleaf, grass, and overall control. These control ratings were grouped using general linear model's Duncan's multiple range test.

Water-Driven Injection System

Design

An experimental direct injection system was designed to use two in-line, water-driven, piston-type formulation injection units. The commercially available injection units delivered a fixed ratio of formulation flow per amount of diluent flow. The injection units produced a pressure drop from diluent entrance to diluent and formulation mixture outlet. The pressure drop was caused by diluent energy consumption to produce formulation flow.

The sprayer boom, which the water-driven units supplied, was designed by Tompkins (1990) to operate over a pressure range of 140 - 690 KPa (20 - 100 psi) and to maintain a line fluid velocity between 1.5 - 1.8 m/s (4.9 - 5.9 ft/s). The boom was equipped with 9 QJ-100 series nozzle bodies (Spraying Systems, Wheaton, IL), spaced 0.5-m (20-in) apart. The nozzle size and number used was varied depending upon tests.

The sprayer was also equipped with a 757 L (200 gal) diluent reservoir which supplied a Hypro (St. Paul, MN) Model N1502 roller pump driven by a 7.5 HP GE (Ft. Wayne, IN) motor. System pressure was controlled by a manual pressure regulator. A GPI (Wichita, KS) electronic digital flow totalizer indicated cumulative water flow into the system, and an Ametek (Largo, FL) 0 - 1379 kPa (0 - 200 psi) pressure transducer provided pressure signals for automated data collection by a Campbell Scientific (Logan, UT) Model 21X data logger (Figure 3).

Diluent was split to three parallel branches at the “flow split cross” (Figure 3). The three outlet branches of the cross each contained a shutoff valve and a Raven turbine flowmeter. Two outlet branches contained the in-line units and the other contained a Spraying Systems 1.3-cm (0.5-in) nominal size throttling valve. Immediately preceding each in-line unit was a Delavan (Lexington, TN) one-inch “Y” filter with 100 mesh screen. Rigid 2.5 cm (1 in) nominal PVC pipe plumbed the system from the inlet valve to the “Y” filter. A 1.3-cm (0.5-in) nominal diameter hose connected each branch to the four way cross indicated as the “flow combining cross” (Figure 3). An Ametek 0 -1379 kPa (0-200 psi) pressure transducer located at the flow combining cross output monitored the pressure downstream of the parallel branches. It should be noted that mounting the pressure transducers, or gauges, in a tee directly at the in-line unit outlet resulted in pressure transducer failure due to pressure shocks attributed to the in-line unit. The spray boom was connected to the outlet of the “flow combining cross” by 1.3-cm (0.5-in) hose. A precision Ashcroft (Stratford, CT) test

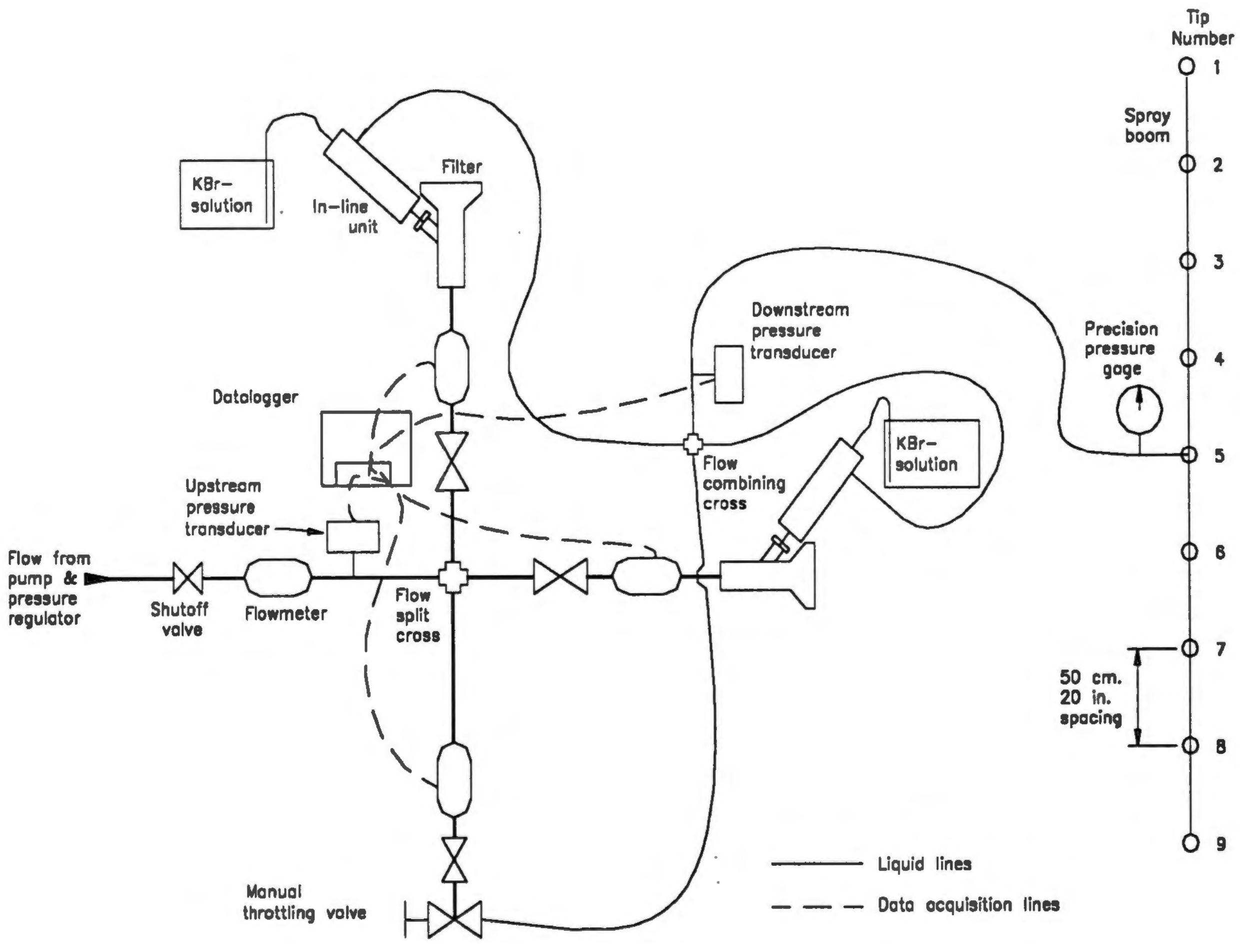


Figure 3. Schematic of water-driven unit test stand indicating hydraulic lines and instrumentation lines.

gauge indicated spray boom pressure and facilitated adjustment of the system pressure regulator.

The data logger recorded (1) the flowrates indicated by the three Raven flowmeters, (2) the pressures indicated by the two Ametek pressure transducers, and (3) the test interval indicated by a manual start button that flagged the data start and stop corresponding to the temporal sampling of chemical concentration. Instantaneous pressure values were logged at 0.6 s intervals and integrated flow rate pulses were logged at 1.0 s intervals.

Rotary Chemical Sampler

A method for determining the chemical concentration discharged from the nozzle in short increments was devised to observe the temporal performance of the in-line injection unit. Use of in-line test probes was investigated but found to be limited in terms of line pressures, tracer chemicals, and verification of distribution in the sampled line. Previous direct injection research used a grid of collection cans, arranged in rows under each nozzle of a spray boom, so that the spray boom was manually moved over the rows of cans while the spray was being discharged (Tompkins, 1990).

The concept of collecting the nozzle discharge was refined for shorter sampling intervals with development of a rotary device for temporal sampling (Figure 4). The circular-shaped sampler was 1.2 m (4 ft) in diameter and was rotated by a synchronous gear motor at one rpm. One hundred and four sampling vials mounted to the perimeter

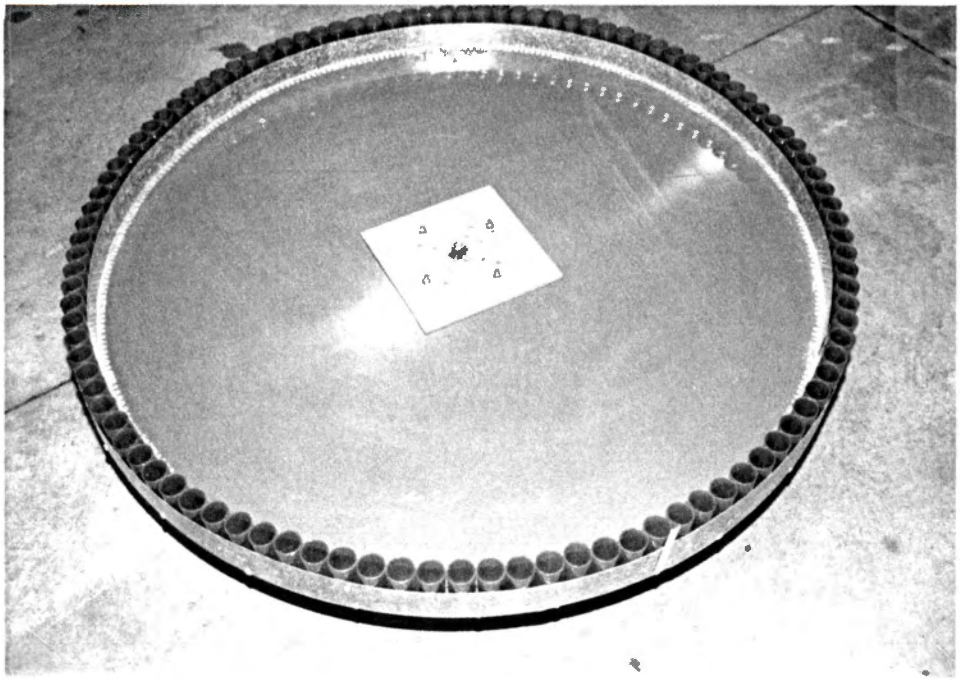


Figure 4. Rotary device for temporal sampling of nozzle output.

collected the spray output from a single nozzle. The sample vials were 7.32 cm (2.88 in) long with a 3.18 cm (1.25 in) diameter. A small plastic funnel directed the spray discharge into the vials to reduce splatter and to insure singular collection by each vial. The start and stop of sampling was coordinated with data acquisition of pressures and flow through use of a hand held switch that flagged the logged data, as discussed previously. The data collection interval was one minute.

The solution contained in sampling vials was measured for KBr concentration. The Orion meter readings were manually recorded and entered into a computer database. Use of the rotary sampling device required clean vials for each test event to reduce contamination. This was periodically monitored for residues by adding water to clean vials and measuring for KBr.

The in-line units injected a KBr solution of approximately 10 000 ppm. However, the exact concentration of each injection solution was measured for calculating concentrations from the nozzle. The concentration at the nozzle output was calculated for in-line unit injection as follows:

for in-line injection,

$$PPM_{Calculated} = \frac{PPM_{Supply}}{Ratio_{Injection}} \tag{4}$$

for in-line injection with bypass,

$$PPM_{Calculated} = \frac{PPM_{Supply}}{Ratio_{Injection}} - \frac{Flow_{Injector}}{Flow_{Total}} \tag{5}$$

for in-line injection with and without bypass,

$$ERROR\ (\%) = \frac{PPM_{Calc} - PPM_{Meas}}{PPM_{Calc}} * 100 \tag{6}$$

Tests

The in-line units were tested in combinations of two possible operating modes: (1) total liquid flow passing through injection units or (2) partial liquid flow passing through injection units. The mode with partial liquid flow through the water-driven units was called "bypass". Possible in-line unit operation during each mode included single or dual unit injection.

Effect of downstream hose arrangement was tested along with the two modes and unit operation choices. Using the plumbing arrangement described previously, twenty tests were conducted to evaluate in-line injector performance during the mentioned modes and with several hose configurations (Table 2). The four hose configurations areas follows; symmetrical setup (Figure 5) - identical 63.5 cm (25 in) hose length in each parallel branch to the flow combining cross, additional hose length (Figure 6) - 6 m (20 ft) hose added between flow combining cross and spray boom, asymmetrical setups - 6m (20 ft) hose length in parallel branch after in-line unit (Figure 7) and 6 m (20 ft) hose length in parallel branch after in-line unit with 63.5 cm (25 in) hose length preceding in-line unit (Figure 8). Test 1 was conducted with the bypass portion of the test stand open. No flow went through the in-line units. This test was conducted determine background information about pressure fluctuations and pressure drop through the system. The test used low flow conditions determined by five 8004 nozzles (Spraying Systems, Wheaton, IL) and the symmetrical hose configuration.

Table 2. Water-driven unit test matrix of flow conditions, hose configurations, unit injection ratios, and parallel branch used.

Hose Configuration									3' hose before in-line unit	
				20' hose addition						
				after flow-combining cross				after in-line unit		
Sample Location	middle nozzle		end nozzle	middle nozzle						
Unit Ratio	32:1					48:1	48:1 & 32:1	32:1		
Flow	Low	High			Low	High				Parallel Branch
Test Numbers	1									Bypass
	2	8		13	15	17				1
	3									2
	4	9	12	14	16		18	19	20	1 & 2
	5	10								1 & Bypass
	6									2 & Bypass
	7	11								1,2 & Bypass

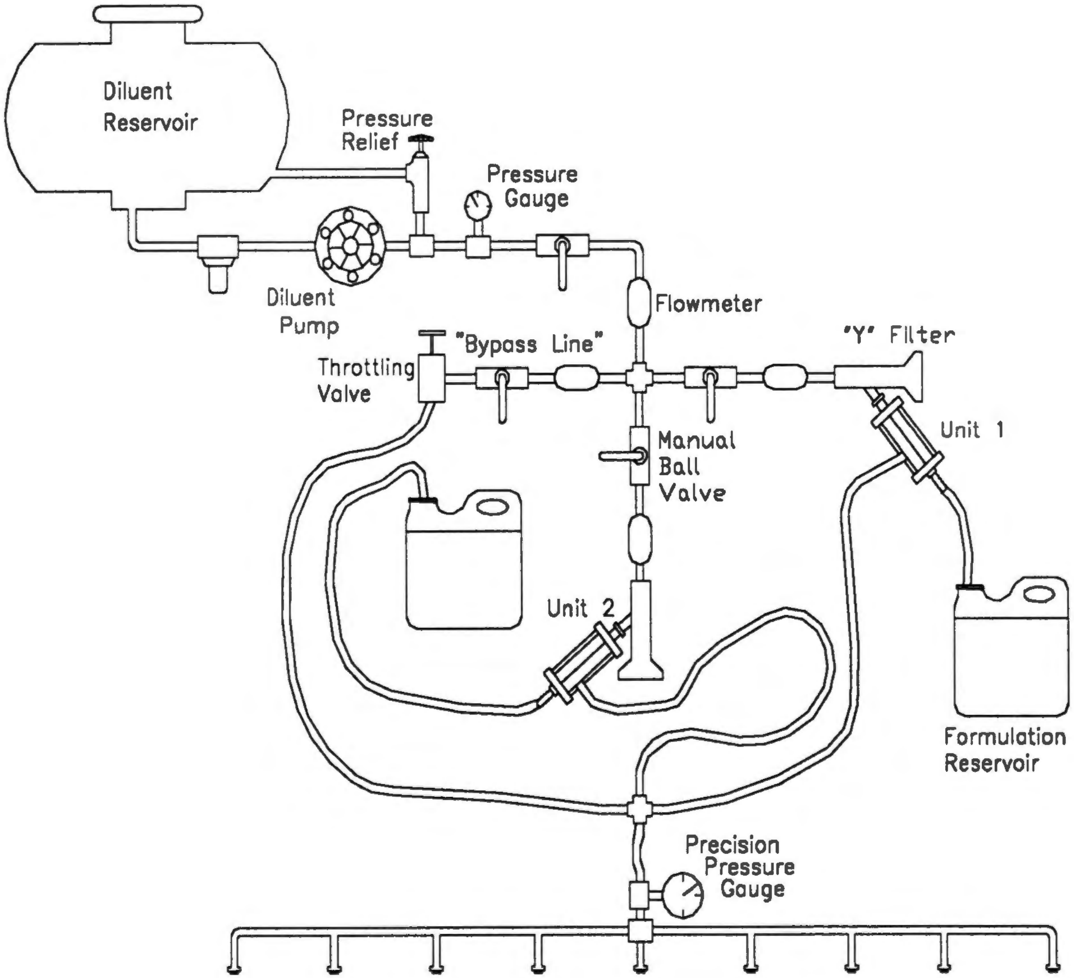


Figure 5. Schematic of symmetrical hose setup downstream of water-driven units for tests 1 through 12.

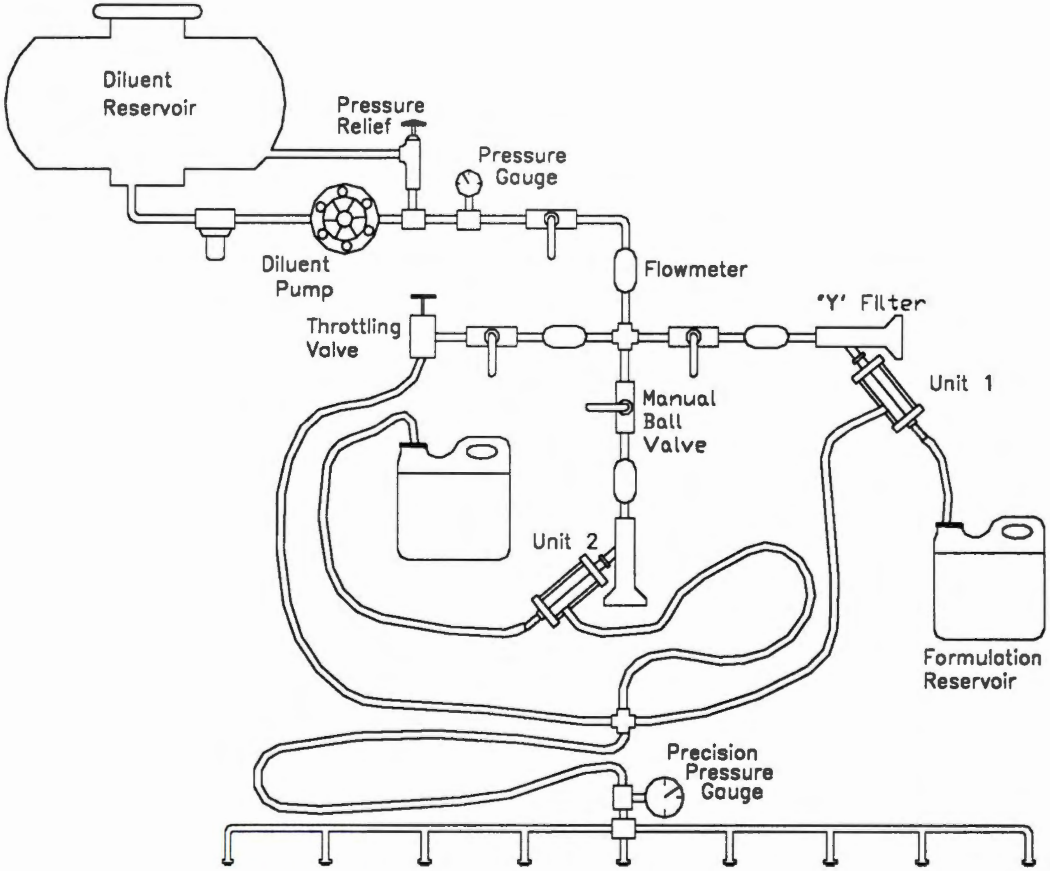


Figure 6. Schematic of additional hose length setup downstream of water-driven units for tests 13 through 18.

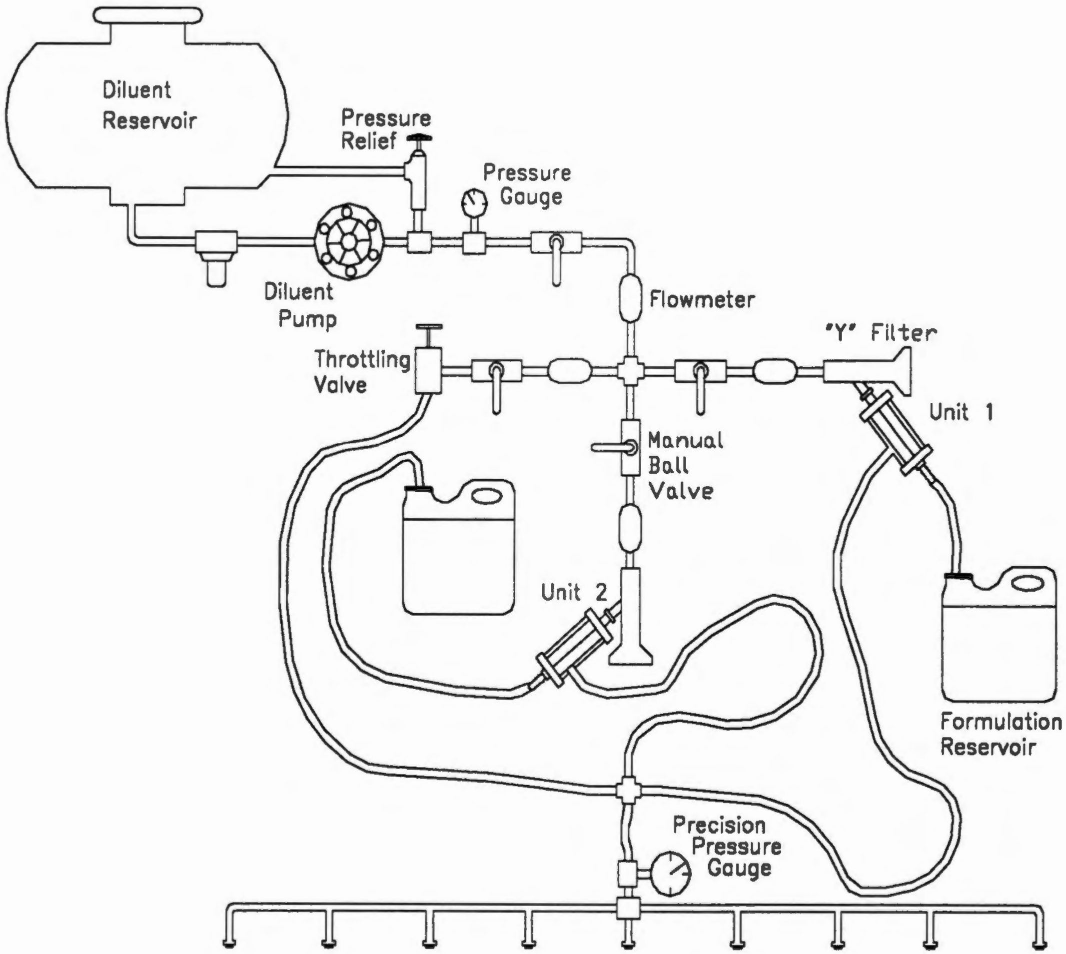


Figure 7. Schematic of asymmetrical hose setup downstream of water-driven units for test 19.

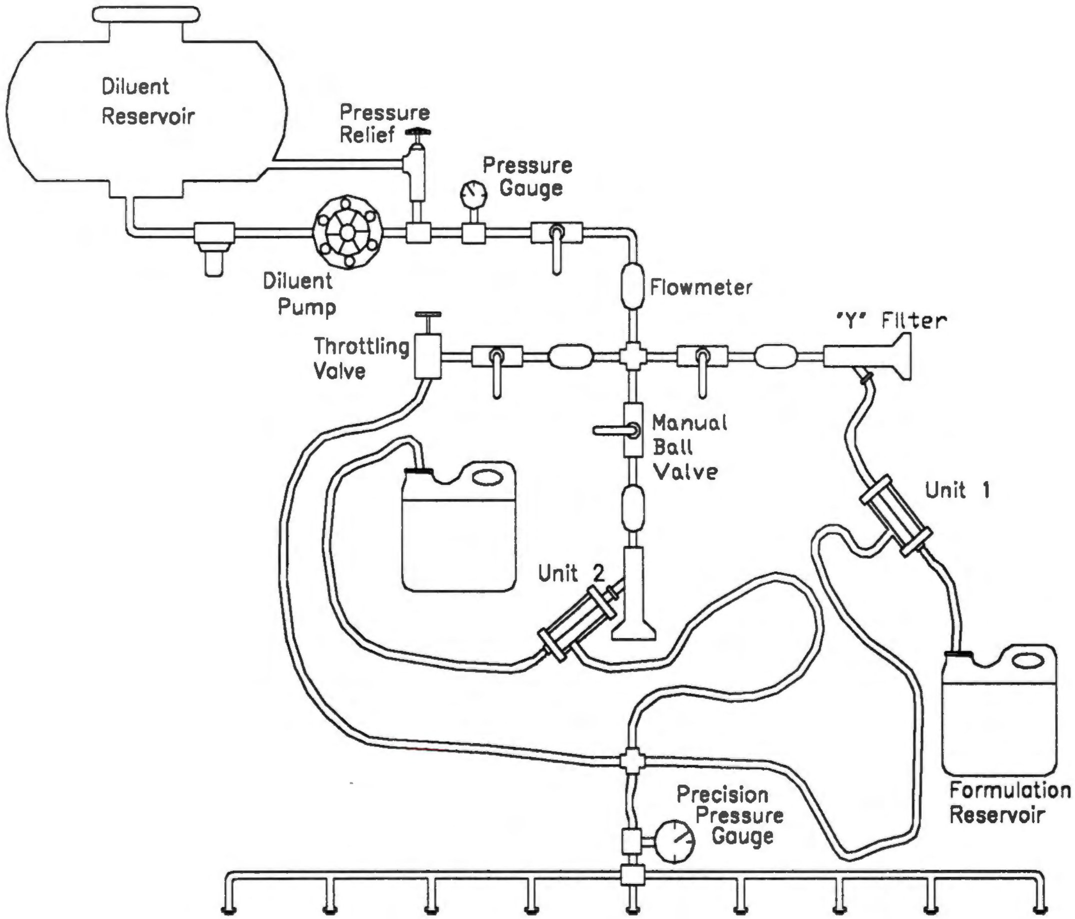


Figure 8. Schematic of asymmetrical hose setup downstream and upstream of water-driven units for test 20.

The first seven tests were conducted under the low flow conditions and symmetrical hose configuration. Test 2 used a single 32:1-ratio in-line unit. Test 3 used a single 32:1 ratio unit located on another branch of the parallel circuit. Test 4 was conducted with two 32:1 in-line units dually operated. All flow went through the respective in-line units.

Test 5, 6, and 7 were nearly identical to 2, 3, and 4 - except the bypass branch of the parallel circuit was opened to allow some water flow through it. The bypass line was investigated as a means of modulating the nozzle discharge KBr concentration for the fixed ratio injection unit.

Test 8 began a series of tests using the high flow conditions determined by the use of nine 8008 nozzles tips (Spraying Systems, Wheaton, IL) on the boom and the symmetrical hose configuration. Test 8 was conducted with one 32:1-ratio in-line unit. Test 9 used two 32:1-ratio in-line units dually. Test 10 used one 32:1-ratio unit plus the bypass. Test 11 used two 32:1-ratio in-line units and the bypass.

Test 12 checked whether KBr concentration was affected by sampling location along the boom. Instead of sampling at the middle nozzle of the nine tip boom, the sampling location was at one boom end. Test 12 was setup identical to test 9, except for sampling location.

Tests 13 through 16 examined the effect of the addition hose length configuration. This change was made to investigate the pressure dampening effect of the hose section. Tests 13, 14, 15, and 16 had setups that corresponded to tests 8, 9, 2, and 4, respectively, regarding unit use.

Test 17 was conducted with a single 48:1-ratio in-line unit. Test 18 used a 48:1-ratio and a 32:1-ratio unit on two separate branches of the parallel circuit. The twenty-foot hose section was still in place during these tests.

The asymmetrical hose configuration was used for Test 19 and Test 20. The asymmetrical hose lengths were examined to determine whether the timing of an in-line unit's pulsations were varied due to an altered hose length. A check of the KBr concentration measurements was also performed . The collected samples were measured twice. One measurement was collected clockwise around the sampler. The second measurement was collected counter-clockwise to check for KBr instrument drift. The setup for Test 20 was similar to that of Test 19 using the second asymmetrical hose configuration.

Experimental Diaphragm Injection Unit

Design

An experimental low-volume, variable-speed, diaphragm injection unit was designed and constructed to supply formulation to a single nozzle on a sprayer boom. The experimental unit was driven by a Dayton (Niles, IL) Model 4Z135D right- angle high torque DC gearmotor. The motor was rated to produce up to 180 RPM with 0.2 N-m (36 in-lbs) of torque at input motor power of 93 W (0.13 HP).

The unit's output was piped to a Teflon cap inserted in a graduated cylinder (Figure 9). The Teflon cap was securely placed in the graduated cylinder to provide a air tight seal using a screw clamp. The Teflon cap had two quick connect tubing fittings. One fitting was for the unit flow and the other was for an air pressure supply. By pumping against air pressure, the volume of unit flow could be visually determined using the graduated cylinder. The air pressure regulator was adjusted to provide different pressure settings between tests.

The sprayer system discussed in the water-driven unit testing was also used to test the experimental diaphragm unit (Figure 10). Nine 8004 flat fan nozzles (Spraying Systems, Wheaton, IL) were used in the spray boom nozzle bodies. Diluent flow through the system was measured with a Raven turbine flowmeter while corresponding pressures were measured with a 0 - 1379 kPa (0-200 psi) Ametek pressure transducer. A precision Ashcroft test gauge indicated spray boom pressure and was referenced during adjustment of the system pressure regulator.

The Campbell Scientific 21X data logger monitored (1) the flowrates indicated by the turbine flowmeter, (2) the pressures indicated by the pressure transducer, and (3) a manual start button that flagged the data collection interval corresponding to the temporal sampling of KBr concentration in the nozzle discharge by the rotary sampler.

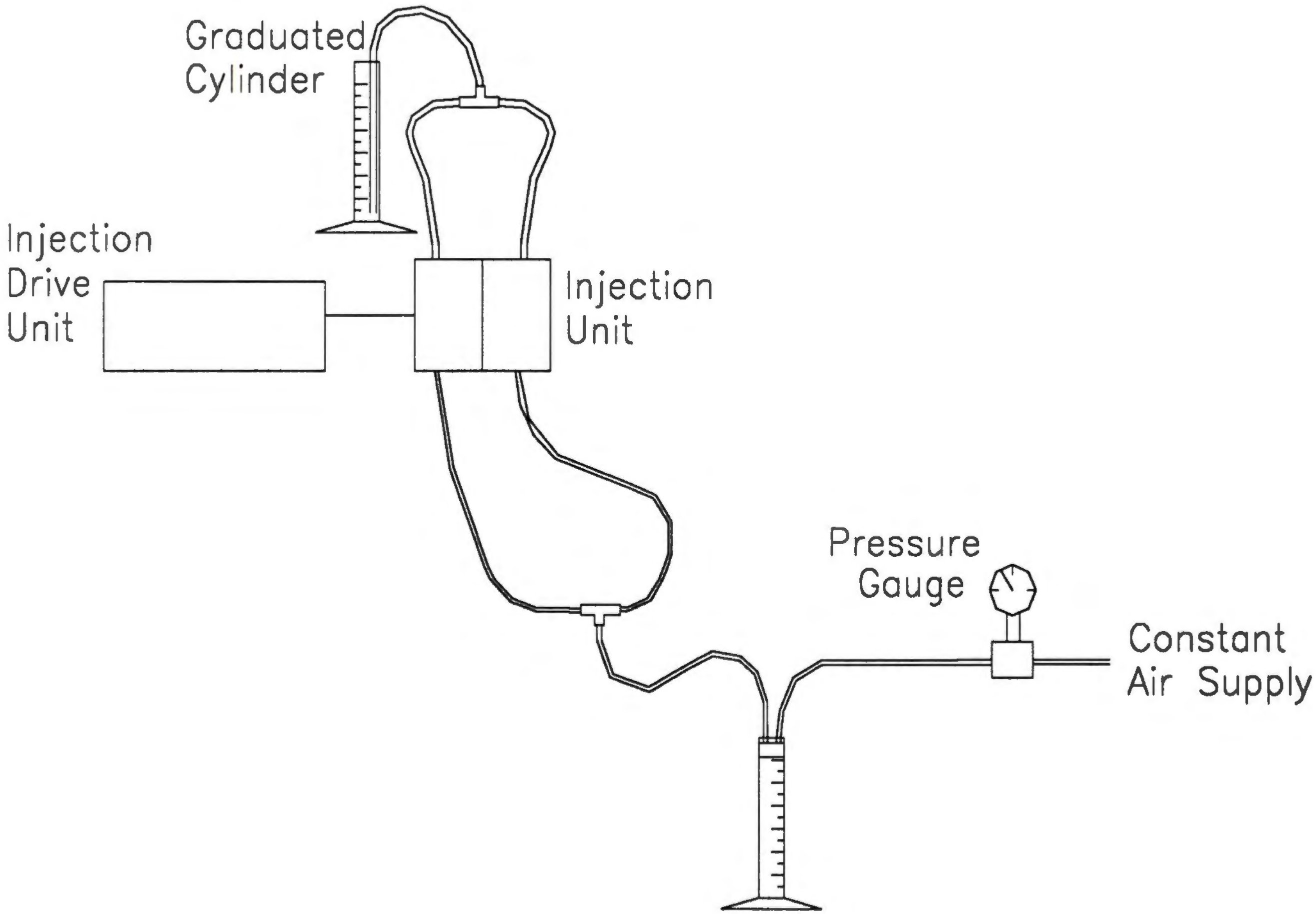


Figure 9. Schematic of experimental setup used to test prototype injection unit.

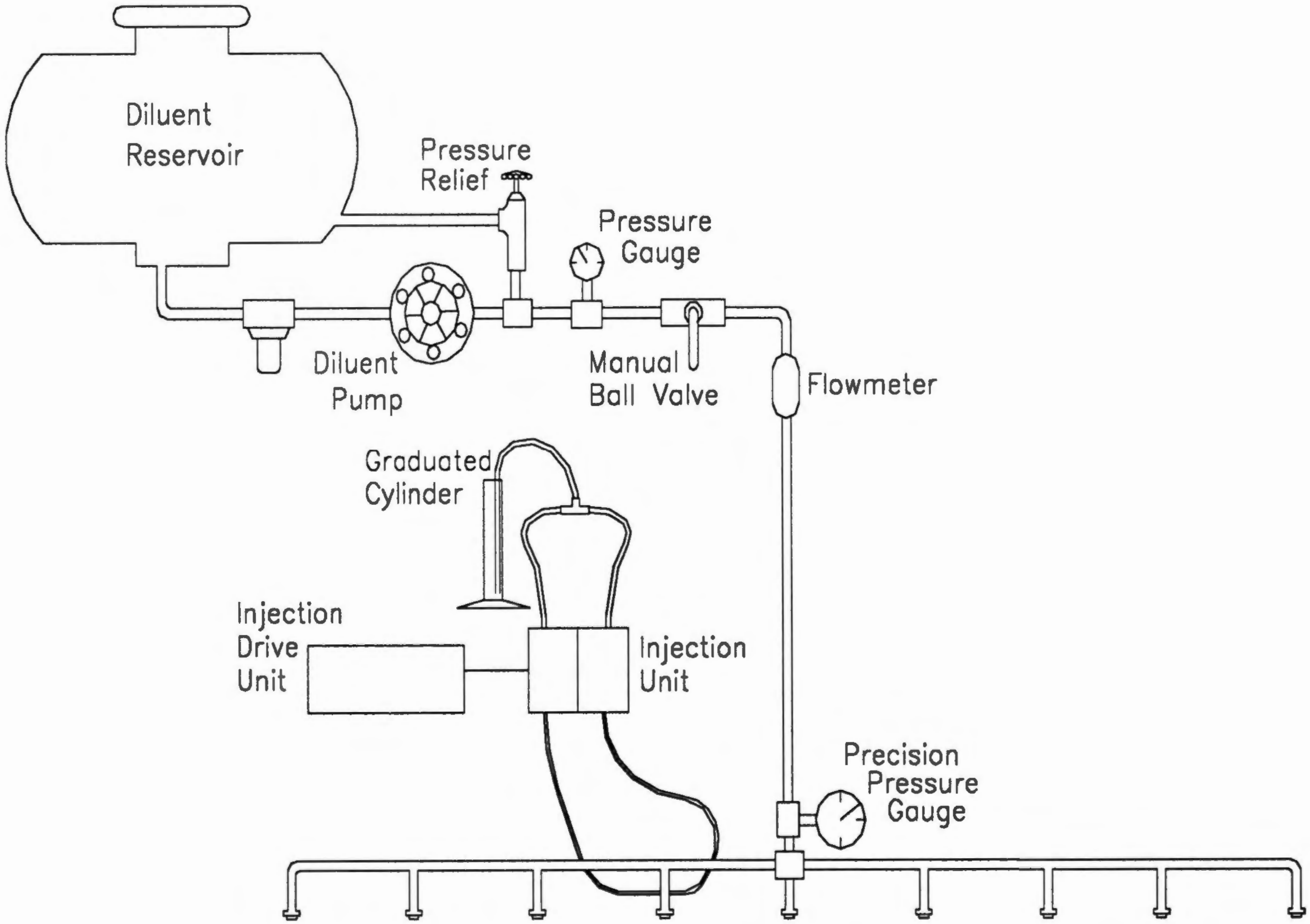


Figure 10. Schematic of experimental setup used to test prototype injection unit in spraying system.

Instantaneous pressure values were logged at 0.6 s intervals and integrated flow rate pulses were logged at 1.0 s intervals.

Tests

The experimental diaphragm-type injection unit was evaluated for (1) determination of unit flow at selected pressures and motor speeds and (2) effect of unit operation on uniformity of KBr concentration in nozzle discharge. The flow rate from the unit was measured at four speeds and four determined pressures (Table 3). Sixteen test combinations were assigned a number, placed into a box, and drawn to randomly determine test sequence. Air pressure provided the four test pressures at which unit flow was measured. The unit's flow was collected and measured in a graduated cylinder. The cylinder was emptied and dried between tests.

The effect of unit operation on uniformity of KBr concentration in nozzle discharge was tested by installing the unit in the spray boom system. The unit's output was injected horizontally into a vertical nozzle body immediately preceding the nozzle tip. System flow and pressure were measured while KBr concentration samples were collected. The KBr concentration of liquid in sampling vials was individually measured with a hand held meter attached to probes inserted into each vial. The meter readings were manually recorded and entered into a computer database. The experimental unit injected a KBr solution of approximately 10 000 ppm.

Table 3. Experimental diaphragm unit test matrix of system pressures and unit speeds.

Pressure kPa (PSI)	Unit Speed RPM			
103 (15)	10	50	90	120
207 (30)	10	50	90	120
310 (45)	10	50	90	120
414 (60)	10	50	90	120

CHAPTER IV

Results

Orifice-Regulated System

Calibration

The boom nozzles for the orifice-regulated system produced flow above the necessary output at 206.8 kPa (30 psi) (Table 4). At 193 kPa (28 psi), the output of the thirteen nozzles averaged 1.29 L/min (0.34 gal/min) (Table 4). Each nozzle, except number eleven, was within 5% of the mean nozzle output (Table 4).

The selected orifice sizes produced flowrates similar to the desired flowrates for the selected differential pressure (Table 5) using a 10 000 ppm KBr solution. However, the pressures were determined using low-precision, 5-cm (2-in) pressure gauges that had 13.8 kPa (2.0 psi) graduations. These coarse graduations affected the repeatability of an accurate pressure setting. A low differential pressure [69 kPa (10 psi)] across the orifice compounded the repeatability problem through sensitivity to pressure regulator adjustment. Differential pressures determined by trial-and-error for five orifices at the two injection locations are summarized (Table 5).

Table 4. Orifice-regulated system sprayer nozzle calibration

Nozzle Number	Nozzle Output L/min (gal/min) Test Pressure 206.8 kPa (30 psi)	193 kPa (28 psi)
1	1.30 (0.343)	1.28 (0.338)
2	1.29 (0.341)	1.28 (0.338)
3	1.32 (0.349)	1.29 (0.341)
4	1.32 (0.350)	1.30 (0.343)
5	1.31 (0.347)	1.28 (0.339)
6		1.35 (0.357)
7		1.34 (0.354)
8		1.34 (0.354)
9		1.27 (0.335)
10		1.29 (0.341)
11		1.19 (0.314)
12		1.26 (0.333)
13		1.31 (0.346)
Average	1.31 (0.346)	1.29 (0.342)

Table 5. Orifice-regulated system injection pressure and flowrate for each orifice size

Formulation Application Rate	Orifice Selection[a]	Desired Mass Flowrate	Injection Before Pump			Injection After Pump		
			Δ Pressure	Actual Flowrate	Flowrate Difference	Δ Pressure	Actual Flowrate	Flowrate Difference
L/ha (gal/ac)	Size Number	kg/min (lb/min)	kPa (psi)	kg/min (lb/min)	%	kPa (psi)	kg/min (lb/min)	%
1.170 (0.125)	18	0.083 (0.183)	55 (8)	0.093 (0.205)	12.4	69 (10)	0.087 (0.194)	4.8
1.76 (0.188)	22	0.124 (0.293)	55 (8)	0.117 (0.257)	8.3	69 (10)	0.128 (0.282)	0.4
2.34 (0.25)	26	0.166 (0.365)	69 (10)	0.183 (0.403)	10.2	69 (10)	0.170 (0.374)	2.4
3.51 (0.375)	32	0.249 (0.500)	69 (10)	0.226 (0.497)	9.1	69 (10)	0.268 (0.590)	7.8
4.10 (0.438)	32	0.290 (0.638)	83 (12)	0.312 (0.686)	2.2	83 (14)	0.312 (0.686)	2.2
4.68 (0.50)	37	0.332 (0.730)	69 (10)	0.376 (0.827)	4.4	69 (10)	0.372 (0.818)	4.0

[a] Orifice selected based upon 6.4 km/h (4 mi/h) sprayer speed and 0.5 m (20 in) nozzle spacing

The needed orifice differential pressure at the "before pump" location tended to be lower than the selection differential pressure. This tendency was probably caused by suction of the diluent pump. Two orifice sizes (18 and 22) had flowrate percent differences from the desired flowrate of 24 and 27 percent at the selection differential pressure of 69 kPa (10 psi). The same orifices had flowrate percent differences of 12 and 8 percent, respectively, from the manufacturer's data at a differential pressure of 55 kPa (8 psi). The remaining three orifices produced flowrate differences of 10, 9, and 4 percent at the selection differential pressure.

The needed pressure for injection at the "after pump" location did not vary from the selection differential pressure. The flowrate percent difference from expected for the five orifice sizes was 5, <1, 2, 8, and 4 percent, respectively, for orifice sizes 18, 22, 26, 32, and 37. The improved flowrate accuracy of the "after pump" injection may have occurred because the system pressure gauge was closely positioned to the injection location.

Nozzle output KBr concentration versus time revealed a sprayer response time of 40 to 50 s for "before pump" injection with orifice 18 (Table 6). "After pump" injection provided a 25 to 35 s delay from solenoid opening to KBr delivery at the correct rate from the nozzle. Orifice size 26 provided a 20 to 30 s response time for "after pump" injection and a 25 to 35 s response time for "before pump" injection. These results were obtained with the formulation lines filled to the injection point. With the size 18 orifice, formulation line filling takes an additional 20 to 30 s.

Table 6. Orifice-regulated system response time

	KBr Concentration (ppm)			
	Orifice 18		Orifice 26	
Time (s)	Before Pump	After Pump	Before Pump	After Pump
0-10	<5	<5	<5	<5
15-25	<5	19	40	42
30-40	15	29	53	43
45-55	25	29	54	45
60-70	31	29	53	46
75-85	35	28	52	46
90-100	33	28	50	46

Variation in KBr concentration from nozzle-to-nozzle was 0.2 ppm^2 (Table 7) for orifice 18 at the "before pump" injection location. The KBR concentration ranged from a high of 35 ppm to low of 33 ppm with an average of 33.8 ppm. However, the expected KBr concentration was 25 ppm for injection with orifice 18. Thus, the difference from the expected ppm was a high 35 percent. The variation of orifice 18 at the "after pump" location was 0.7 ppm^2 with a mean of 22.1 ppm (Table 7). Although the KBr concentration variation was higher, the difference from expected KBr concentration (12 percent) was lower. The nozzle-to-nozzle KBr variation for orifice 26 at the "before pump" injection location was 3.94 ppm^2 (Table 7). The KBr concentration values ranged from 52 to 47 ppm with a mean of 48.1 ppm (Table 7).

Table 7. Orifice-regulated system nozzle-to-nozzle KBr concentration

Nozzle Number		KBr Concentration (ppm)			
		Orifice 18		Orifice 26	
		Before Pump	After Pump	Before Pump	After Pump
1		35	21	52	48
2		34	24	51	47
3		34	23	50	47
4		34	21	49	47
5		34	22	49	48
6		34	22	49	48
7		33	22	48	47
8		34	22	47	47
9		34	21	47	47
10		34	23	45	47
11		33	22	47	47
12		34	21	46	46
13		33	22	47	46
Expected	(ppm)	25	25	50	50
Mean	(ppm)	33.8	22.1	48.1	47.1
Variance	(ppm^2)	0.2	0.7	3.9	0.7
Difference	(percent)	35	12	4	6

The difference from the expected KBr concentration value (50 ppm) was a small 4 percent. The variation of KBr concentration using the "after pump" injection location was 0.7 ppm^2(Table 7). The values ranged from 48 to 46 ppm with a mean of 47 ppm. The difference from expected KBr concentration was a low 6 percent.

The large difference of measured KBr concentration to expected KBr concentration for orifice 18 injection at either location was possibly caused by different sprayer settings between the tests. The sprayer pressure setting was reset between the "before pump" and "after pump" injection using orifice 18. However, no reset of sprayer pressure occurred between the "before pump" and "after pump" injection using orifice 26. Thus the orifice 26 tests had consistency of KBr concentration that the orifice 18 tests lacked. An accurate pressure setting occurred for the injection using orifice 26, thus resulting in the small reported differences in KBr concentration.

The KBr concentration for three of the four tests showed a tendency to decrease from nozzle 1 to nozzle 13. This tendency, rather than an actual difference of KBr concentration across the boom, may have resulted from a temperature effect on the sensor. The temperature effect is possible since the tests were conducted outside and the samples from the thirteen nozzle were collected in pairs and then measured individually. The KBr concentration measurement process lasted thirty to thirty-five minutes allowing sample temperature to gradually change from calibration temperature.

Field Tests

Field operation of the orifice-regulated system produced a large range of control ratings across tests (Table 8). Test B's overall rating (26.2) was significantly lower than the five other tests as seen by the Duncan grouping of C (Table 9). Test D's overall rating (71.2) (Table 9) was slightly lower than the four other tests and received a Duncan grouping of B. The A Duncan grouping was received by Test A, C, E, and F with overall ratings of 90.0, 87.5, 90.0, and 82.5, respectively (Table 9).

Test A, C, E, and F showed no difference in control between broadleaf and grass control, which matched each Test's overall control rating (Table 9). Test B's poorest rank was broadleaf control (16.2) with improved but still low grass control (36.2) (Table 9). Test D's broadleaf control (65.0) was also lower than grass control (77.5) (Table 9).

Test A, C, and E, were closely matched in control ratings (90, 87.5, and 90, respectively) suggesting that the orifice-regulated system has potential applying the 2.34 L/ha (1 qt/ac) formulation rate. Test B's, D's, and F's control ratings (26.2, 71.2, and 82.5) showed the orifice-regulated system less effective at the 1.17 L/ha (1 pt/ac) formulation rate. Possible reasons for the orifice-regulated system's lack of effectiveness using the smaller orifice include improper pressure difference across orifice or orifice obstruction. The small orifice sizes are prone to obstruction by system contaminants. However, the tested orifice showed no signs of obstruction

Table 8. Orifice-regulated system grass and broadleaf control

Plot Identification	Grass Control Rating	Broadleaf Control Rating
A-1	90	90
B-1	50	20
C-1	85	85
D-1	70	50
E-1	90	90
F-1	75	75
A-2	90	90
B-2	50	25
C-2	85	85
D-2	85	80
E-2	95	95
F-2	90	90
A-3	90	90
B-3	20	10
C-3	90	90
D-3	80	70
E-3	90	90
F-3	85	85
A-4	90	90
B-4	25	10
C-4	90	90
D-4	75	60
E-4	85	85
F-4	80	80

Table 9. Orifice-regulated system test parameters and control summary

Test Label	Injection Location	Orifice	Broadleaf Control Rating	Duncan Grouping	Grass Control Rating	Duncan Grouping	Overall Control Rating	Duncan Grouping
A	Before Pump	# 26	90.0	A	90.0	A	90.0	A
B	Before Pump	# 18	16.2	C	36.2	B	26.2	C
C	After Pump	# 26	87.5	A	87.5	A	87.5	A
D	After Pump	# 18	65.0	B	77.5	A	71.2	B
E	Tank Mixed	#26 Rate	90.0	A	90.0	A	90.0	A
F	Tank Mixed	#18 Rate	82.5	A	82.5	A	82.5	A

after removal from the injection system. Also Test B's control ratings were consistently low throughout the replications. Thus the likely cause of Test B's poor control was a low pressure difference across the orifice. A low pressure difference across the orifice would supply a reduced flowrate and possibly provide less grass and broadleaf control.

Water-Driven Injection System

Introduction

The water-driven injection system was tested under a symmetrical hose, an additional hose length, and two asymmetrical hose configurations. The specific test conditions such as boom nozzle setup, flowrates through plumbing branches, mean pressures upstream and downstream from the water-driven units, bromide concentrations, and error percentages for the twenty tests were tabulated for reference (Tables 10-11). The mean, variance, and number of observations were computed by test number for the upstream pressure (Table 12), downstream pressure (Table 13), and bromide concentration (Table 14). Pressure, flow, and chemical traces (Appendix A, B, and C, respectively) were graphed when applicable.

Table 10. Water-driven unit test summary - S.I. units

Test	Nozzle Selection		Mean Flow Rate (L/min)			Mean Pressure (kPa)		Bromide Concentration (ppm)				
	Size	Number	Unit 1	Unit 2	Bypass	Downstream	Upstream	Injected		Measured	Calculated	Error(%)
1	8004	5			1.73	362	389					
2	8004	5	7.27			261	360	10400		324	335	3.4
3	8004	5				273	392		9120	256	294	13.1
4	8004	5	2.72	4.88		278	411	13600	13500	326	437	25.3
5	8004	5	5.34		4.31	271	384	9960		100	177	43.7
6	8004	5		2.99	2.76	249	375		9500	118	160	26.4
7	8004	5	3.10	0.30	2.46	285	394	10500	10600	311	198	-56.9
8	8008	9	22.10			187	425	10800		269	348	22.7
9	8008	9	8.48	12.04		243	358	9480	9440	283	305	7.1
10	8008	9	9.46		13.21	254	358	10400		126	140	10.1
11	8008	9	10.82	8.82	2.76	241	354	9730	9730	248	275	10.0
12	8008	9	8.21	10.26		232	340	10100	10100	344	325	-5.9
13	8008	9	14.04			154	384					
14	8008	9	11.66	4.96		211	383					
15	8004	5	6.85			206	317					
16	8004	5	3.48	0.76		234	338					
17	8008	9	18.17			118	316	9780		238	208	-14.2
18	8008	9	8.44	10.67		196	327	10500	10500	285	286	0.2
19	8008	9	8.36	7.27		235	347	10800	10300	354	385	8.1
20	8008	9	11.13	7.49		128	243	10600	10400	359	337	-6.7

Table 11. Water-driven unit test summary - English units

Test	Nozzle Selection		Mean Flow Rate (gal/min)			Mean Pressure (psi)		Mean Bromide Concentration (ppm)				
	Size	Number	Unit 1	Unit 2	Bypass	Downstream	Upstream	Injected		Measured	Calculated	Error(%)
1	8004	5			1.73	52.5	56.5					
2	8004	5	1.92			37.9	52.2	10400		324	335	3.4
3	8004	5				39.6	56.9		9120	256	294	13.1
4	8004	5	0.72	1.29		40.4	59.6	13600	13500	326	437	25.3
5	8004	5	1.41		1.14	39.3	55.7	9960		100	177	43.7
6	8004	5		0.79	0.73	36.1	54.5		9500	118	160	26.4
7	8004	5	0.82	0.08	0.65	41.3	57.2	10500	10600	311	198	-56.9
8	8008	9	5.84			27.1	61.7	10800		269	348	22.7
9	8008	9	2.24	3.18		35.3	51.9	9480	9440	283	305	7.1
10	8008	9	2.50		3.49	36.9	51.9	10400		126	140	10.1
11	8008	9	2.86	2.33	0.73	34.9	51.4	9730	9730	248	275	10.0
12	8008	9	2.17	2.71		33.6	49.3	10100	10100	344	325	-5.9
13	8008	9	3.71			22.3	55.6					
14	8008	9	3.08	1.31		30.6	55.5					
15	8004	5	1.81			29.9	46.0					
16	8004	5	0.92	0.20		33.9	49.1					
17	8008	9	4.80			17.1	45.8	9780		238	208	-14.2
18	8008	9	2.23	2.82		28.4	47.5	10500	10500	285	286	0.2
19	8008	9	2.21	1.92		34.1	50.4	10800	10300	354	385	8.1
20	8008	9	2.94	1.98		18.5	35.2	10600	10400	359	337	-6.7

Table 12. Water-driven unit upstream pressure measurements

Test	1	2	3	4	5	6	7	8	9	10
Mean										
kPa	389	360	392	411	384	375	394	425	358	358
(psi)	(56.5)	(52.2)	(56.9)	(59.6)	(55.7)	(54.5)	(57.2)	(61.7)	(51.9)	(51.9)
Variance										
kPa^2	107	399	766	565	266	423	224	395	739	348
(psi^2)	(2.2)	(8.4)	(16.1)	(11.9)	(5.6)	(8.9)	(4.7)	(8.3)	(15.6)	(7.3)
Count	111	178	178	178	178	178	178	178	178	178

Test	11	12	13	14	15	16	17	18	19	20
Mean										
kPa	354	340	384	383	317	338	316	327	347	243
(psi)	(51.4)	(49.3)	(55.6)	(55.5)	(46.0)	(49.1)	(45.8)	(47.5)	(50.4)	(35.2)
Variance										
kPa^2	664	749	2311	1276	678	436	2001	1548	1437	527
(psi^2)	(14.0)	(15.7)	(48.6)	(26.8)	(14.3)	(9.2)	(42.1)	(32.6)	(30.2)	(11.1)
Count	178	178	178	178	178	178	178	178	178	178

Table 13. Water-driven unit downstream pressure measurements

Test	1	2	3	4	5	6	7	8	9	10
Mean										
kPa	362	261	273	279	271	248.9	285	187	243	254
(psi)	(52.5)	(37.9)	(39.6)	(40.4)	(39.3)	(36.1)	(41.3)	(27.1)	(35.3)	(36.9)
Variance										
kPa^2	48	875	1260	4150	708	1065	4474	361	2363	894
$(psi)^2$	(1.1)	(18.4)	(26.5)	(87.3)	(14.9)	(22.4)	(94.1)	(7.6)	(49.7)	(18.8)
Count	111	178	178	178	178	178	178	178	178	178

Test	11	12	13	14	15	16	17	18	19	20
Mean										
kPa	241	232	154	211	206	233.7	118	196	235	128
(psi)	(34.9)	(33.6)	(22.3)	(30.6)	(29.9)	(33.9)	(17.1)	(28.4)	(34.1)	(18.5)
Variance										
kPa^2	1830	2163	5	532	1402	1074	71	1635	784	1716
$(psi)^2$	(38.5)	(45.5)	(0.1)	(11.2)	(29.5)	(22.6)	(1.5)	(34.4)	(16.5)	(36.1)
Count	178	178	178	178	178	178	178	178	178	178

Table 14. Water-driven unit KBr concentration measurements

Test		2	3	4	5	6	7	8	9
Mean	ppm	324	256	327	100	118	311	269	284
Variance	ppm^2	87	36	45	35	106	2037	16	35
Count		93	93	93	93	93	93	93	93
Test		**10**	**11**	**12**	**17**	**18**	**19**	**19a**	**20**
Mean	ppm	126	247	344	238	285	355	367	360
Variance	ppm^2	5	70	41	9	92	30	84	90
Count		93	93	93	93	93	93	93	93

Symmetrical Setup

The symmetrical setup operated with very little pressure fluctuation with only the bypass leg open (Test 1) as indicated by the low pressure variances of 107 and 48 kPa^2 (2.2 and 1.1 psi^2)(Tables 12-13). This test provided one of the smoother pressure traces (Appendix A-1) with slight pressure fluctuations resulting from hunting of the pressure relief valve. It should be noted by comparing the variance of upstream pressure to downstream pressure that the bypass throttling valve further smoothed the variation in pressure. The ripples in the flow trace (Appendix B-1) for this test most likely resulted from unsteady flow sensor characteristics.

Unit 1 operating alone increased pressure fluctuations both upstream and downstream of the unit, as compared to operation of the bypass branch alone. The variances in pressure were 399 and 875 kPa^2 (8.4 and 18.4 psi^2), upstream and downstream respectively (Tables 12-13). The mean pressure drop through in-line unit one was from 360 to 261 kPa (52.2 to 37.9 psi) (Δp = 99 kPa (14.3 psi)). Pressure traces (Appendix A-2) displayed fluctuation patterns at similar upstream and downstream locations indicating pressure transients being introduced through the system. Also, variation in the flow trace (Appendix B-2) increased with the use of the in-line unit compared to the bypass alone. The KBr trace (Appendix C-1) indicated some variation (87 ppm^2) (Table 14) although the amount of variation relative to the mean (324 ppm) was not severe. KBr delivery had a low percent error of 3 from the measured KBr concentration (324 ppm) and the calculated KBr concentration (335 ppm)(Tables 10-11).

Unit 2, operating alone on a branch parallel to Unit 1, (Test 3) produced pressure variances [766 and 1260 kPa^2 (16.1 and 26.5 psi^2)(Tables 12-13)] greater than the variances of Unit 1 use. The mean pressure drop through Unit 2 was from 392 to 273 kPa (56.9 to 39.6 psi)(Δp = 119 kPa (17.3 psi)) (Tables 12-13). The flow trace was invalidated and not included because the turbine flowmeter was jammed with a small piece of dried PVC glue. A flowrate of 8.33 L/min (2.20 gal/min) was determined from a totalizing flow meter. The KBr trace (Appendix C-2) for Test 3 was similar to Test 2 while variance was less (36 ppm^2) (Table 14). KBr delivery had a percent error of 13 from the measured KBr^- concentration (256 ppm) and the calculated KBr^- concentration (294 ppm) (Tables 10-11).

Simultaneous operation of Units 1 and 2 (Test 4) produced a pressure variance of 565 and 4150 kPa^2 (11.9 and 87.3 psi^2) (Tables 12-13). Pretest speculation had predicted dual operation would smooth the pressure transients with in-line units alternating during operation. However, several dual runs were performed with Test 4 being indicative of the other runs. One exception, which could not be duplicated, existed which produced alternating operation of the units such that their opposing strokes resulted in smooth pressure output as noted by a precision test gauge on the boom.

Each in-line unit showed different flow properties with mean flowrates of 2.72 and 4.88 L/min (0.72 and 1.29 gal/min) (Tables 10-11) for Unit 1 and 2, respectively. However, KBr concentration variance (45 ppm^2) (Table 14) was similar to the variance present in single unit operation tests. However, KBr delivery had a high percent error of 25 from the measured KBr concentration (326 ppm) and the calculated KBr concentration (437 ppm) (Tables 10-11).

Operation of Unit 1 and the bypass (Test 5) showed a smoother pressure trace (Appendix A-5) than traces of tests without the bypass. Analyzation of recorded pressures concurred with lowered pressure variances 266 and 708 kPa^2 (5.6 and 14.9 psi^2) (Tables 12-13). Similar flowrates of 5.34 L/min (1.41 gal/min) and 4.31 L/min (1.14 gal/min) were observed between Unit 1 and the bypass (Tables 10-11). The bromide concentration trace (Appendix C-4) was similar to earlier tests with a concentration variation of 35 ppm^2 (Table 14). While the test showed the concentration output effectively lowered through the use of the bypass, KBr delivery percent error of 44 between the measured KBr concentration (100 ppm) and the calculated KBr concentration (177 ppm) was noticeably higher than earlier tests (Tables 10-11).

In-line Unit 2 and the bypass combined (Test 6), like Test 5, reduced pressure variances [423 and 1065 kPa^2 (8.9 and 22.4 psi^2) (Tables 12-13)]. Overall flowrates were reduced from Test 5 with 3.00 L/min (0.79 gal/min) through Unit 2 and 2.76 L/min (0.73 gal/min) through the bypass (Tables 10-11). However, the concentration variance (106 ppm) was three times the variance of Test 5 (Table 14). Yet, KBr delivery percent error decreased to 26 between the measured KBr concentration (118 ppm) and the calculated KBr concentration (160 ppm) (Tables 10-11).

Operation of all three branches (Test 7) produced preferential flow with 3.10 L/min (0.82 gal/min) through Unit 1 and 2.46 L/min (0.65 gal/min) through the bypass (Tables 10-11). Only 0.30 L/min (0.08 gal/min) flowed through Unit 2 (Tables 10-11). The upstream pressure variance of 224 kPa^2 (4.7 psi^2) was comparable to previous tests of the units (Table 12). The variance downstream was 4474 kPa^2 (94.1 psi^2) (Table 13), the maximum variance observed during the twenty tests. Large KBr concentration variances were observed (2037 ppm^2) (Table 14). This variation was one to two orders of magnitude greater than the KBr variance of other tests. Test 7 represented a worst-case scenario in terms of pressure and KBr concentration variance. Likewise, the KBr delivery percent error increased to 57 between the measured KBr concentration (311 ppm) and the calculated KBr concentration (198 ppm) (Tables 10 - 11).

The rated boom flow at 275.8 kPa (40 psi) was increased from 7.6 to 27.2 L/min (2.0 to 7.2 gal/min)(Tables 10-11) (Tests 8 - 14) to increase flow through the units. Unit 1, operating individually at the high flow condition (Test 8), exhibited a mean pressure drop from 425 to 187 kPa (61.7 to 27.1 psi) (Tables 12-13). The large pressure drop was caused by the high flow [22.1 L/min (5.84 gal/min)] through the unit which exceeded the unit's rated capacity of 18.9 L/min (5.0 gal/min) (Tables 10-11). Even though the pressure drop was increased, the upstream and downstream pressure variance of 395 and 361 kPa^2 (8.3 and 7.6 psi^2) was reduced from tests under low flow conditions (Tables 12-13). KBr concentration variance (16 ppm^2) was also lower than most tests (Table 14). KBr delivery percent error was 23 between the measured KBr concentration (269 ppm) to the calculated KBr concentration (348 ppm) (Tables 10-11).

The high flow split between the two units (Test 9) caused a pressure drop from 358 to 243 kPa (51.9 to 35.3 psi) which was lower than the pressure drop of Test 8 (Tables 12-13). The pressure variance of 739 and 2363 kPa^2 (15.6 and 49.7 psi^2) (Tables 12-13) were higher than Test 8. Flow of 8.48 and 12.04 L/min (2.24 and 3.18 gal/min) (Tables 10-11) through the respective units were again split inexactly, yet more evenly than Test 7. Even so, the KBr variance was (35 ppm^2) (Table 14) and the trace (Appendix C-7) was smooth. Likewise, the KBr delivery percent error decreased to 7 between the measured KBr concentration (283 ppm) and the calculated KBr concentration (305 ppm) (Tables 10-11).

Operation of Unit 1 and the bypass (Test 10) showed smooth pressure traces (Appendix A-10) with a variance of 348 and 894 kPa^2 (7.3 and 18.8 psi^2) (Tables 12-13). The flow trace (Appendix B-10) had ripples similar to previous tests. The high flowrate of 9.46 L/min (2.50 gal/min) through Unit 1 and 13.2 L/min (3.49 gal/min) (Tables 10-11) through the bypass did not influence the flow trace patterns. The KBr trace (Appendix C-9) for this test was extremely smooth as indicated by the low variance 5 ppm^2 (Table 14). The KBr delivery percent error (10) remained low between the measured KBr concentration (126 ppm) and the calculated KBr concentration (140 ppm)(Tables 10-11).

Operation of all three branches under high flow conditions (Test 11) produced flow of 10.82 L/min (2.86 gal/min) through Unit 1, 8.82 L/min (2.33 gal/min) through Unit 2, and 2.76 L/min (0.73 gal/min)(Table 8) through the bypass. The flow was more evenly split through the individual branches than compared to the low flow test with all three branches operating. The traces of pressure (Appendix A-11) and flow (Appendix B-11) showed erratic variance. The pressure variances were 664 and 830 kPa^2 (14.0 and 38.5 psi^2)(Tables 11-12). However, the KBr concentration variance was not extremely high at 70 ppm^2 (Table 14). The KBr delivery percent error (10) remained low between the measured KBr concentration (248 ppm) and the calculated KBr concentration (275 ppm)(Table 14). Operation of all three branches simultaneously produced better results under high flow conditions than under low flow conditions.

Unit 1 and Unit 2 were operated dually (Test 12) to determine if sampling location provided any difference in reported KBr variance. Each unit had an adequate flowrate of 8.21 and 10.26 L/min (2.17 and 2.71 gal/min)(Tables 10-11) and a satisfactory flow split between the branches. Trends in the variances and traces of pressure (Appendix A-12) and flow (Appendix B-12) for Test 12 were similar to the previous tests of dual-operating units. The KBr concentration variance (41 ppm^2)(Table 14) was consistent to the previous test with the different sampling location.

Additional Hose Length Setup

Operation of Unit 1, with the additional hose length between the flow combing cross and the boom (Test 13), showed smoother pressure pulsations downstream [5 kPa^2 (0.1 psi^2)(Table 13)] than compared to upstream pressure pulsations [2311 kPa^2 (48.6 psi^2)(Table 12)]. These variances were reported at a flow rate of 14.04 L/min (3.71 gal/min)(Tables 10-11). The contrast between the upstream and downstream pressure traces (Appendix A-13) proved the effectiveness of the hose damping.

Operation of both units (Test 14) showed the twenty-foot hose was still effective but not as well as with the single unit. Pressure variances were 1276 and 532 kPa^2 (26.8 and 11.2 psi^2) for upstream and downstream transducers respectively (Tables 12-

13). The flow trace for Test 14 (Table B-14) indicated a somewhat erratic flow response of the units.

Unit 1 operated (Test 15) with a flow of 6.85 L/min (1.81 gal/min)(Tables 10-11). The pressure fluctuations increased as shown by the variance of 678 and 1402 kPa^2 (14.3 and 29.5 psi^2)(Tables 12-13). The reduced frequency of the in-line unit may have caused the resulting flow surges.

Operation of Unit 1 and 2 under low flow conditions (Test 16) produced flows through the units of 3.48 and 0.76 L/min (0.92 and 0.20 gal/min)(Tables 10-11), respectively. However the flow preferred Unit 1 over Unit 2 essentially making this test similar to Test 15. Pressure variances were 436 and 1074 kPa2 (9.2 and 22.6 psi^2) (Tables 12-13).

Operation of a 48:1 ratio unit (Test 17) produced a smooth pressure, flow and KBr trace (Appendix A-17, B-17, and C-12, respectively). These lowered variances may have resulted from the 20-foot hose and the high pulse rate of the 48:1 unit at a flow of 18.17 L/min (4.80 gal/min)(Tables 10-11). The KBr concentration variance (9 ppm^2)(Table 14) was low compared to previous tests.

Dual operation of a 48:1 and a 32:1 ratio in-line unit with the 20-foot hose section (Test 18) produced pressure variation of 1548 and 1635 kPa^2 (32.6 and 34.4 psi^2) (Tables 12-13) which were similar to earlier tests. However, KBr concentration variation (92 ppm^2)(Table 14) was higher than most previous tests. Yet, the KBr delivery percent error of 0.2 between the measured KBr concentration (285 ppm) and the calculated KBr concentration (286 ppm) was the lowest of the tests (Tables 10-11).

Asymmetrical Setup

Unit 1 and 2 operated (Test 19) with the 20-foot section of hose immediately behind the output of Unit 1 before the flow-combining cross. The 32:1 ratio units produced a low frequency, pressure pulse (Appendix A-19) with variances of 1437 and 784 kPa^2 (30.2 and 16.5 psi^2) (Tables 12-13). The first measurement of KBr concentration provided a variance of 30 ppm^2 (Table 14), while the second measurement provided a variance of 84 ppm^2 (Table 14). No instrument drift was located. However, the question of variance utility was raised because of the large difference in measurement variance. The KBr concentration produced a similar trace (Appendix C-14) and the percent error of 8 between the measured (354 ppm) and the calculated KBr concentration (385 ppm) was low (Tables 10-11).

In Test 20, a three-foot section of hose added upstream of in-line unit 1 provided no effective reduction of pressure variance (527 and 1716 kPa^2)(11.1 and 36.1 psi^2)(Tables 12-13). Likewise KBr distribution was not changed with the KBr concentration variance (90 ppm^2)(Table 14) and the percent error 7 between the measured KBr concentration (359 ppm) and the calculated KBr concentration (337 ppm) was unchanged from Test 19 (Tables 10-11).

Experimental Unit

Injection Against Air Pressure

The experimental unit showed a large decrease of flow [18.8 mL/min (0.63 oz/min)] between the 103 kPa (15 psi) to 207 kPa (30 psi) pressure setting for the unit speed of 120 RPM (Figure 11). However, the largest difference (39 percent) in flow rates between the two pressure settings was present at the 10 RPM setting (Table 15). The speed settings of 50 and 90 rpm showed little change (4 and 4 percent, respectively) between the 103 kPa (15 psi) to 207 kPa (30 psi) pressure settings (Table 15).

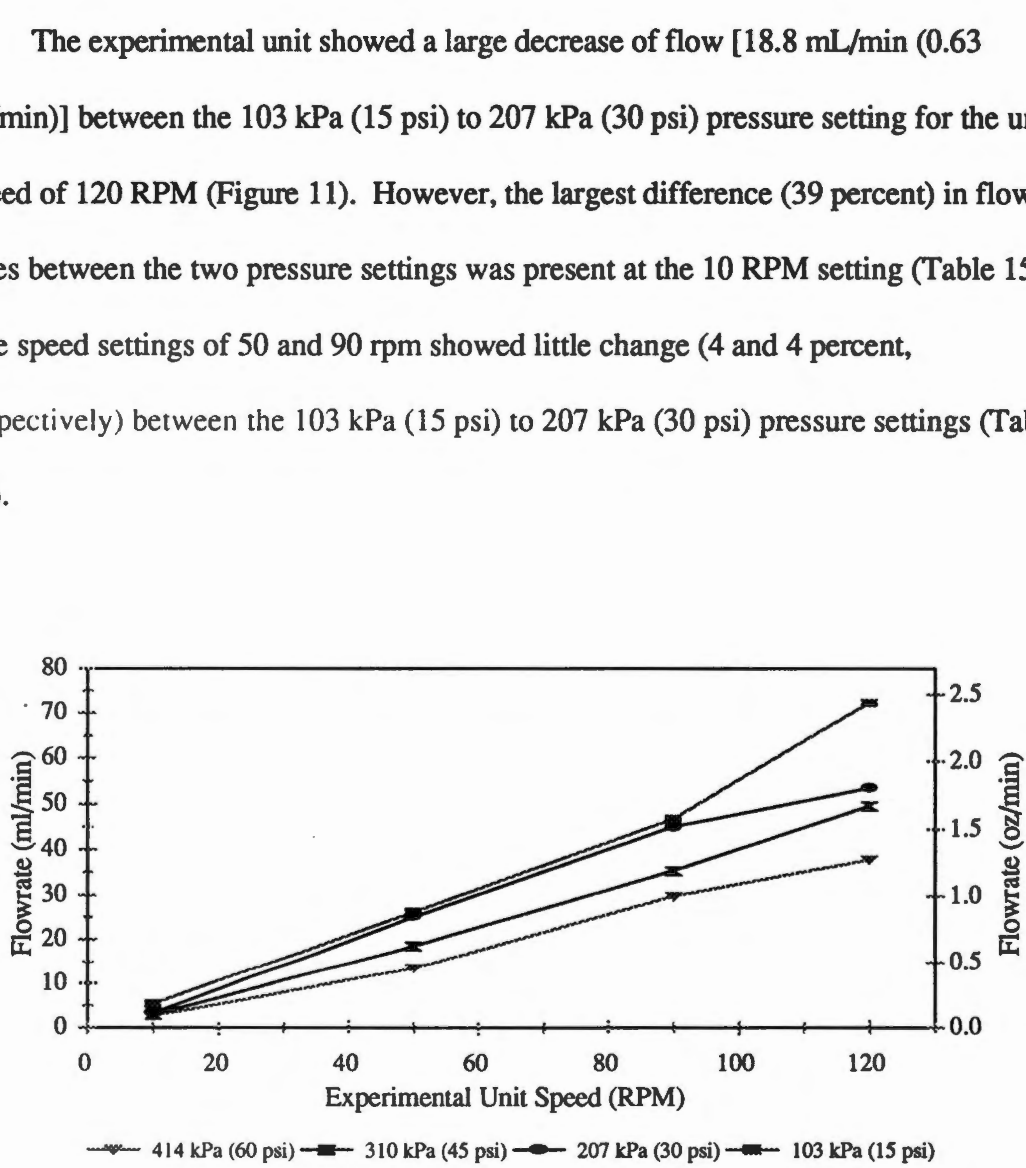


Figure 11. Experimental unit flowrate versus unit speed at four pressure settings

Table 15. Experimental unit flowrates for certain pressures and unit speeds

Pressure kPa (psi)	Flowrate mL/min (oz/min) — Experimental Unit Speed RPM				Flowrate Percent Difference Across Pressure			
	10	50	90	120	10	50	90	120
103 (15)	5.4 (0.18)	26.2 (0.88)	46.8 (1.58)	72.3 (2.44)				
					39	4	4	26
207 (30)	3.3 (0.11)	25.0 (0.84)	45.0 (1.52)	53.5 (1.81)				
					14	26	22	7
310 (45)	2.9 (0.1)	18.6 (0.63)	35.3 (1.19)	49.5 (1.67)				
					11	27	16	24
414 (60)	2.5 (0.08)	13.5 (0.46)	29.7 (1.00)	37.8 (1.28)				

At the high and low speed, check valve effectiveness may be the cause of the sharp decline in unit flow.

A noticeable change in flowrates was also seen between the pressure settings of 207 kPa (30 psi) and 310 kPa (45 psi). However, the highest percent change of flowrate was at the speeds of 50 and 90 rpm instead of 10 and 120 rpm. For the speeds of 10, 50, 90, and 120 rpm, the percent change was 12, 26, 22, and 7, respectively.

Between 310 kPa (45 psi) and 414 kPa (60 psi), flowrate changes were 14, 27, 16, and 24 percent, respectively, for 10, 50, 90, and 120 rpm. Again the highest percent change was present at a different speed. The higher flowrate changes were present at 50 and 120 rpm, instead of 50 and 90 rpm as between the pressure settings of 207 kPa (30 psi) and 310 kPa (45 psi).

Injection Into Individual Nozzle

After understanding of the unit's performance versus changes in pressure and speed, the unit was operated to inject into a nozzle body. The pressure variances were low (Table 16), which was expected since no source of pulsations was present except for the diluent roller pump and pressure relief valve opening or closing. The measured flowrates were consistent with little variation (Table 16).

The KBr concentration statistics reveal the large pulsations measured during the unit's operation at 10 rpm (Table 16). The KBr samples showed a consistent pattern of unit operation (Figure 12) which alternated between a high KBr concentration (above 200 ppm) and a low KBr concentration (below 100 ppm). The high concentration points fluctuated between approximately 250 ppm and 200 ppm during Test 1. After an adjustment of the experimental unit, test 2 produced more consistent KBr concentration high levels at approximately 250 ppm with the concentration lows below 100 ppm (Figure 13).

Table 16. Experimental unit at-the-nozzle injection statistics

Test	System Pressure			Flowrates			KBr Concentration		
	Mean kPa (psi)	Variance kPa^2 (psi^2)	Count	Mean L/min (gal/min)	Variance L/min^2 $(gal/min)^2$	Count	Mean ppm	Variance ppm^2	Count
1	285 (41.4)	95 (2.2)	93	6.1 (1.62)	0.3 (0.02)	56	139	3517	93
2	266 (42.4)	100 (2.1)	93	5.9 (1.57)	0.1 (0.01)	56	146	3619	93

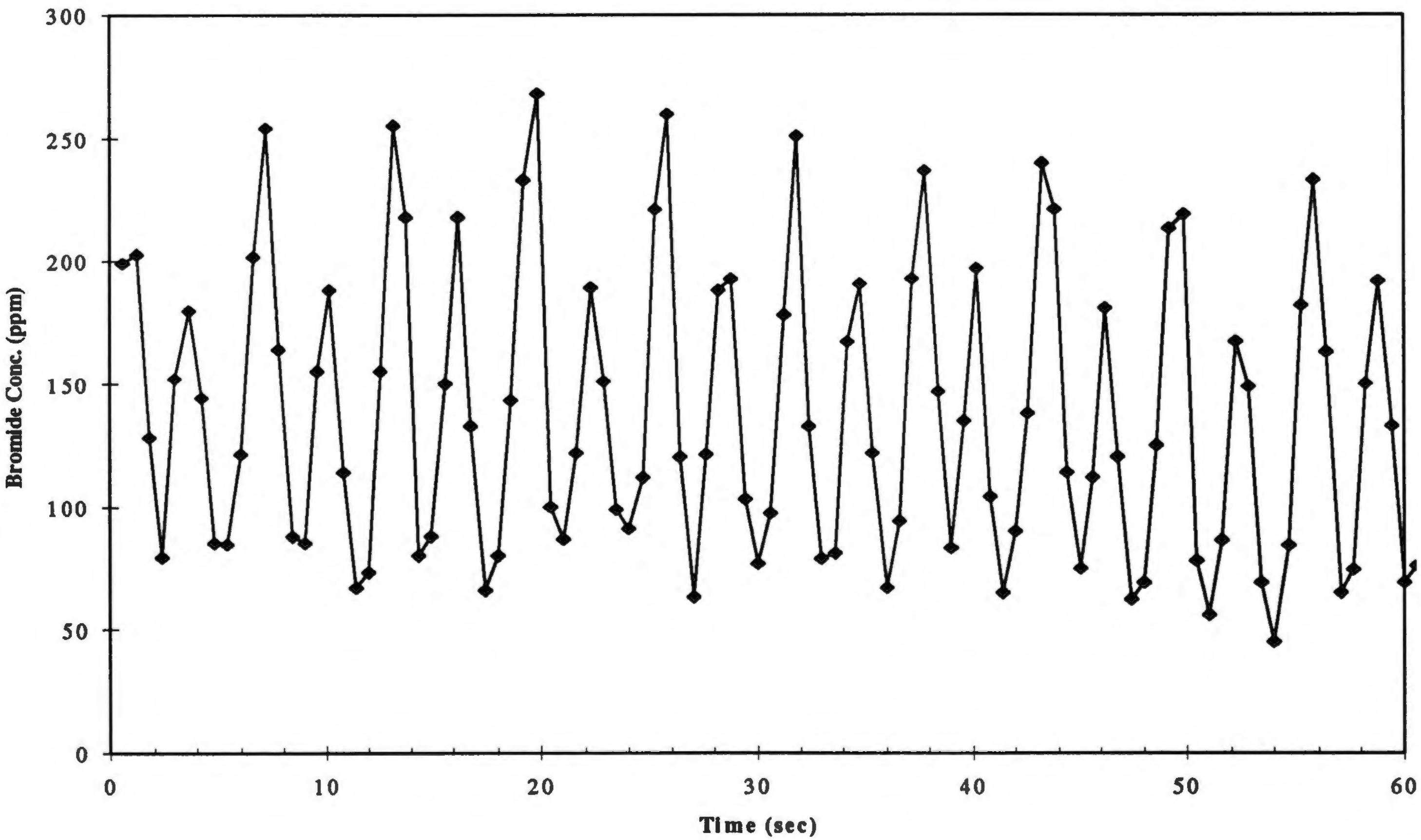


Figure 12. Bromide concentration trace of nozzle discharge samples from experimental unit operation at 10 RPM with deformed diaphragm.

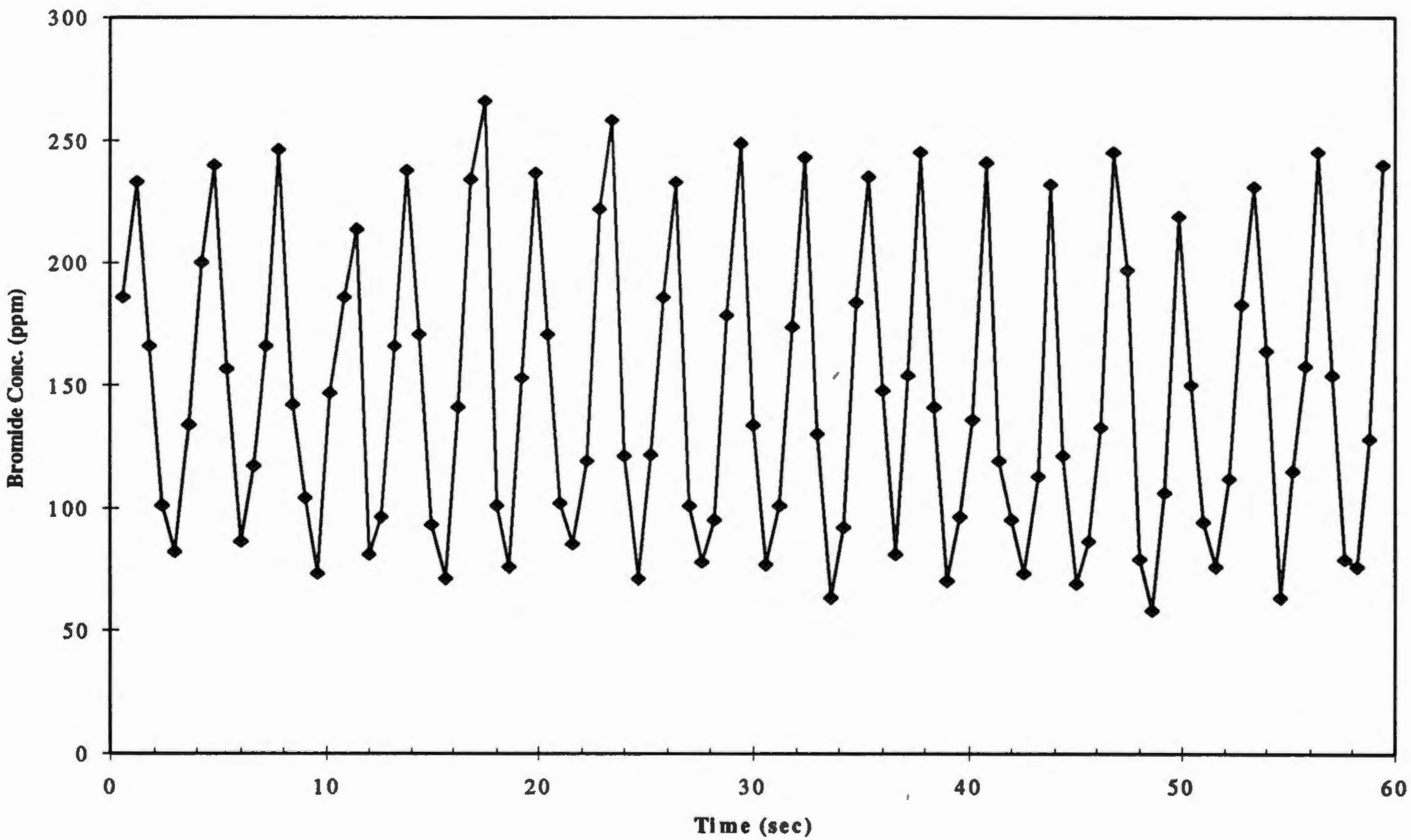


Figure 13. Bromide concentration trace of nozzle discharge samples from experimental unit operation at 10 RPM with new diaphragm.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Three types of formulation injection systems were analyzed to determine the transient performance of the systems. An orifice-regulated system was designed and installed on a conventional sprayer. The orifice-regulated system was calibrated under laboratory conditions before field tests were conducted. The orifice-regulated system's efficacy using "before pump" and "after pump" injection application was compared to conventional tank-mix applications in the field study.

Commercially-available, water-driven, piston-type injection unit(s) were tested in a three branch system. The three branch system was used to provide variable dilution rates from fixed rate injection units. Two branches consisted of water-driven injection units while the third leg contained a throttling valve. The pressure transients from the pulsating units were of particular importance. The KBr concentration versus time and flowrate through the branches were also measured.

An experimental, low-flowrate, diaphragm unit was designed and operated to improve the possibility of at-the-nozzle-injection. Operation determined the unit's flow at different unit speed settings and system pressures provided by air pressure. The unit was also used for injection into an individual nozzle on the boom. A KBr solution was used as a tracer and samples collected to determine effects of diaphragm pulsation on concentration uniformity versus time.

The orifice-regulated system delay time and nozzle-to-nozzle variation was measured using a manual method of KBr sample collection. The water-driven units and the experimental unit were tested using a rotary sampler that provided more samples per minute than the manual method. The rotary method collected 103 samples per test with a test duration of one minute.

Conclusions

In the laboratory setup using a 5000 ppm KBr solution, the orifice-regulated system produced the desired formulation rate at the selected differential pressure [68.9 kPa (10 psi)] across the orifice for "after pump" injection. The differential pressure across the orifice for the "before pump" injection was affected by diluent pump suction, such that pressure supplied to the orifice had to be reduced approximately 14-kPa (2-psi) to maintain the desired rate. In the field study applying paraquat dichloride and Latron AG-98 spreader, the orifice-regulated direct injection system provided broadleaf and grass control ratings that ranged from 26 to 90 percent, as compared to the tank-mix system ratings that ranged from 82 to 90 percent. The lowest rating (26 percent) was possibly caused by an orifice that plugged after calibration, or due to incorrect pressure differential across the orifice. The orifice-regulated system provided direct injection capability with efficacy comparable to conventional application, especially at higher formulation rates, i.e. larger orifice size. No significant difference (α=0.05) in control ratings were observed between "before pump" and "after pump" injection sites and conventional tank-mix applications for the 2.43 L/ha (0.25 gal/ac) formulation application rate.

The performance of the water-driven, piston pump unit varied based upon system branch selection, hose length configuration, and flowrate. The concept of using a bypass branch provided a potential method of varying KBr concentration by modulating flows through the bypass and the fixed-rate injection units. However, flow through the water-driven unit(s) was sensitive to adjustment of the bypass throttling valve due to the pressure loss [103 kPa (15 psi)] in the water-driven units. Dually-operated units did not generally lessen pressure pulse output, but rather tended to pulse simultaneously. The pressure variances indicated this trend with individual water-driven unit operation variances of 71 kPa^2 (1.5 psi^2) - 361 kPa^2 (7.6 psi^2) compared to dual unit variation of 532 kPa^2 (11.2 psi^2) - 4150 kPa^2 (87.3 psi^2). Pressure variance showed no clear trend between high and low system flowrates. Errors in KBr metering ranged from -57 to 26 percent and was attributed to KBr measurement accuracy, flowmeter accuracy, and the pumping efficiency of the water-driven unit at different flowrates. At higher flow rates, the water-driven units produced generally lower concentration variation (16 - 92 ppm^2) and generally improved KBr metering errors

(-14 to 22.7%) compared to low flow KBr concentration variation (35 - 2037 ppm^2) and metering error (-57 - 26%).

The additional hose length downstream of the combining cross increased upstream pressure variance of 436 - 2001 kPa^2 (9.2 - 42.1 psi^2) as compared to pressure variances of 266 - 766 kPa^2 (5.6 - 16.1 psi^2) without the additional hose. In contrast, the downstream pressure variance of 5 - 1635 kPa^2 (0.1 - 34.4 psi^2) with the hose was less than the pressure variance of 361 - 4474 kPa^2 (7.6 - 94.1 psi^2) without the hose. Thus, the water-driven unit needs the additional hose length to smooth the pressure spikes that are inherent to its operation. The asymmetrical setup of the branches had no smoothing effect upon system operating characteristics.

The experimental-unit provided flowrates comparable to the rates required for injection at an individual nozzle. Specifically, the experimental unit produced flowrates for formulation application rates from 1.17 L/ha (0.125 gal/ac) to 4.68 L/ha (0.50 gal/ac) using a 6.4 km/h (4 mi/h) sprayer speed and 0.5 m (20 in) nozzle spacing (Tables 5 and 15). The experimental unit's flowrate range was provided by a twelve-fold increase in unit speed. Operating speeds greater than 10 rpm are required to increase nozzle discharge concentration uniformity across time.

LITERATURE CITED

LITERATURE CITED

Akesson, N.B., W. E. Yates, R. W. Brazelton, and J. B. Knaak. 1978. Monitoring airborne pesticide chemical levels and their effects on workers mixing, loading, and applying or entering treated fields. Paper No. 783565, ASAE, St. Joseph, MI 49085.

Akesson, N. B. 1987 Introduction to session on closed mixing, handling, and application systems. Pesticide Formulation and Application Systems: Seventh Volume, ASTM STP 968, G. B. Beesman and D. I. B. Vander Hooven, Eds., American Society for Testing and Materials, Philadelphia, PA pp. 13-14.

Analytical Technology, Inc. 1995. Orion bromide electrode instruction manual. Boston MA 02129.

Bode, L. E., T. E. Langley, and B. J. Butler. 1979. Performance characteristics of by-pass spray nozzles. Transactions of the ASAE 22(5):1016-1022.

Brown, R. B. and J.-P. G. A. Steckler 1995. Prescription maps for spatially variable herbicide application in no-till corn. Transaction of the ASAE 38(6):1659-1666.

Bridges, D.C. 1992. Crop losses due to weeds in the United States. Weed Science Society of America, Champaign, IL 61820.

Brown, R.B. and K.A. Bennett. 1995. Improving direct injection for spatially variable herbicide application. Paper No. AETC 95106. ASAE, St. Joseph, MI 49085.

Chancellor, W. J. and M. A. Goronea. 1994. Effects of spatial variability of nitrogen, moisture, and weeds on the advantages of site-specific application for wheat. Transactions of the ASAE 37(3):717-724.

Cho, H. K., S. J. Marley, and J. L. Baker. 1985. Injection metering of spray concentrates. Paper No. MCR 85138 ASAE, St. Joseph, MI 49085.

Doherty, J. 1986. Cancer and agricultural herbicides. Journal Embargo, HHS news, Department of Health and Human Services, National Cancer Institute, September 4.

Environmental Protection Agency. 1992. Federal Worker Protection Standard. Code of federal regulations, Title 40, Part 170. Washington, DC.

Gephardt, M. R. , A. R. Kliethermes, and C. E. Goering. 1984. Metering concentrated pesticides. Transactions of the ASAE 27(1):18-23. St. Joseph, MI 49085.

Ghate, S. R. and S. C. Phatak. 1990. A new sprayer for applying pesticides and biocontrol agents. Paper No. 901056, ASAE, St. Joseph, MI 49085.

Ghate, S. R. and C. D. Perry. 1993. Varying pesticide application rates with ground speed in a compressed air direct injection sprayer. Paper No. 931115, ASAE, St. Joseph, MI 49085.

Grisso, R. E., E. J. Hewett III, E. C. Dickey, R. D. Schnieder, and E. W. Nelson. 1987. Calibration accuracy of pesticide application equipment. Paper No. 871044, ASAE, St. Joseph, MI 49085.

Hart, W.E., J. L. Davis, F. D. Tompkins, and C. R. Mote. 1991. Sprayer tank rinsing parameters: laboratory studies. Paper No. 911543, ASAE, St. Joseph, MI 49085.

Hou, J., K. A. Sudduth, S. C. Bourgelt. 1993. Performance of a chemical injection system. Paper No. 9311, ASAE, St. Joseph, MI 49085.

Koo, Y. M., S. C. Young, and D. K. Kulhman. 1987. Flow characteristics of injected concentrates in spray booms. Paper No. 871602, ASAE, St. Joseph, MI 49085.

Ksiazek, T. F. 1985. Automatic controls for chemical application. Proceedings of the Agri-Mation 1 Conference and Exposition. pp. 165-172.

Miller, M. S. and D. B. Smith. 1989. A direct injection controlled rate spray boom. Paper No. 891611, ASAE, St. Joseph, MI 49085.

Miller, P. and J. Stafford. 1995. Patch spraying. Silsoe Research Institute. Bedford MK45 4HS

Ollila, D. G., J. A. Schumacher and D. P. Froehlich. 1990. Integrating field grid sense system with direct injection technology. Paper No. 901628, ASAE, St. Joseph, MI 49085.

Reichard, D. L. and T. L. Ladd. 1983. Pesticide injection and transfer system for field sprayers. Transactions of the ASAE 26(3):683-686. St. Joseph, MI 49085.

Reichenberger, L. 1986. Zero in on metering mistakes. Farm Journal 110(7):20-23.

Rider, A. R. and E. C. Dickey. 1982. Field evaluation of calibration accuracy for pesticide application equipment. Transactions of the ASAE 25(2):258-260. St. Joseph, MI 49085.

Rhodes, G. N., P. P. Shelby, J.D. Burns, and W. T. Flinchum. 1994. Publication Bulletin 652, 671, 1091, 1190, 1229, 1283, 1284, and 1411. The University of Tennessee, Agricultural Extension Service, Knoxville, TN 37895

Shearer, S.A., SG. McNeill, and L.D. Swetnam. 1992. Demonstration spray rig with direct chemical metering. Paper No. 921092, ASAE, St. Joseph, MI 49085.

Shearer, S.A., W. Qiu, G. A. Watkins, C. J. Sobolik, and S. A. Shearer. 1995. A feasibility study of direct injection for variable rate herbicide application. Paper No. 951567, ASAE, St. Joseph, MI 49085.

Tompkins, F. D., K. D. Howard, C. R. Mote, and R. S. Freeland. 1990. Boom flow characteristics with direct chemical injection. Transactions of the ASAE. 33(3):737-743. St. Joseph, MI 49085.

Valcore, D.L., D.S. Mallory, and J.L. Voorheis. 1994. Economical water powered in-line injection meter and on-line accuracy test system. ASAE Paper No. 94-1066, ASAE, St. Joseph, MI 49085.

Vidrine, C. G., C. E. Goering, C. L. Day, M. R. Gephardt, and D. B. Smith. 1975. A constant pesticide application rate spray model. Transactions of the ASAE 18(3):439-443. St. Joseph, MI 49085.

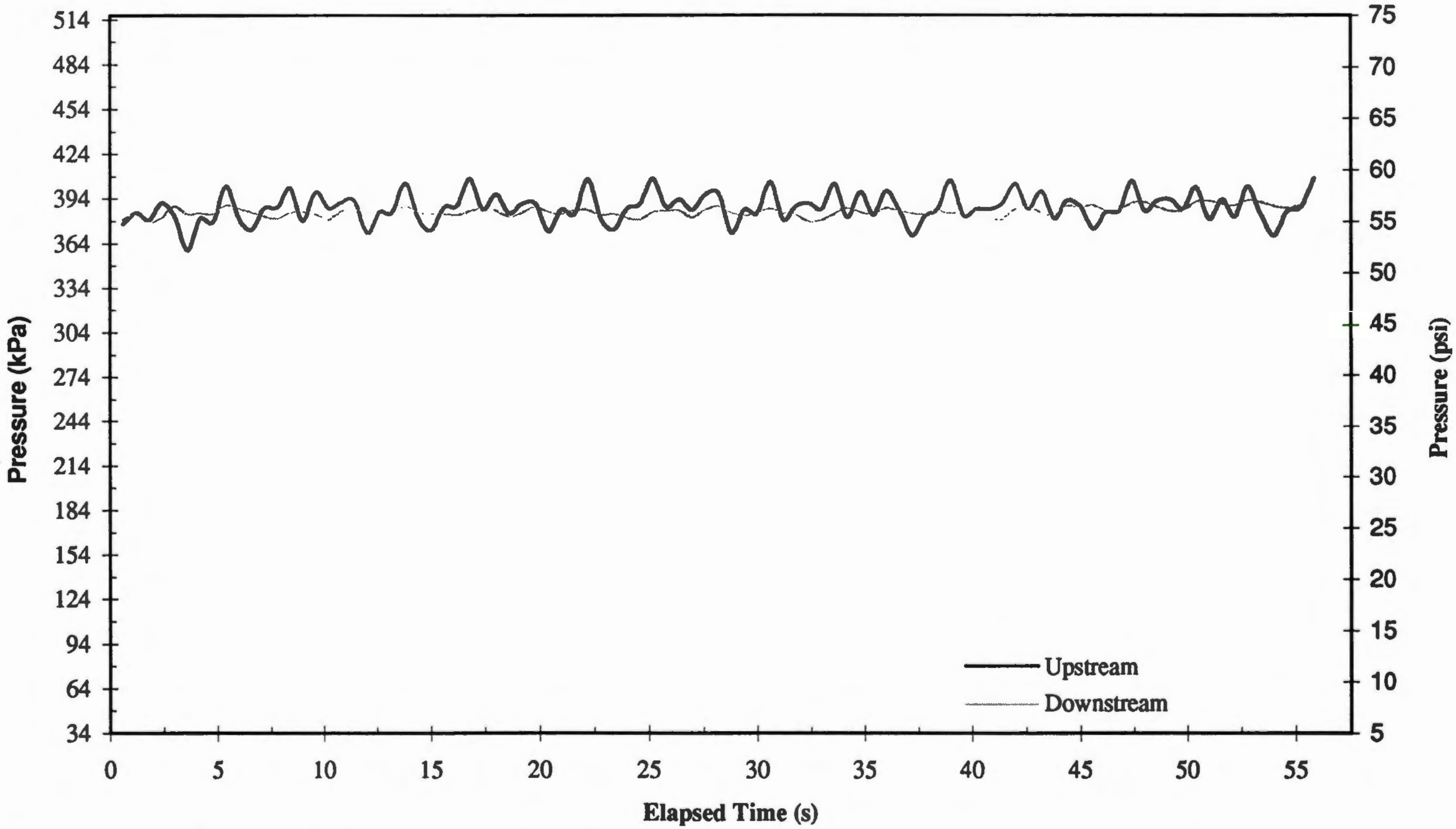
Windholtz, M., S. Budavari., R. F. Blumetti, and E. S. Otterbein. eds. 1983. The Merck Index: An Encyclopedia of Chemicals, Drugs, and Biologicals, 10th edition. Merck and Company, Inc. Rahway, N.J.

Wolf, R.E. 1996. Development of a 'state of the art' injection sprayer for use in spraying research plots. ASAE Paper No. 96-1085, ASAE, St. Joseph, MI 49085.

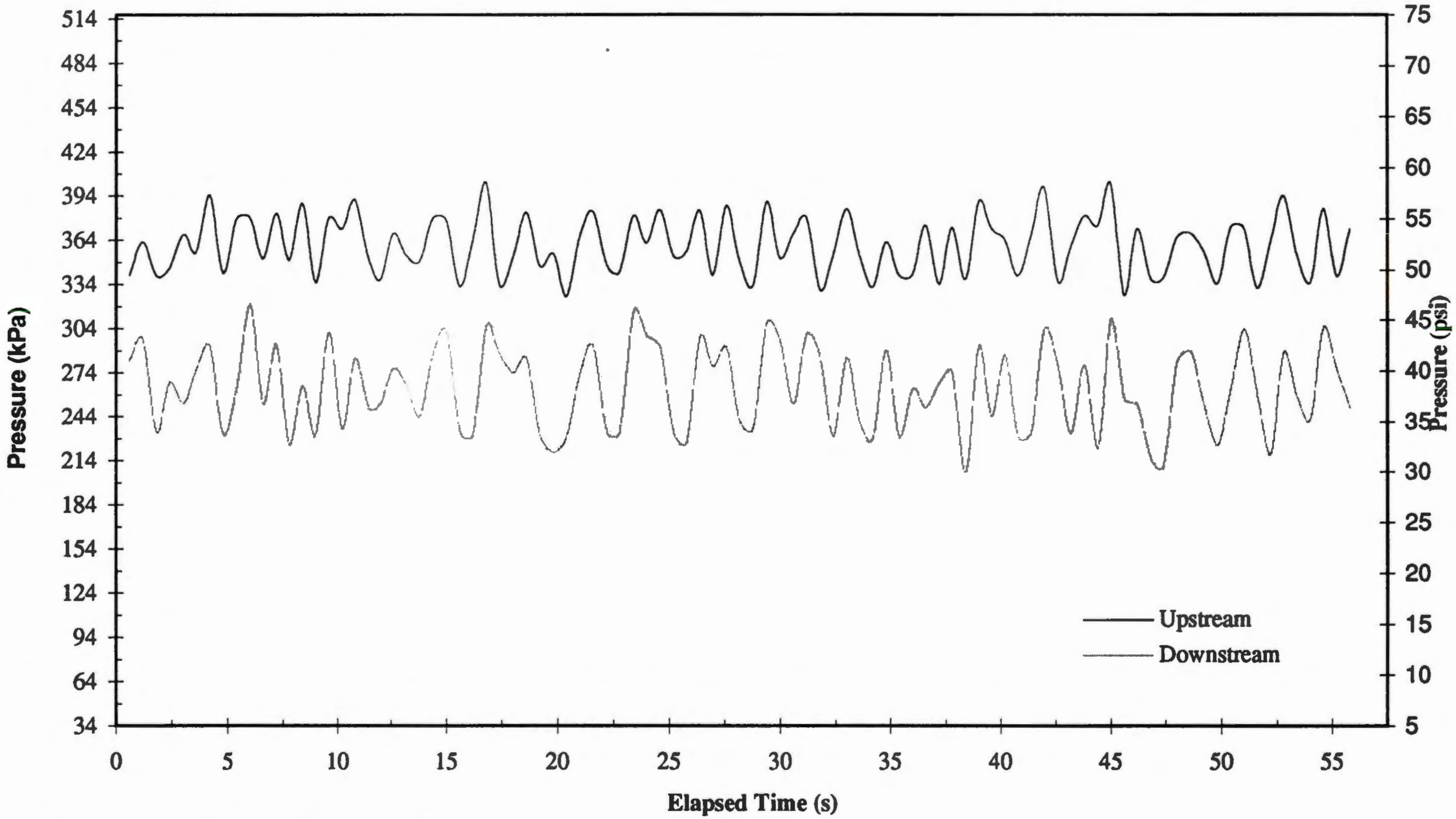
APPENDIXES

APPENDIX A

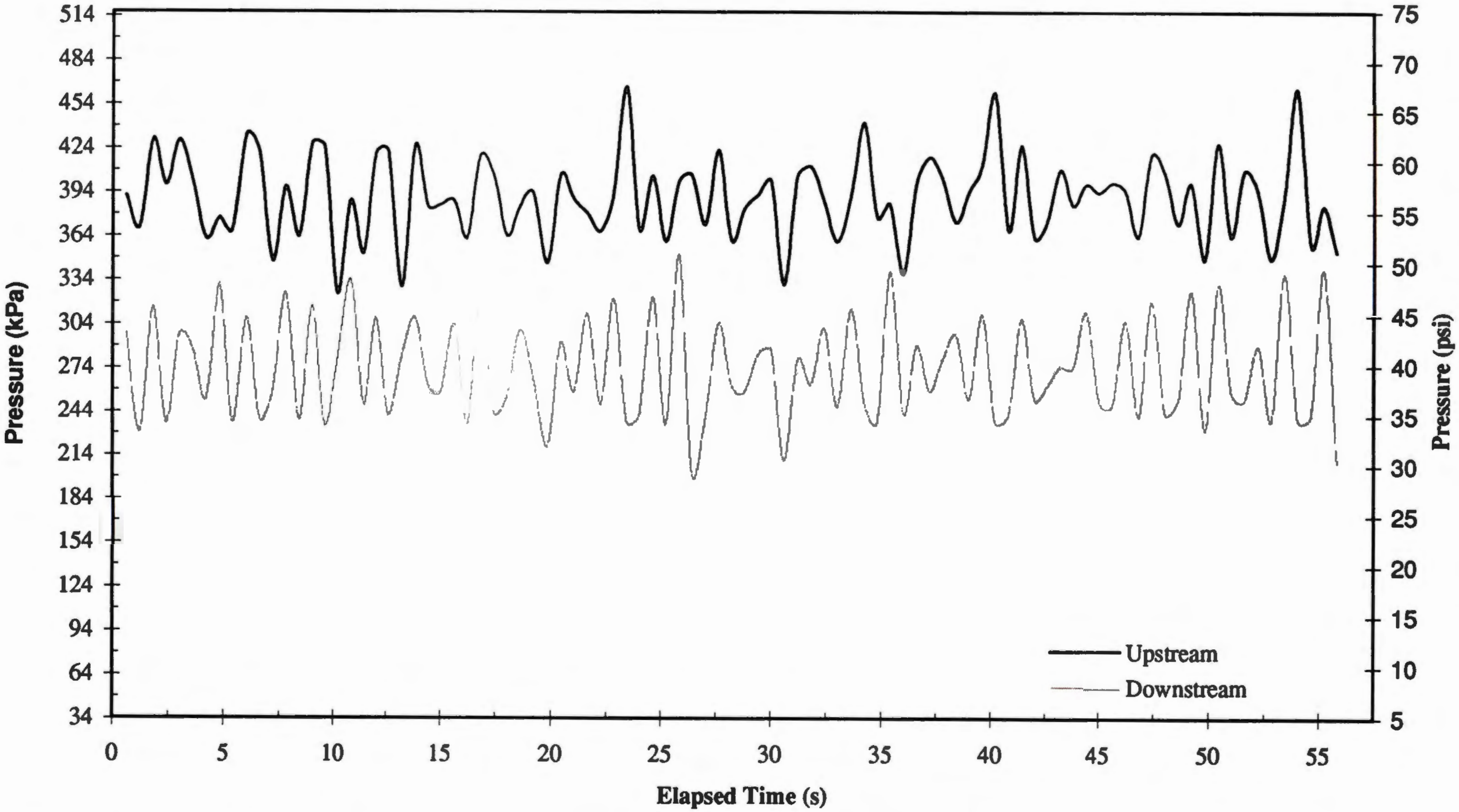
WATER-DRIVEN UNIT PRESSURE TRACES



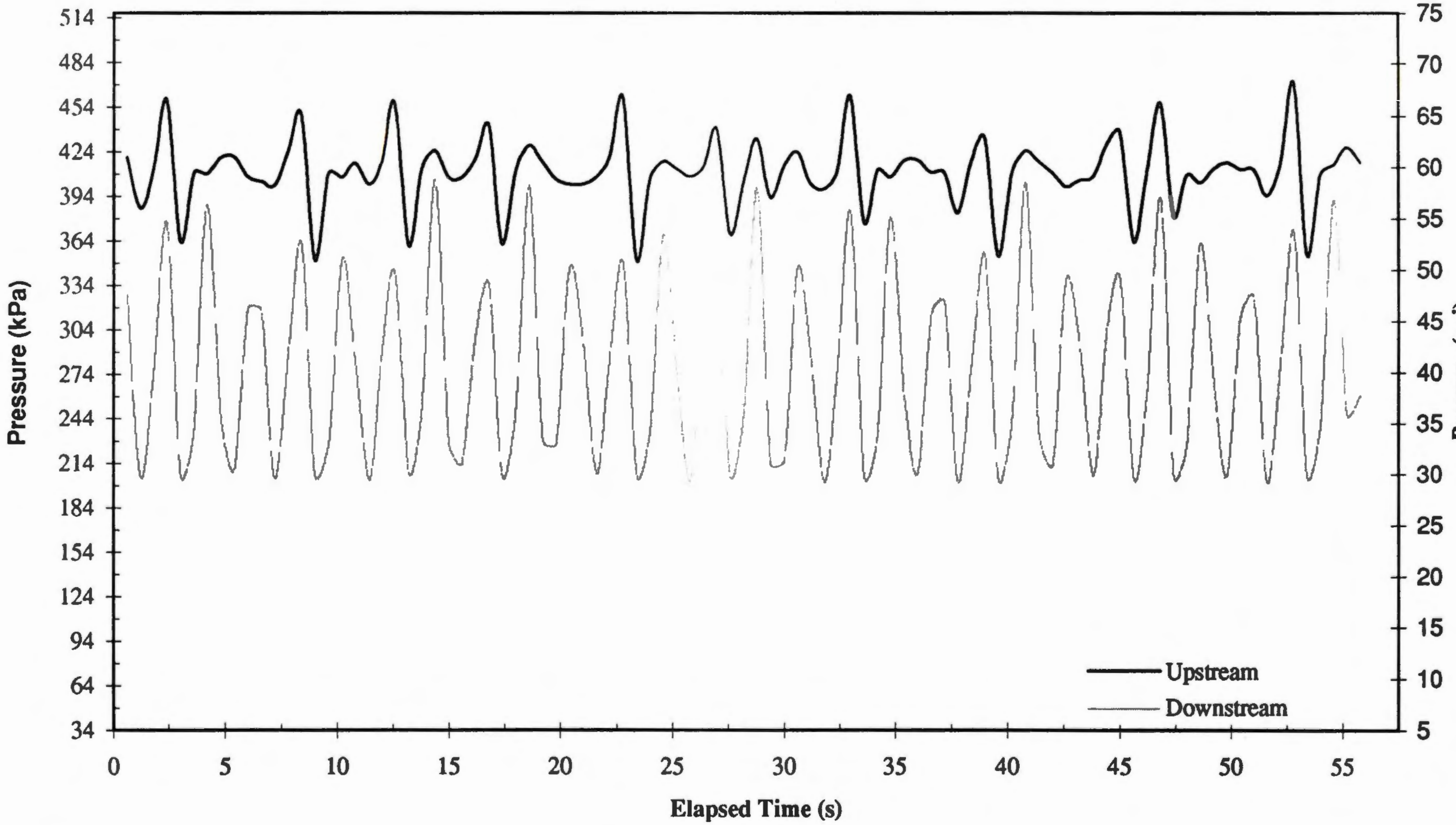
A-1 Pressure trace for water-driven injection system during bypass operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



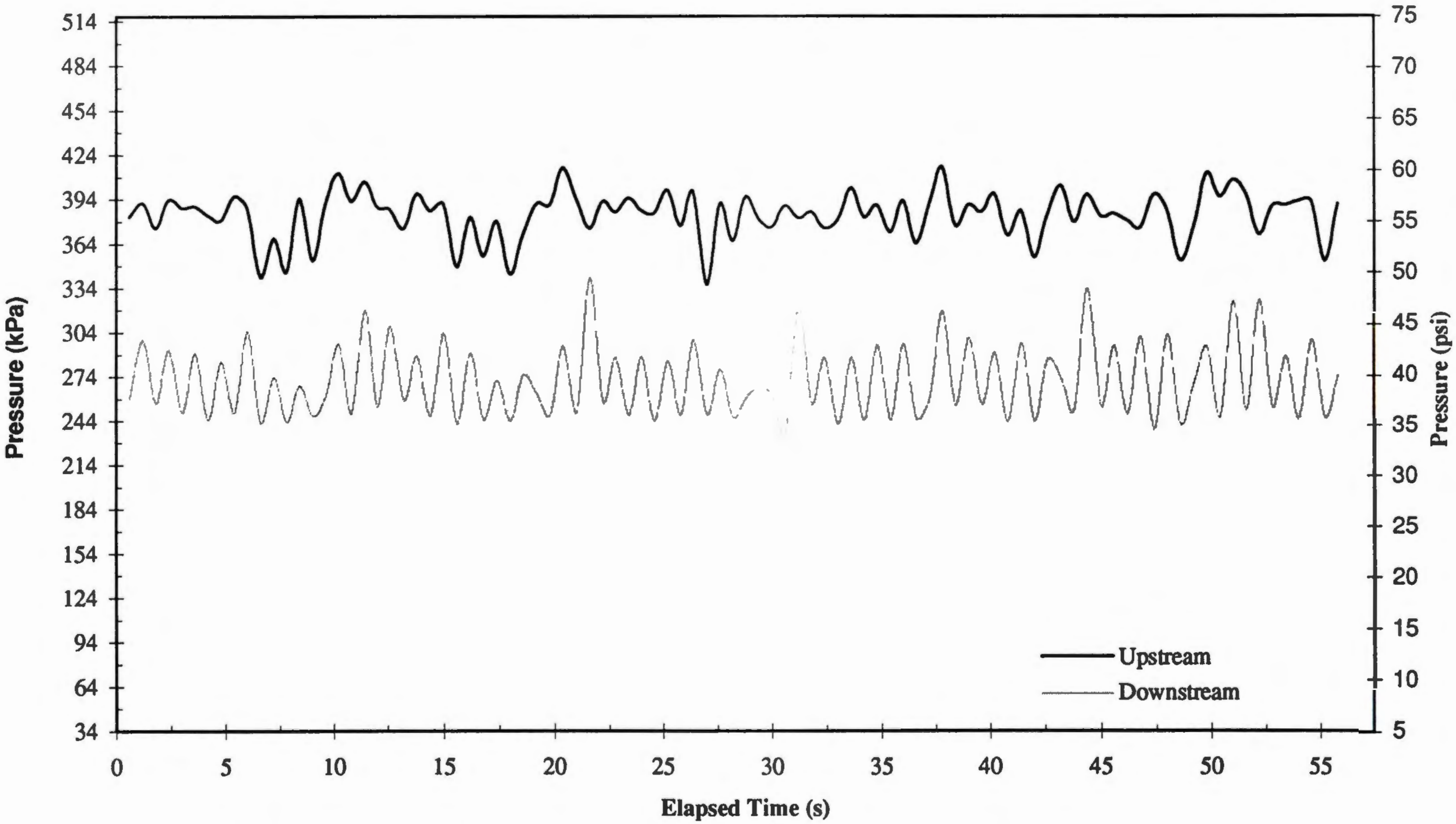
A-2 Pressure trace for water-driven injection system during unit 1 operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



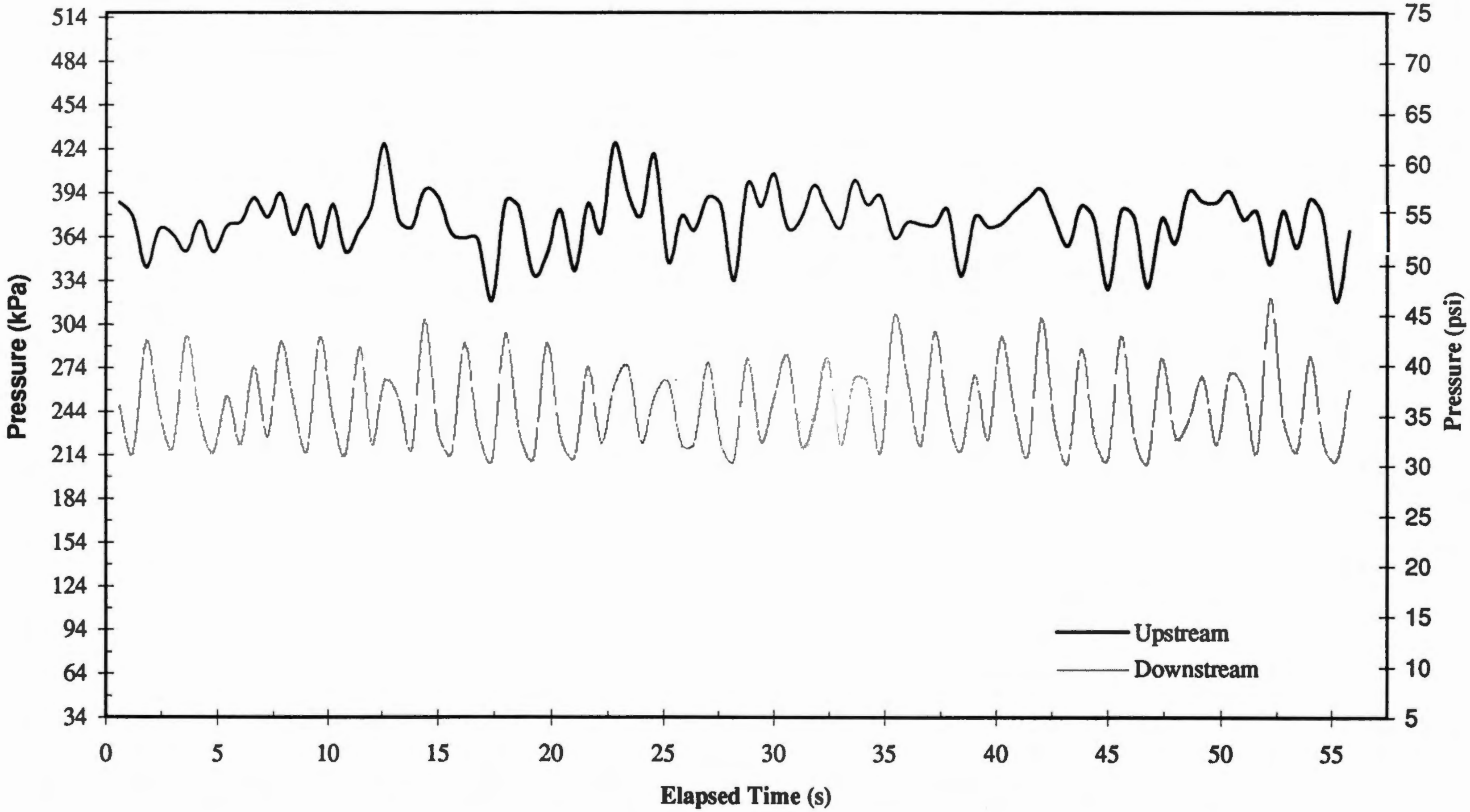
A-3 Pressure trace for water-driven injection system during unit 2 operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



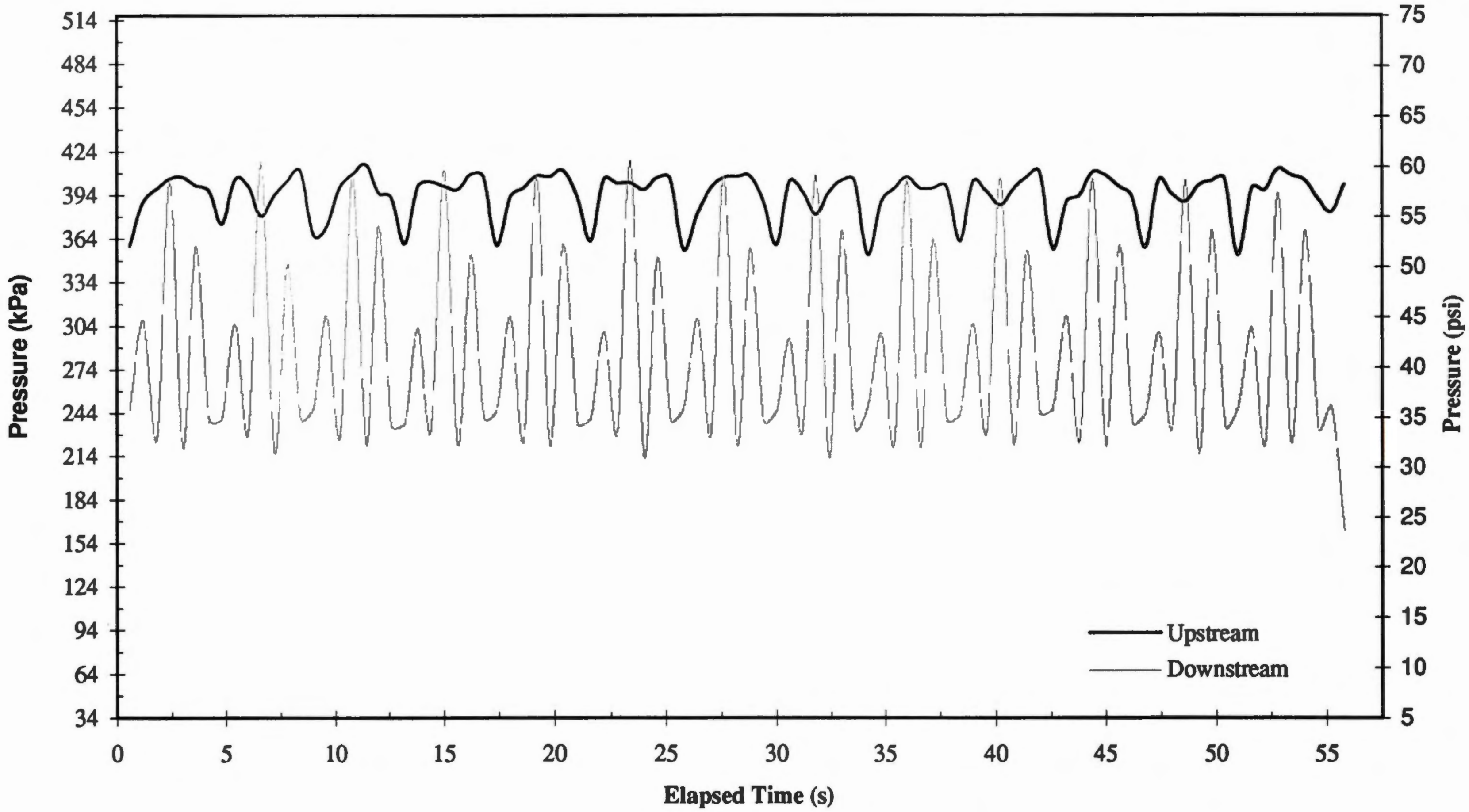
A-4 Pressure trace for water-driven injection system during unit 1 and 2 operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



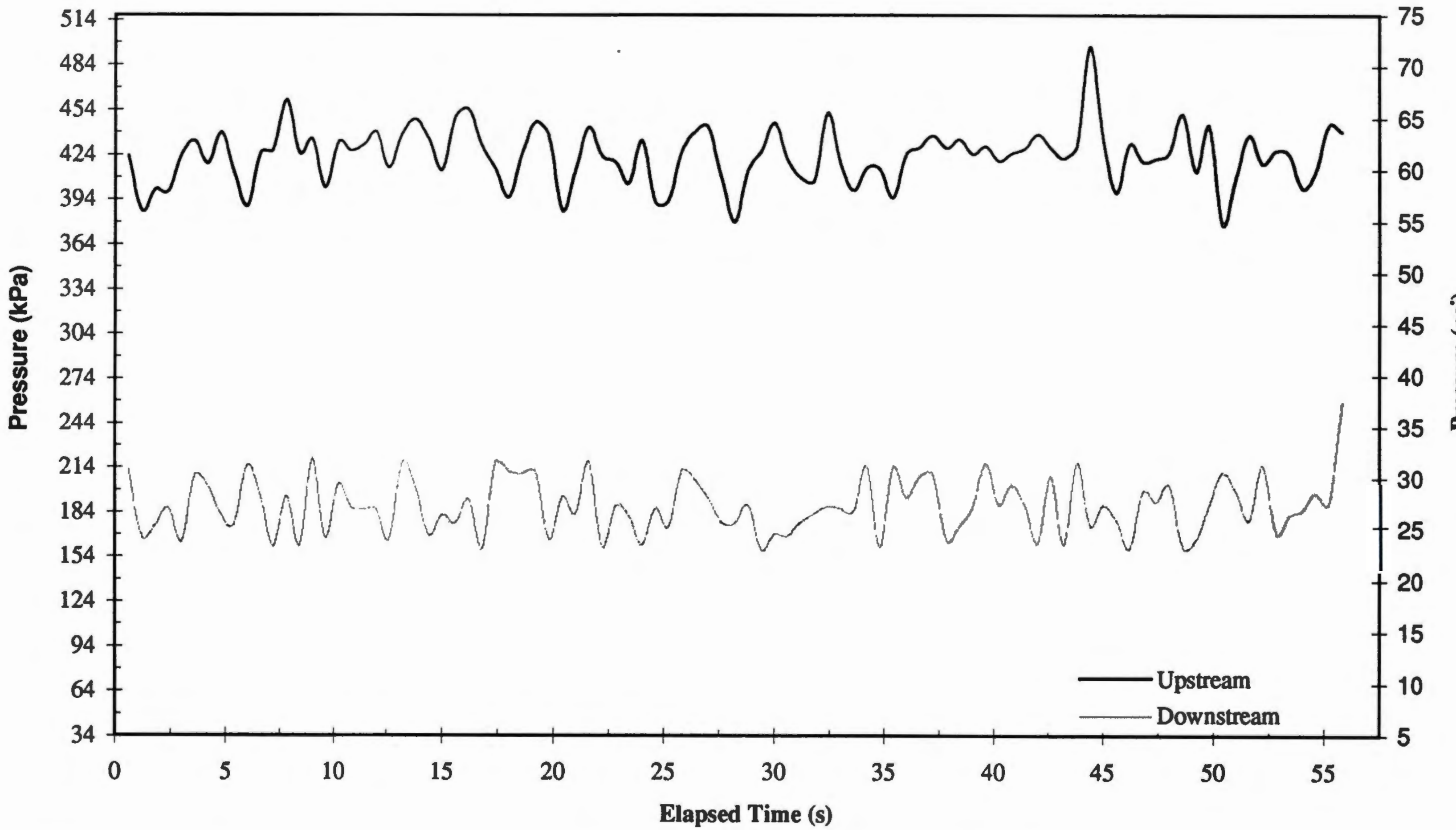
A-5 Pressure trace for water-driven injection unit during unit 1 and bypass operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



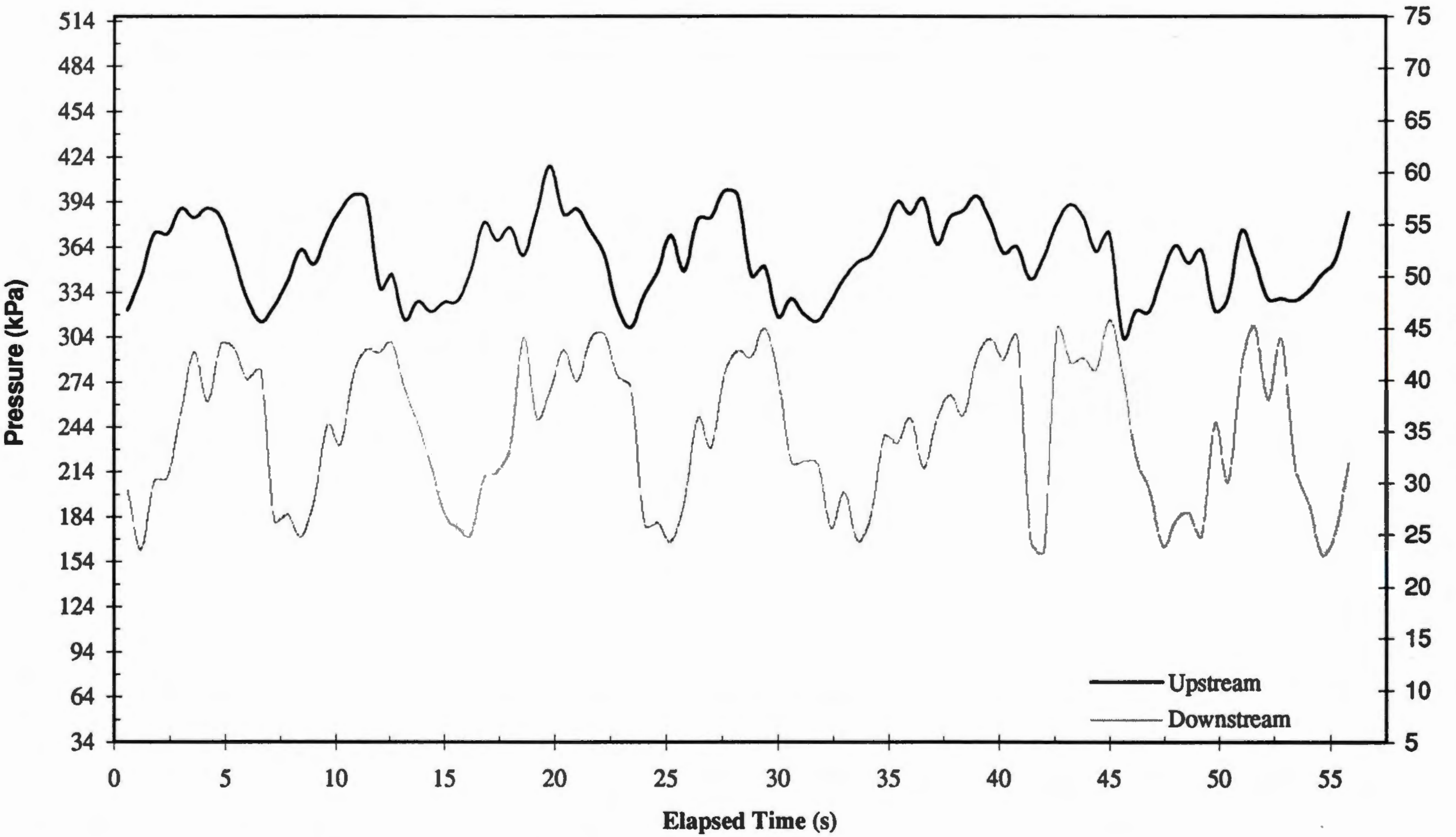
A-6 Pressure trace for water-driven injection system during unit 2 and bypass operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



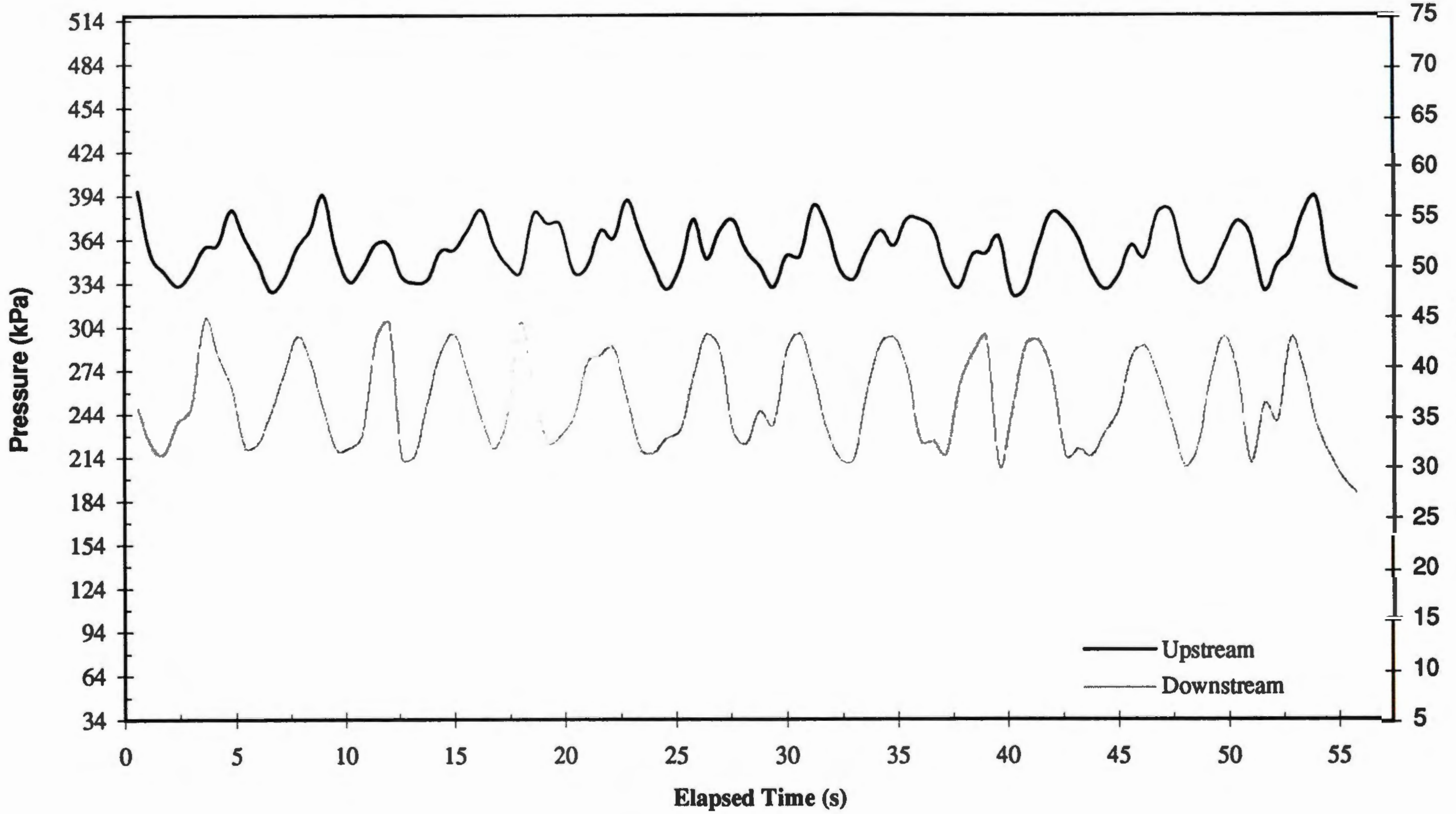
A-7 Pressure trace for water-driven injection system during unit 1, 2, and bypass operation at low flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



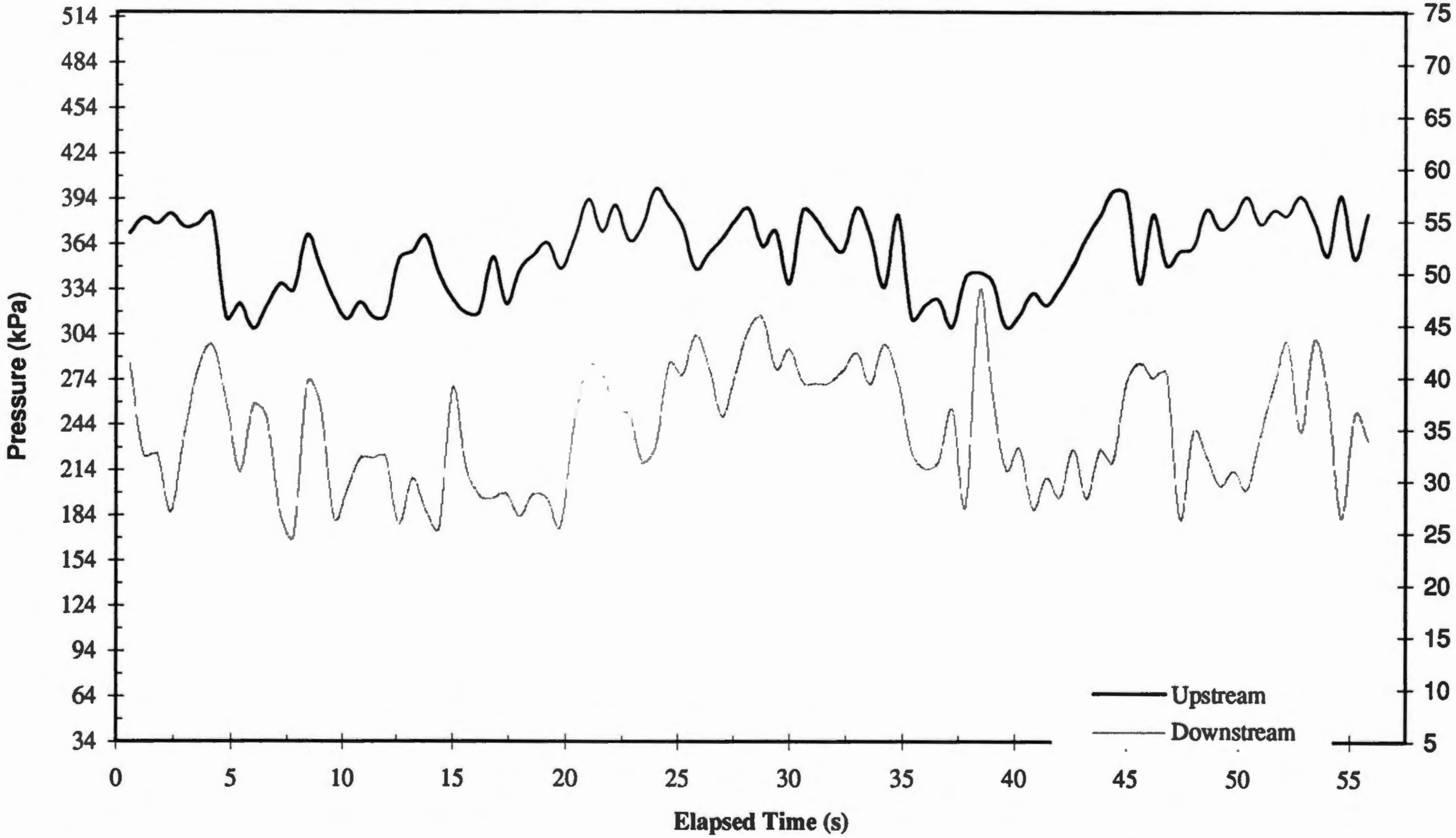
A-8 Pressure trace for water-driven injection system during unit 1 operation at high flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



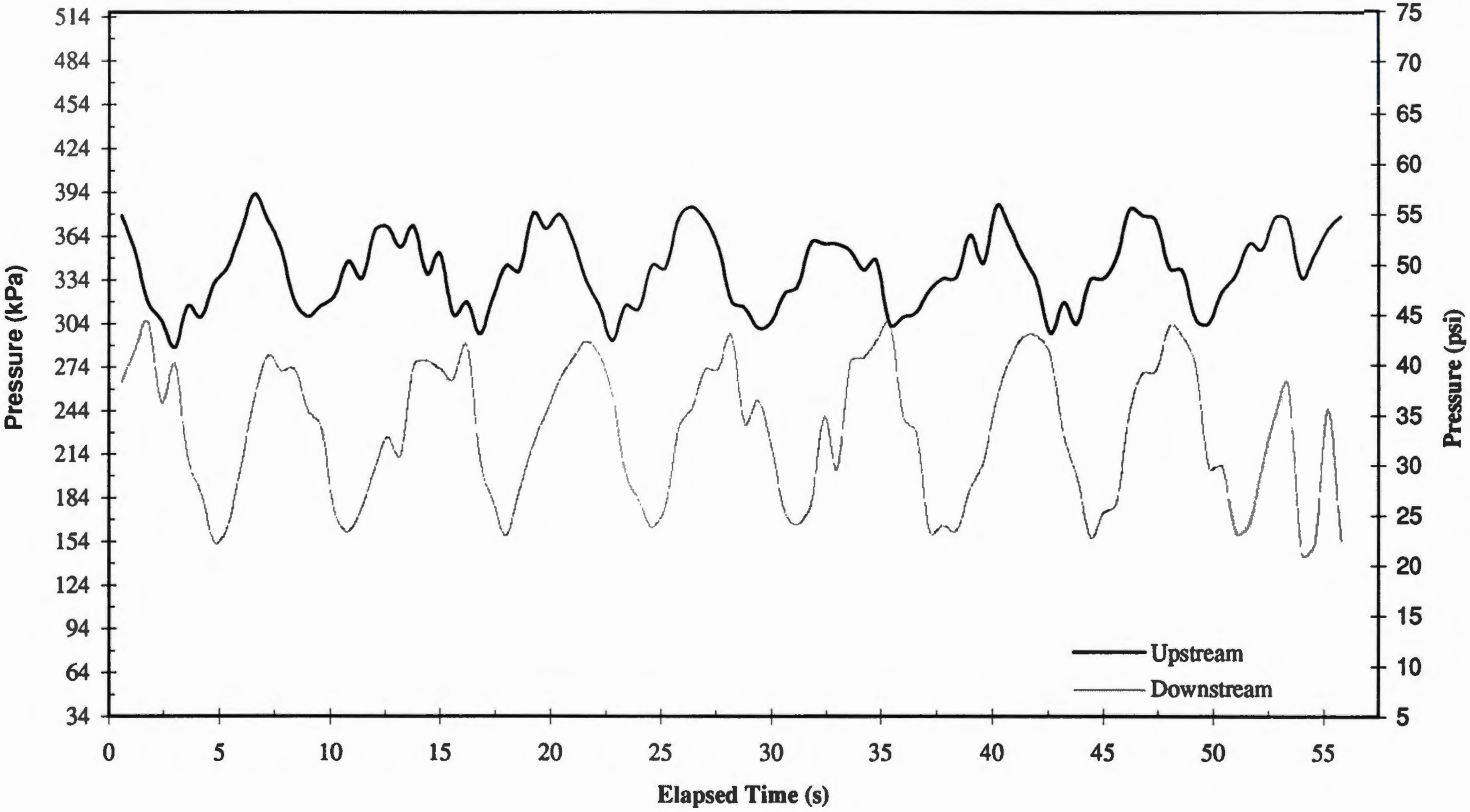
A-9 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



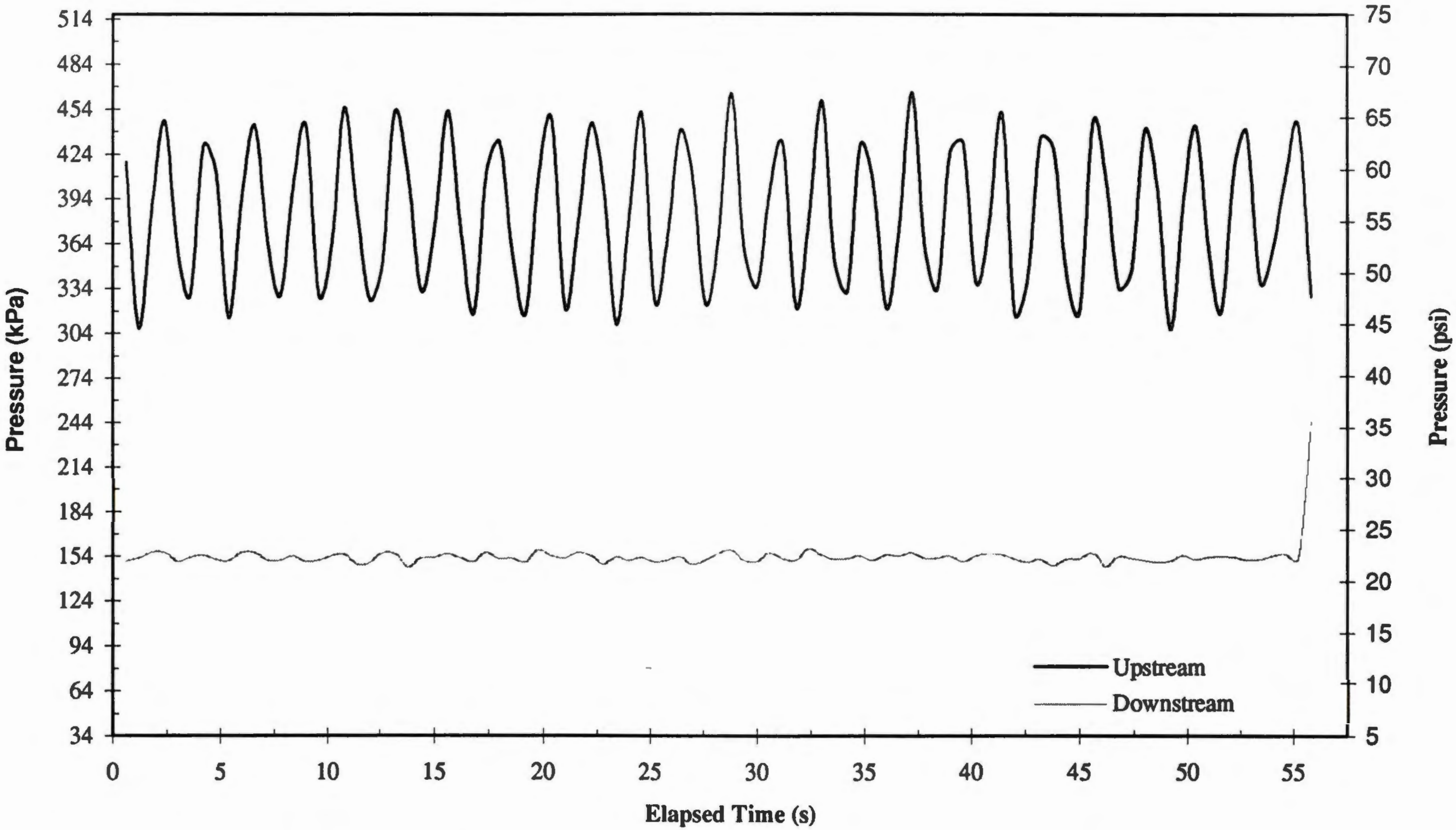
A-10 Pressure trace for water-driven injection system during unit 1 and bypass operation at high flow with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



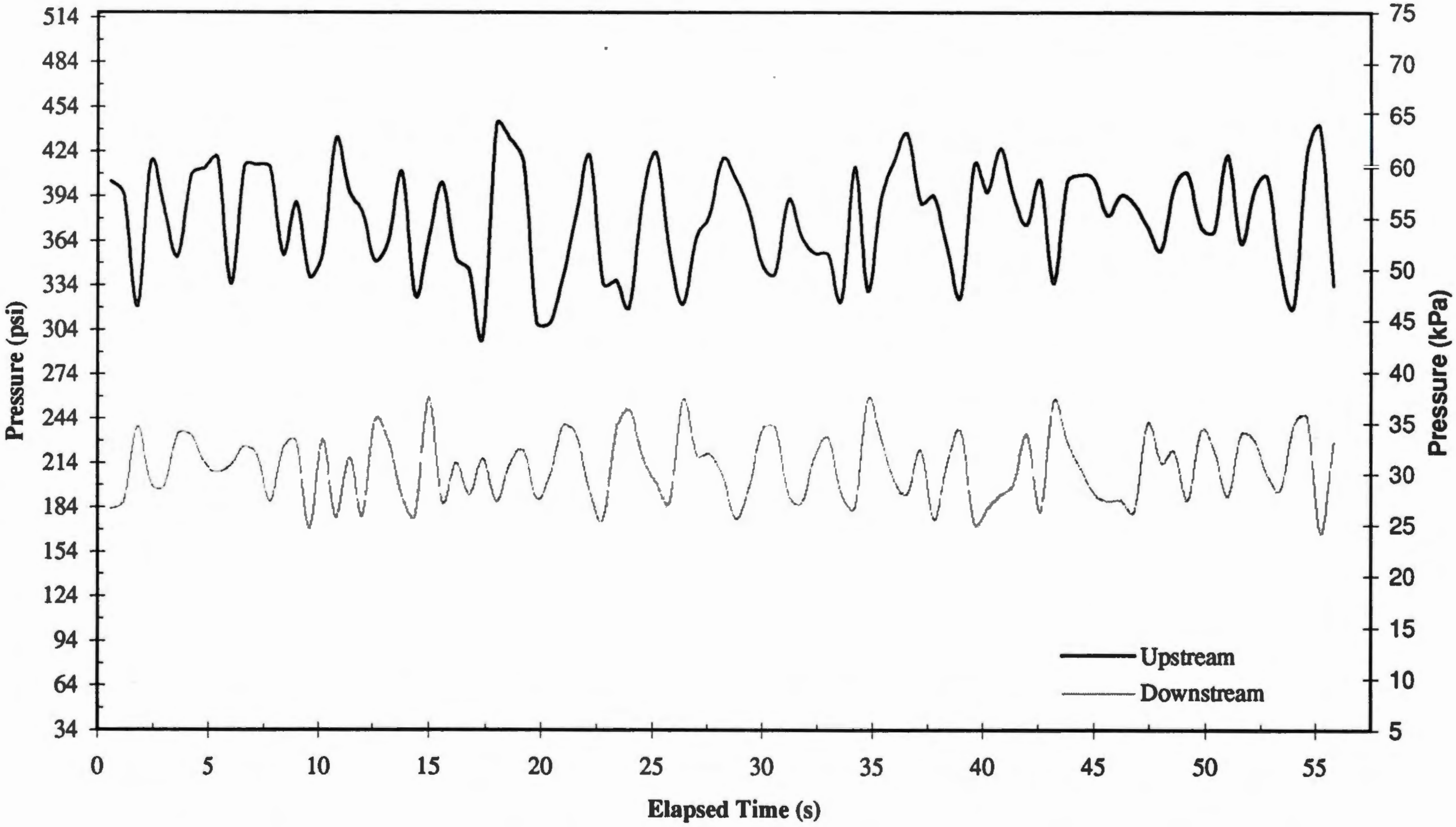
A-11 Pressure trace for water-driven injection system during unit 1, 2, and bypass operation at high flowrate with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



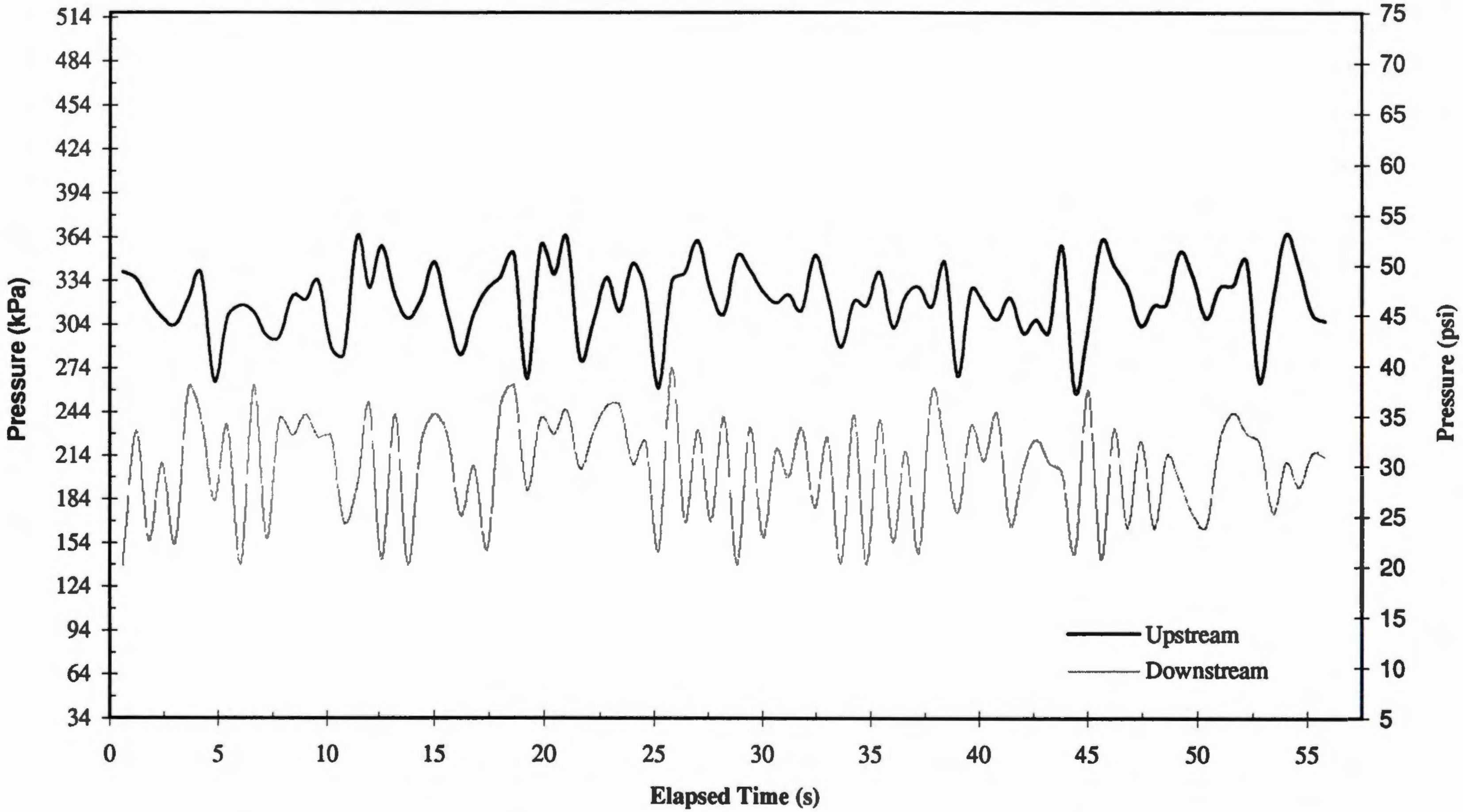
A-12 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with symmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



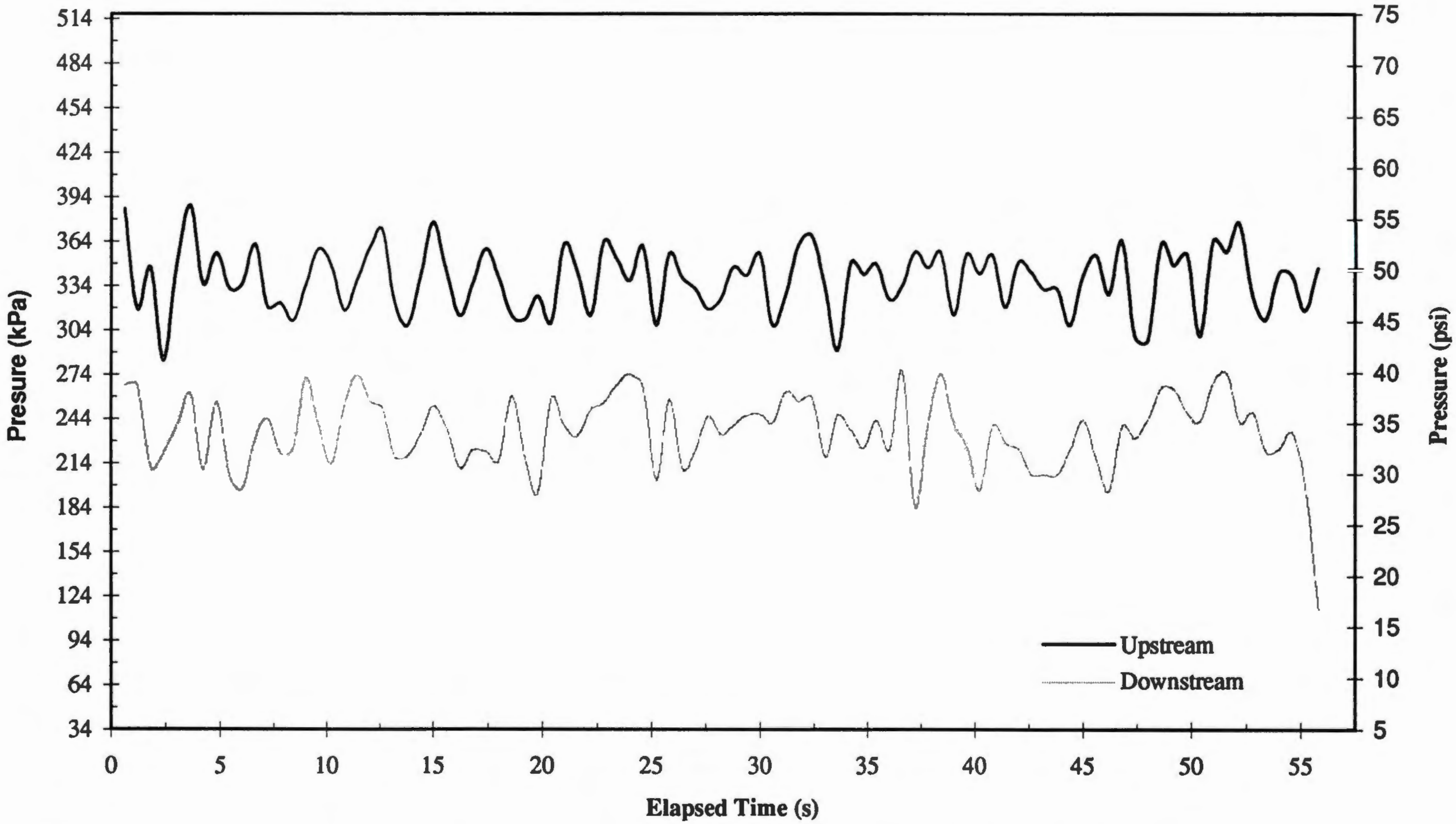
A-13 Pressure trace for water-driven injection system during unit 1 operation at high flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



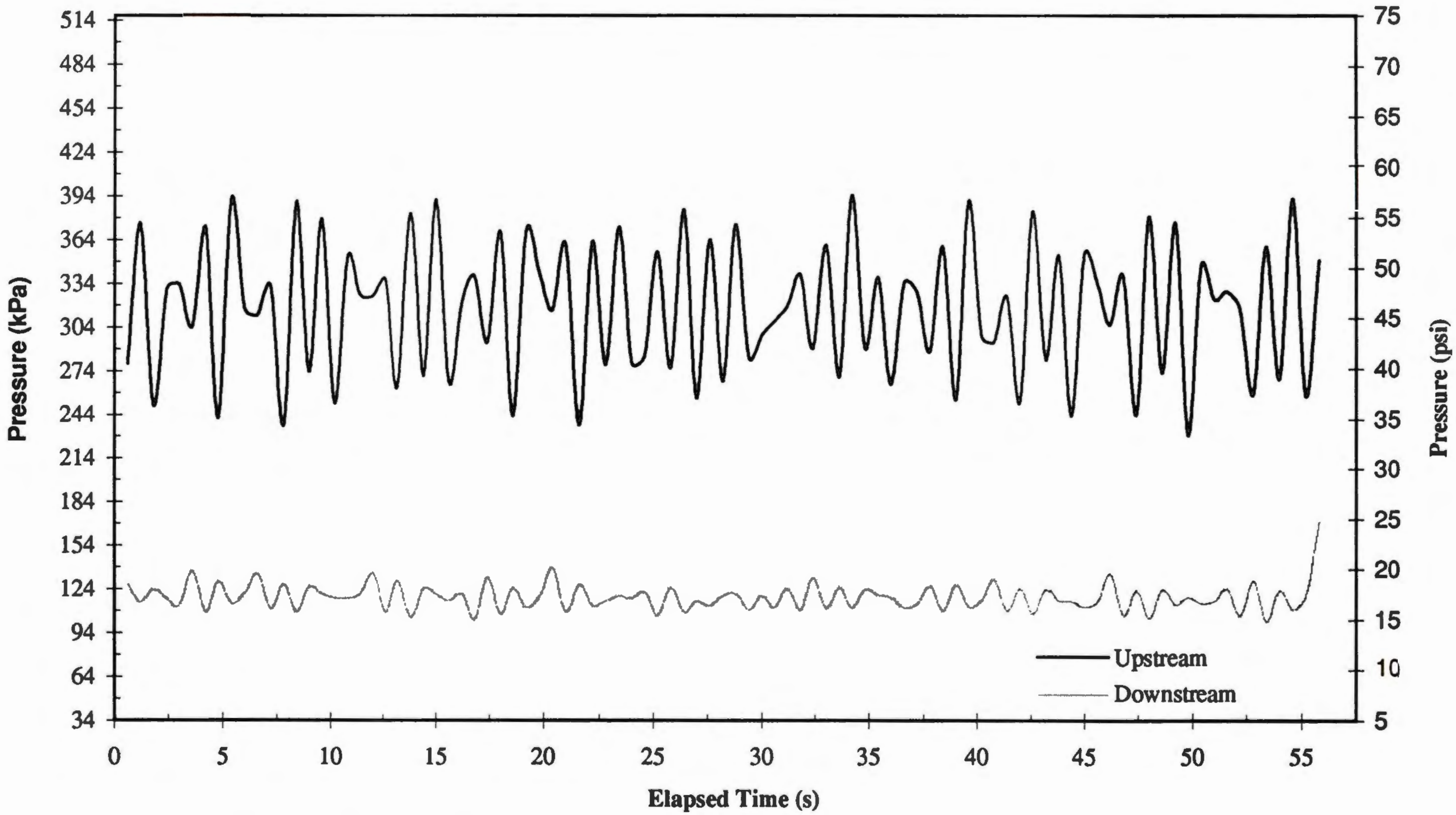
A-14 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



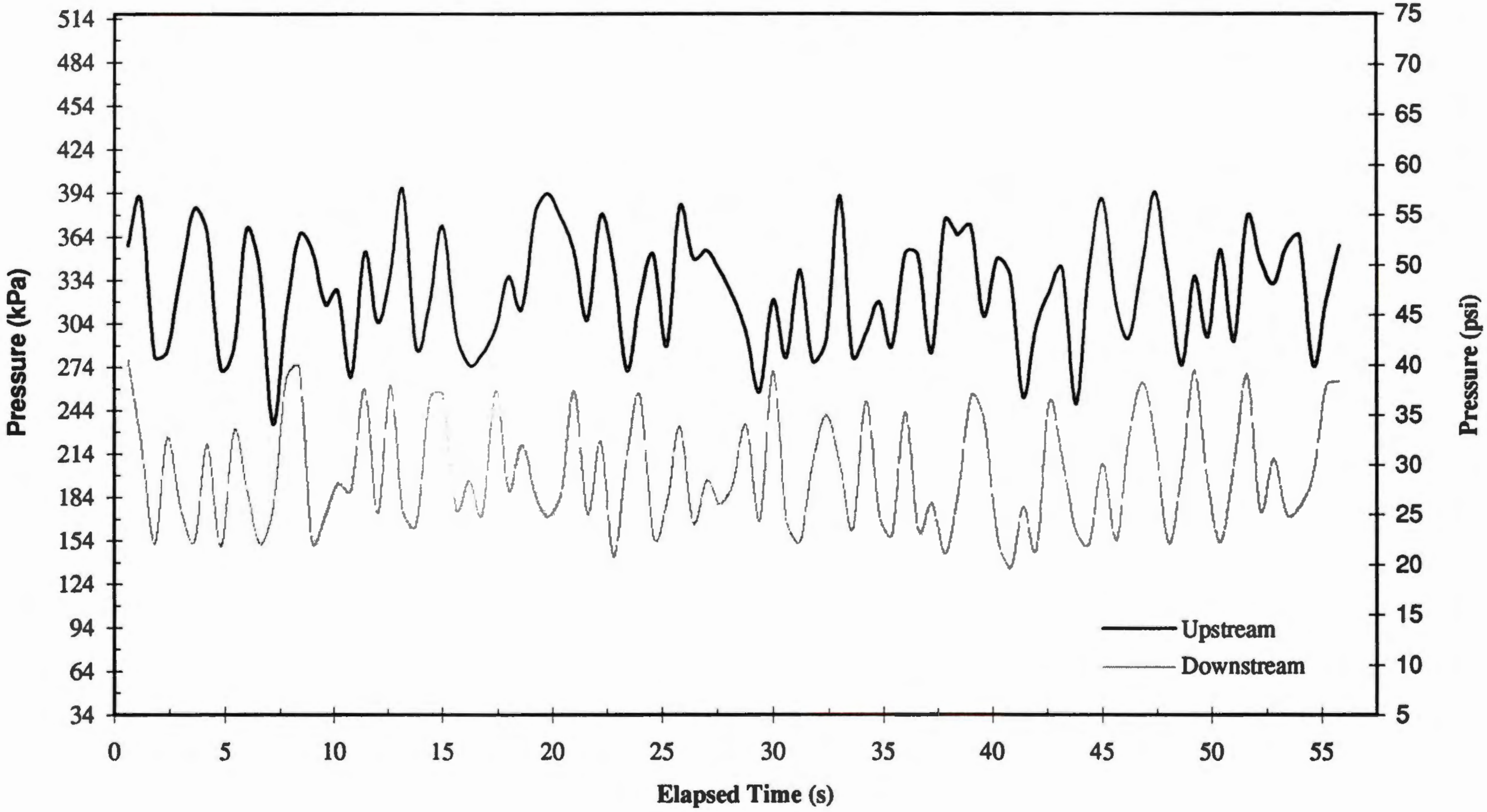
A-15 Pressure trace for water-driven injection system during unit 1 operation at low flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



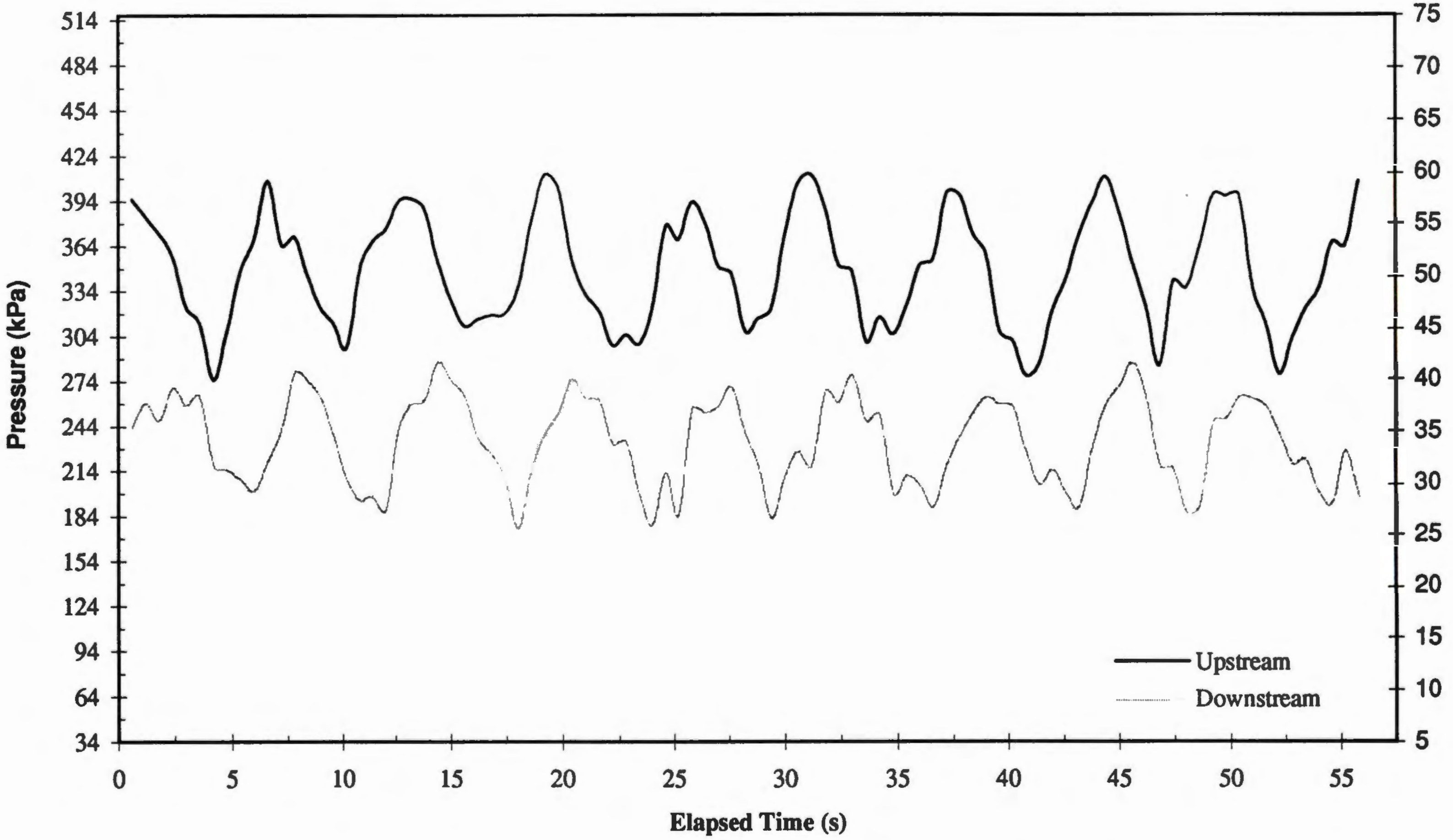
A-16 Pressure trace for water-driven injection system during unit 1 and 2 operation at low flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



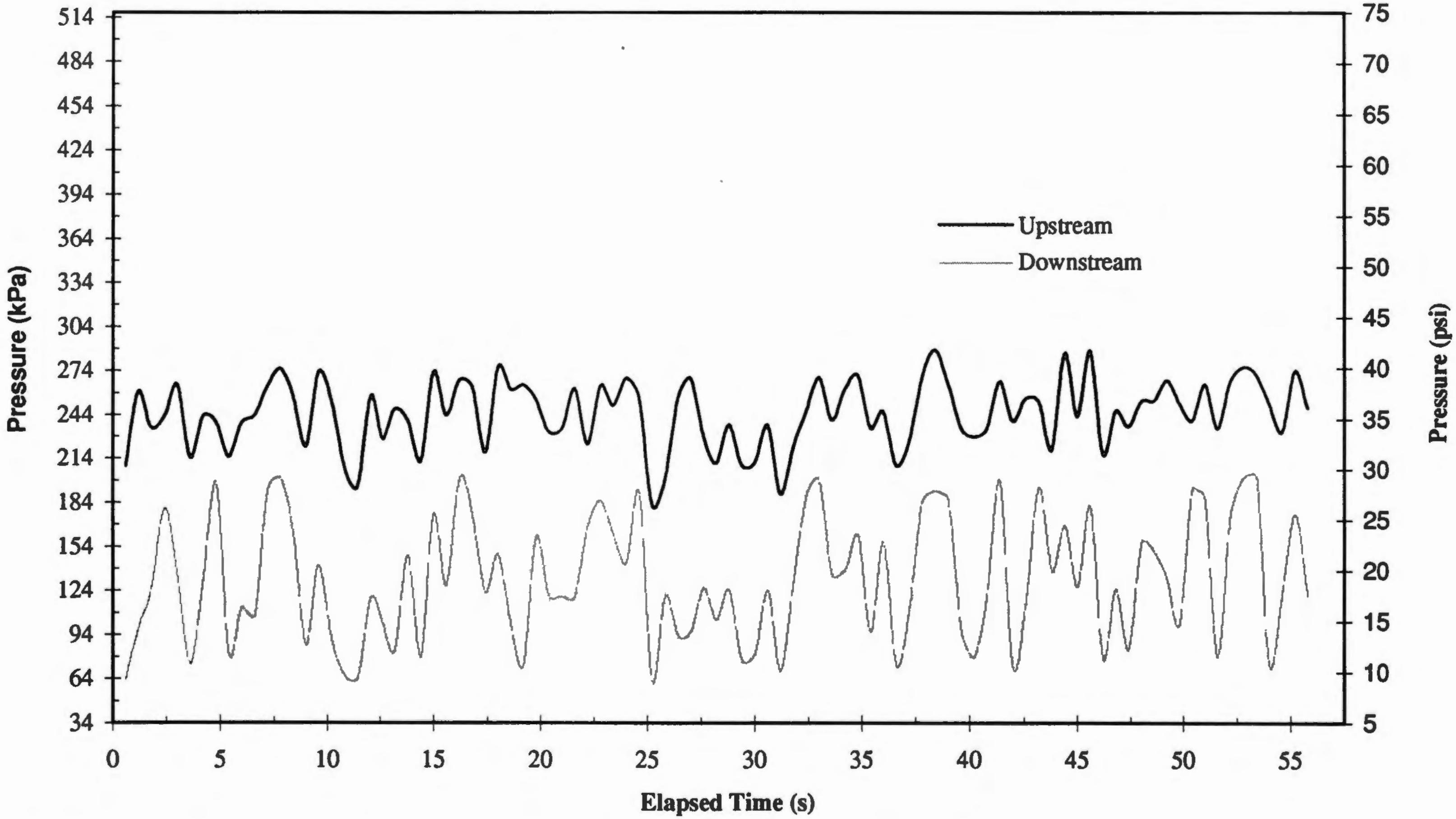
A-17 Pressure trace for water-driven injection system during unit 1 operation at high flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



A-18 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with additional hose length configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



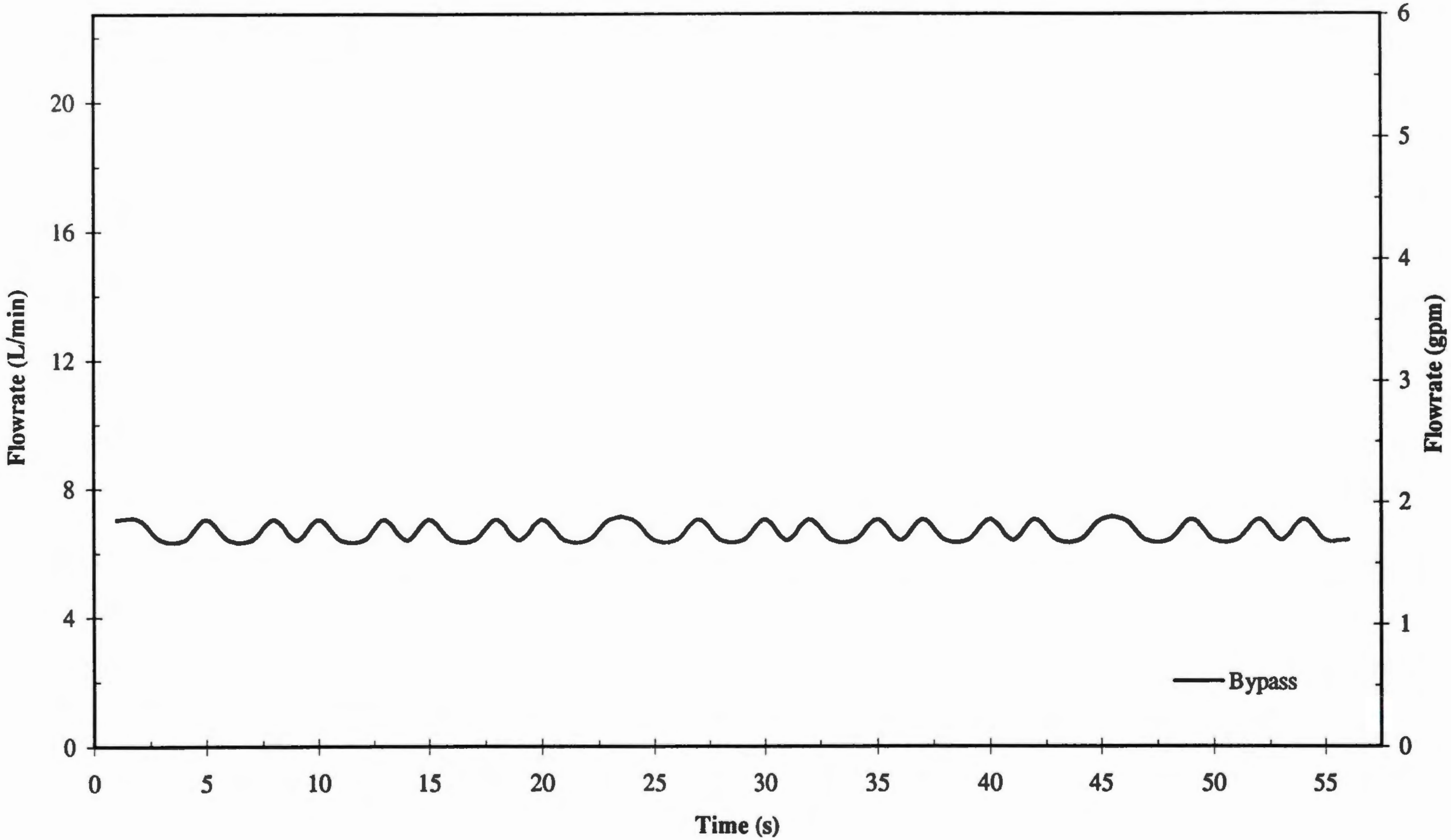
A-19 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with asymmetrical hose configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.



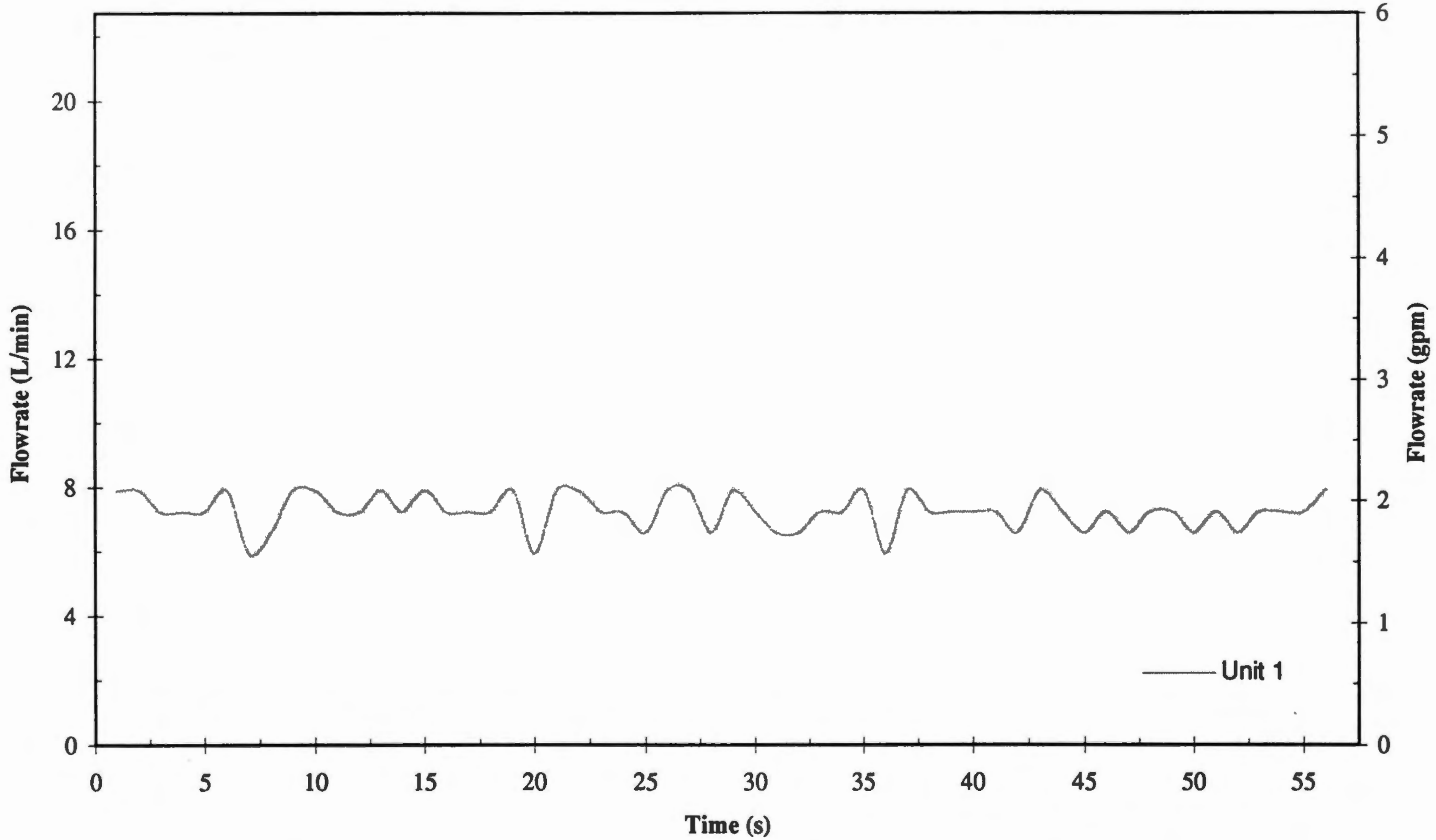
A-20 Pressure trace for water-driven injection system during unit 1 and 2 operation at high flow with asymmetrical configuration. Upstream and downstream describe pressure measurement location in reference to the three parallel branches.

APPENDIX B

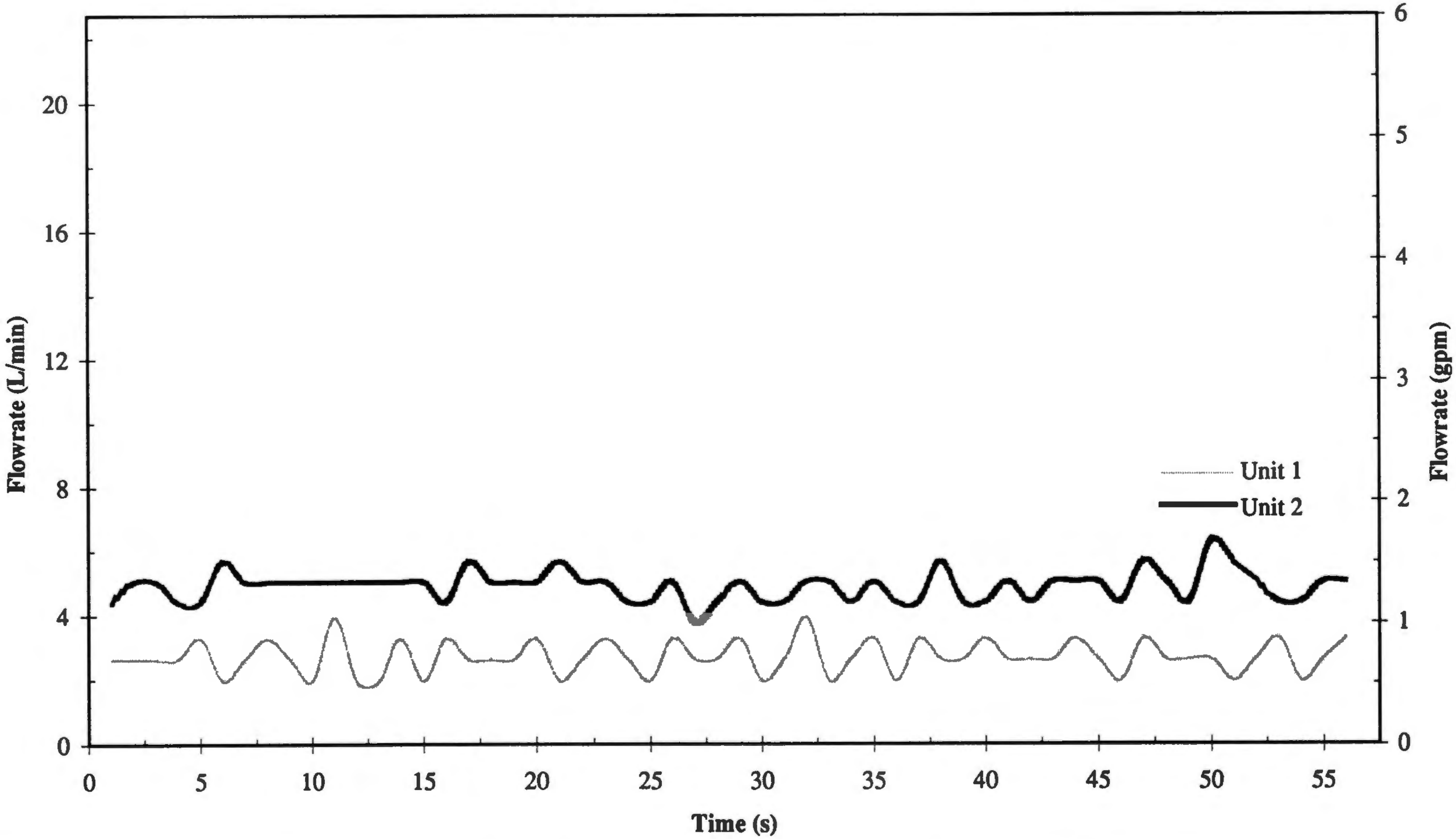
WATER-DRIVEN UNIT FLOW TRACES



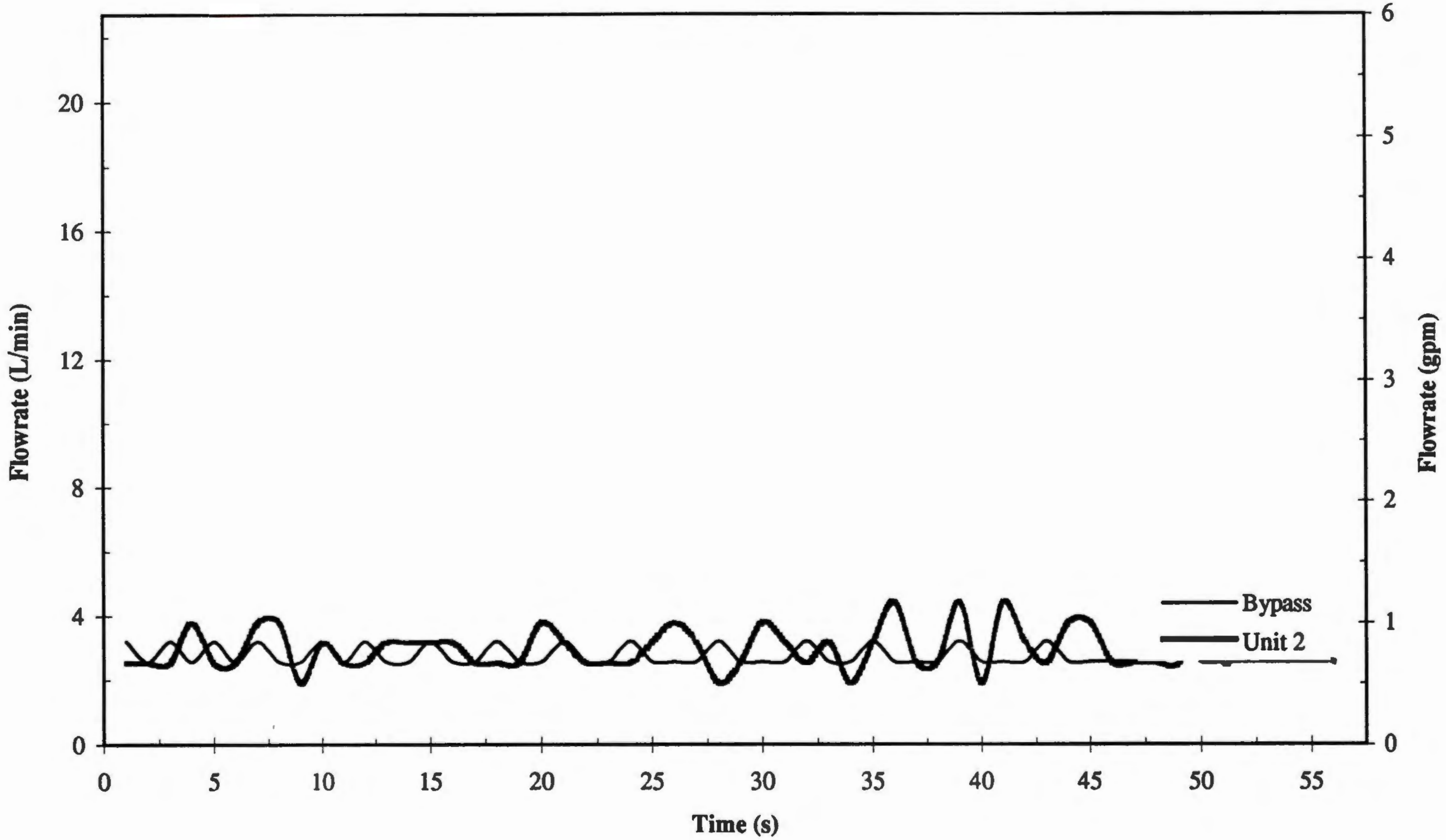
B-1 Flow trace for bypass branch during water-driven injection system operation at low flow with symmetrical hose configuration.



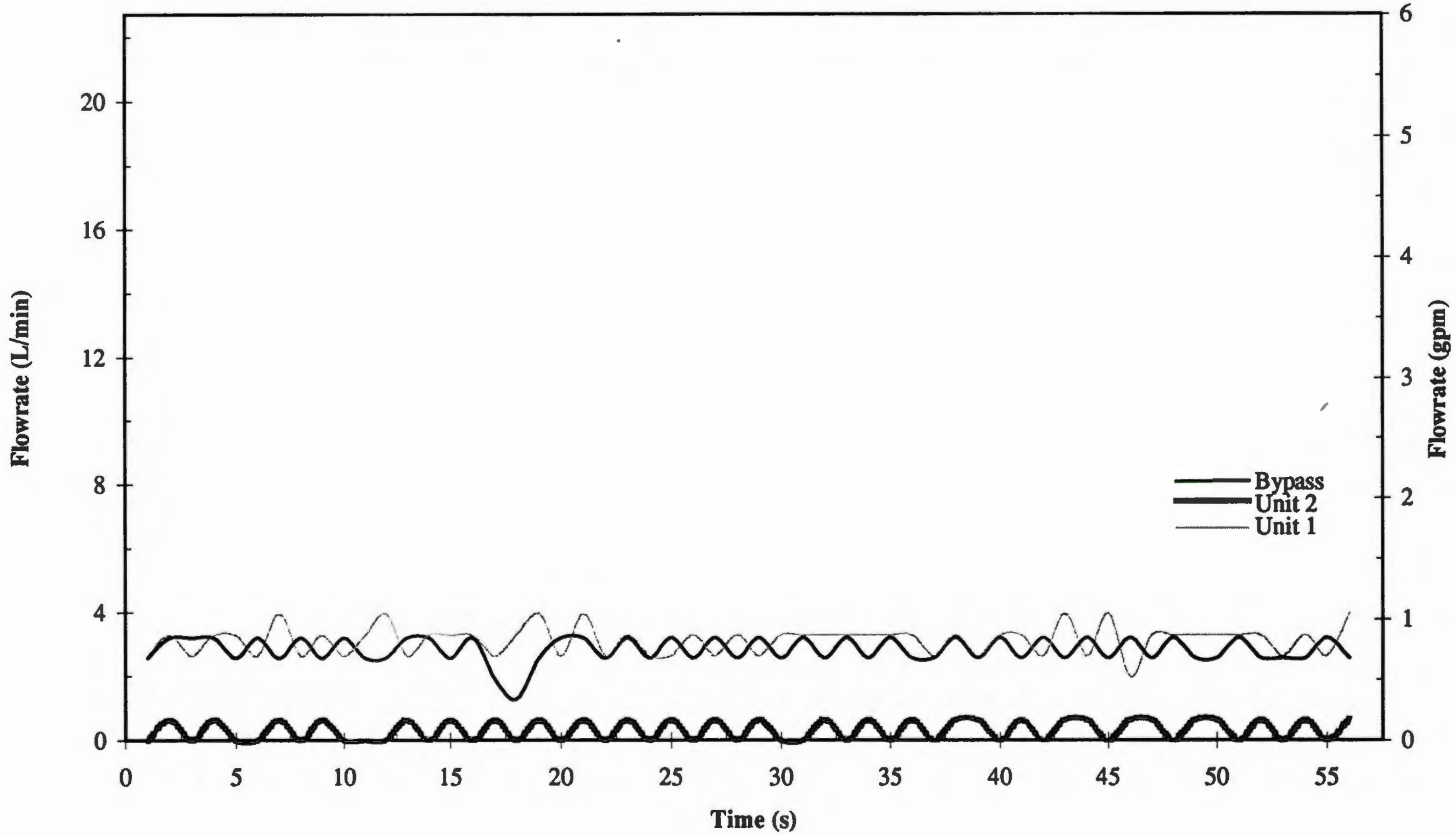
B-2 Flow trace for unit 1 during water-driven injection system operation at low flow with symmetrical hose configuration.



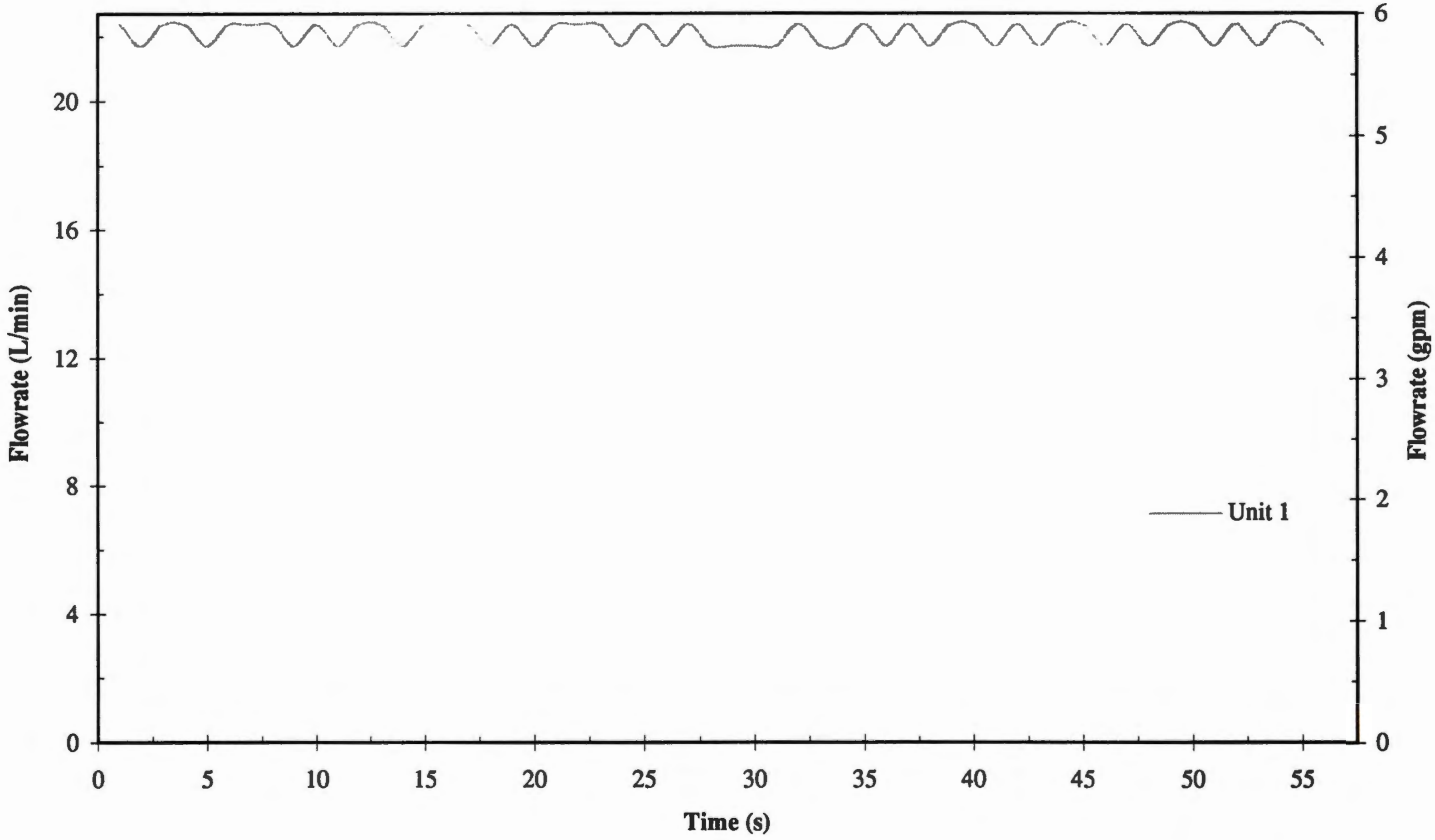
B-4 Flow trace for unit 1 and 2 during water-driven injection system operation at low flow with symmetrical hose configuration.



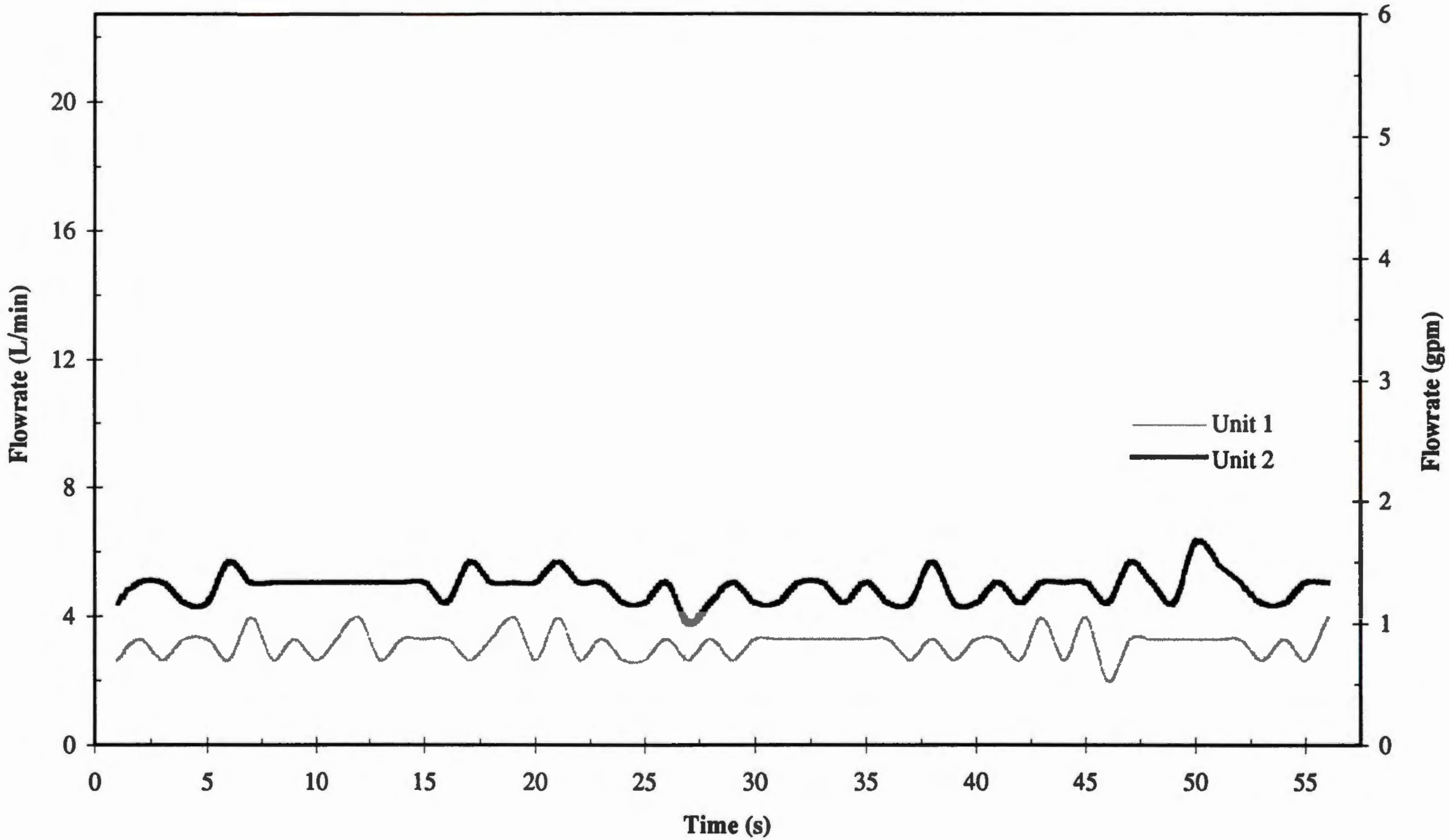
B-6 Flow trace for unit 2 and bypass during water-driven injection system operation at low flow with symmetrical hose configuration.



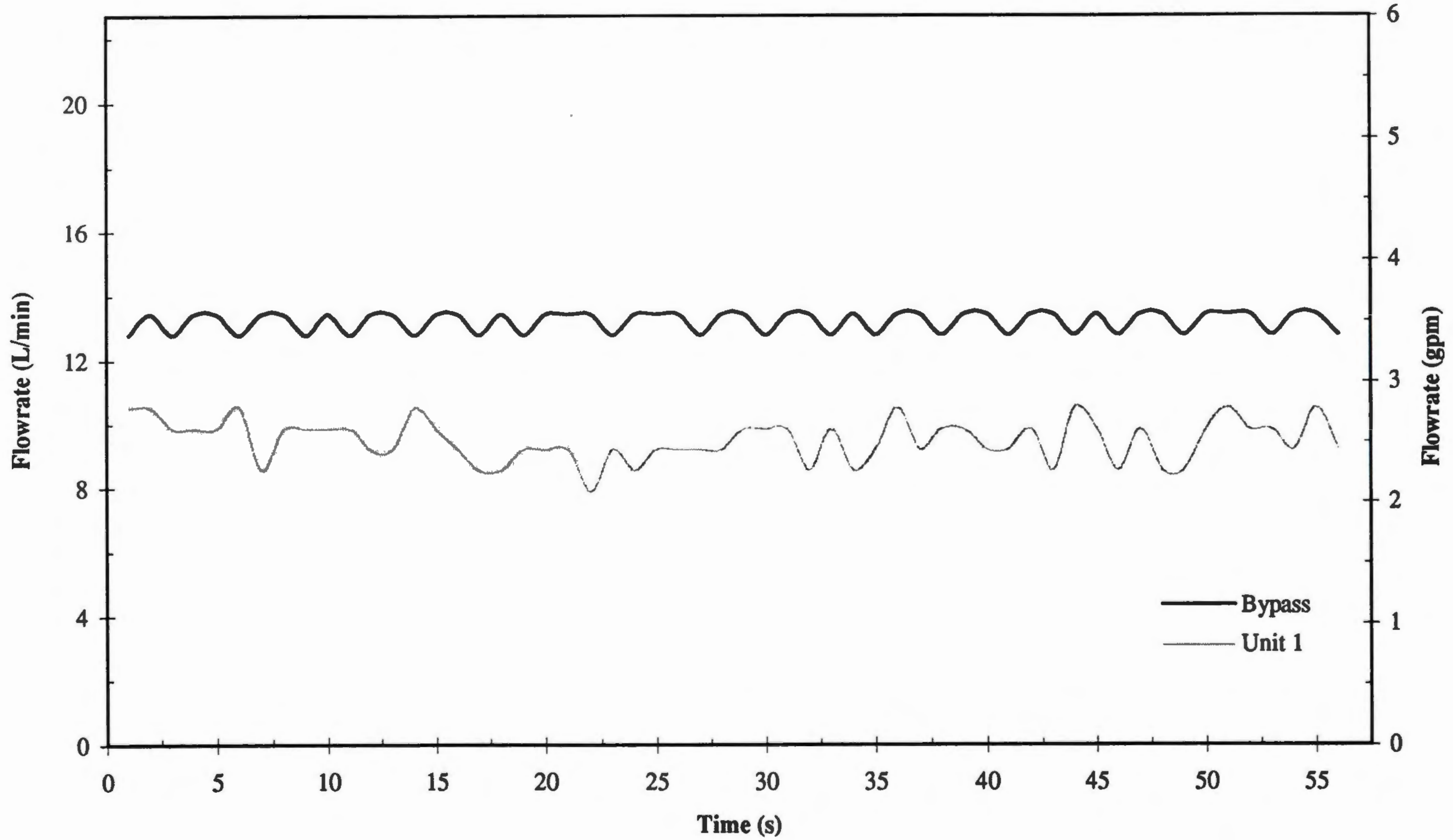
B-7 Flow trace for unit 1, 2, and bypass during water-driven injection system operation at low flow with symmetrical hose configuration.



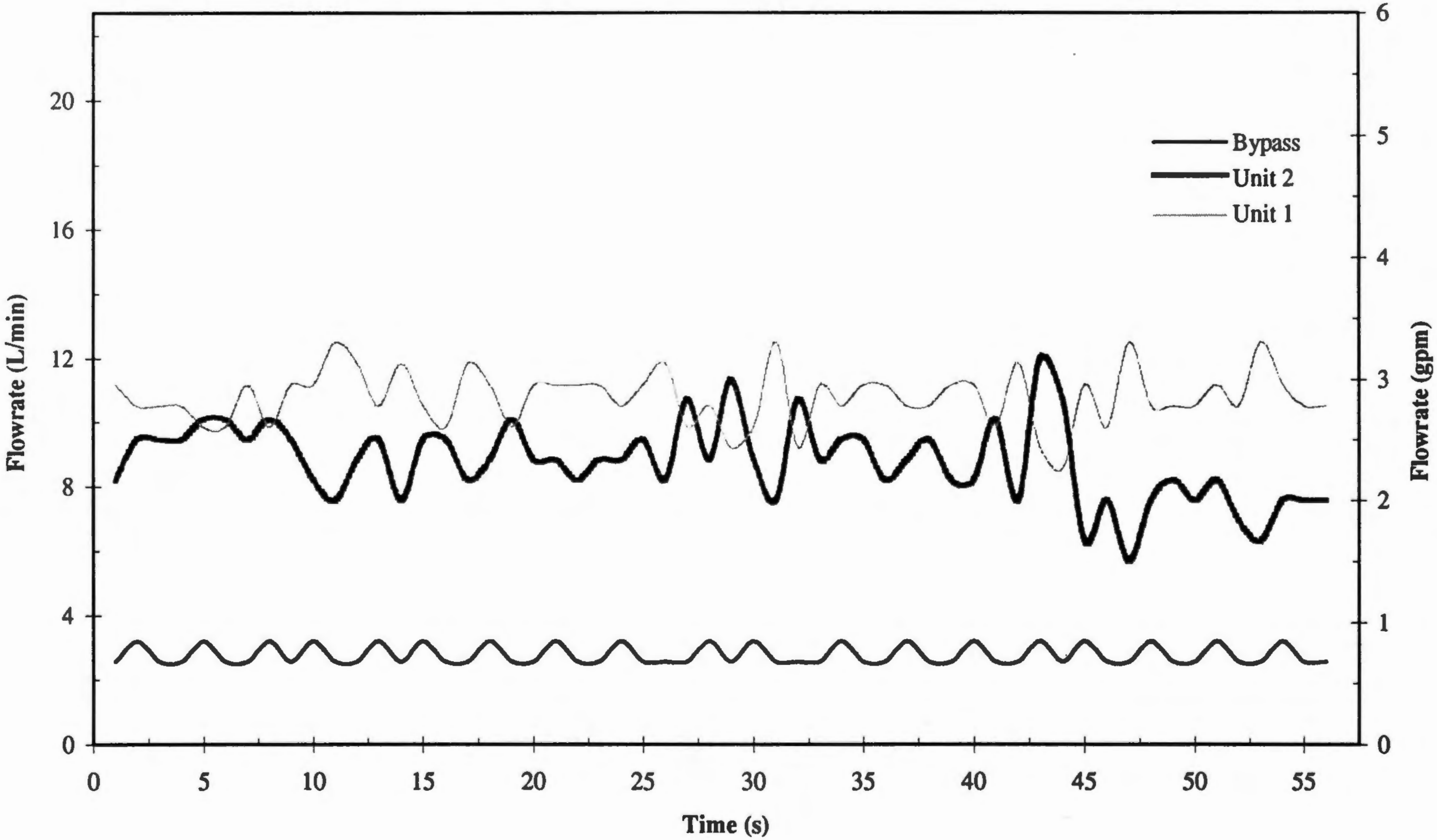
B-8 Flow trace for unit 1 during water-driven injection system operation at high flow with symmetrical hose configuration.



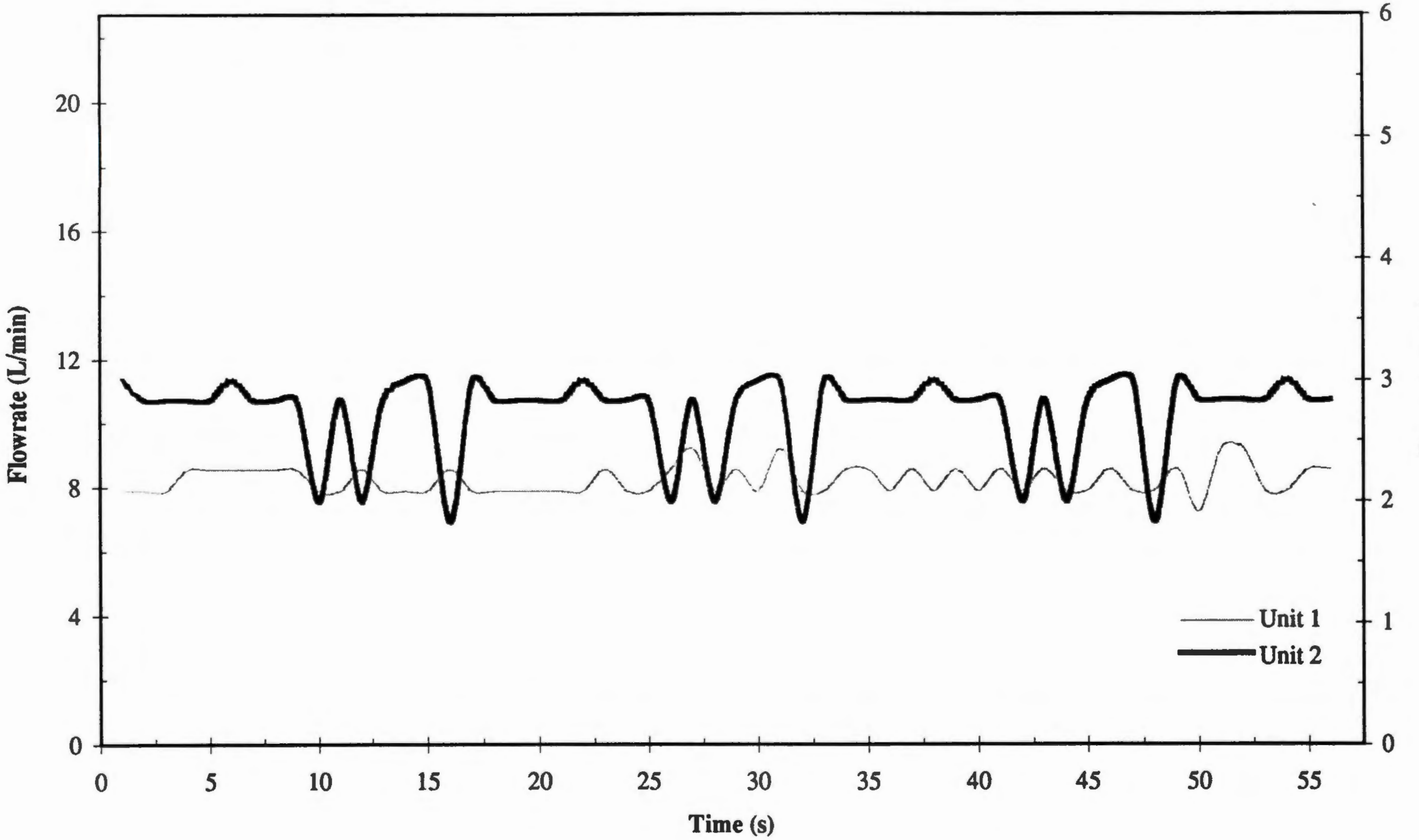
B-9 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with symmetrical hose configuration.



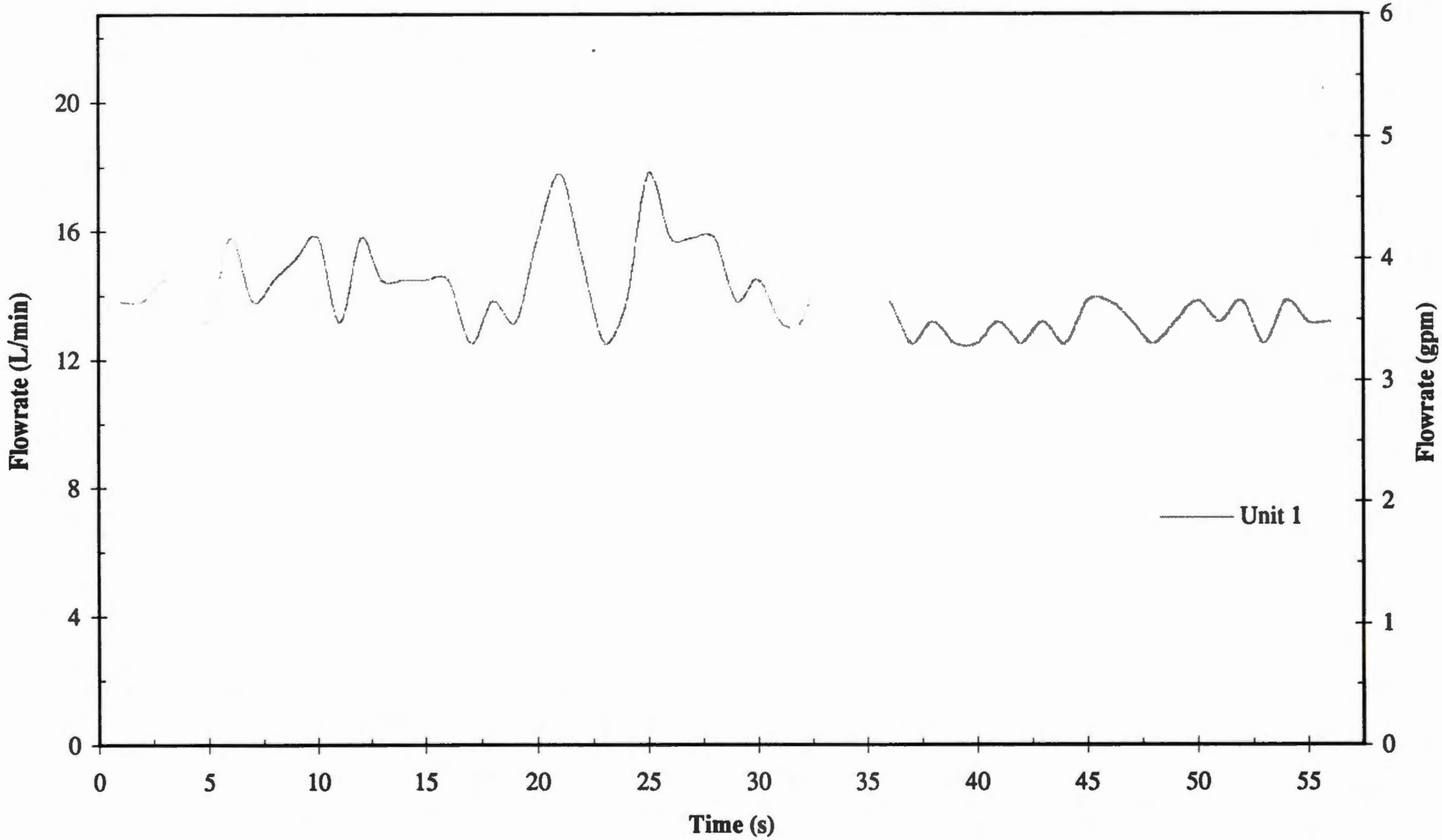
B-10 Flow trace for unit 1 and bypass during water-driven injection system operation at high flow with symmetrical hose configuration.



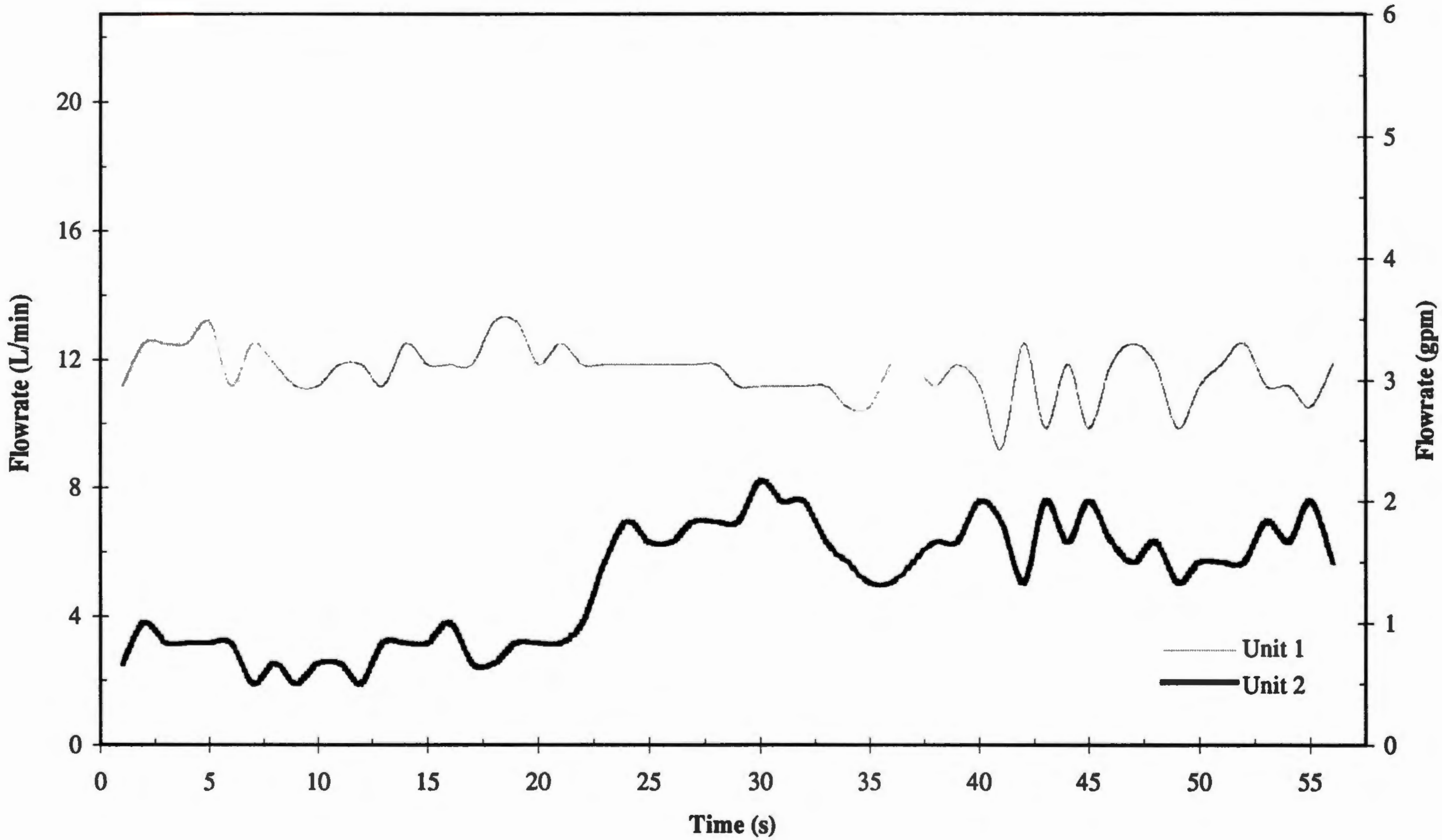
B-11 Flow trace for unit 1, 2, and bypass during water-driven injection system operation at high flow with symmetrical hose configuration.



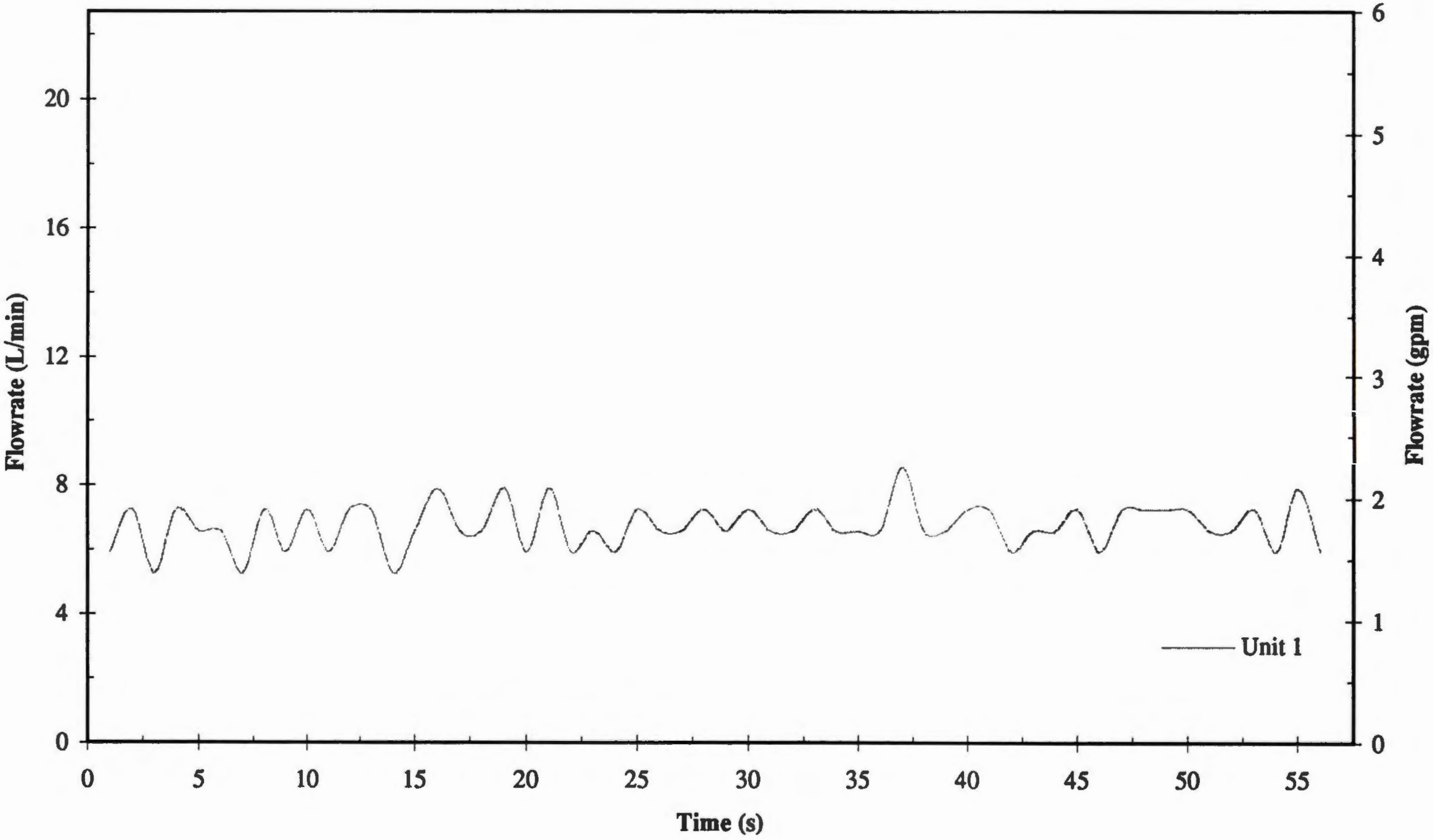
B-12 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with symmetrical hose configuration.



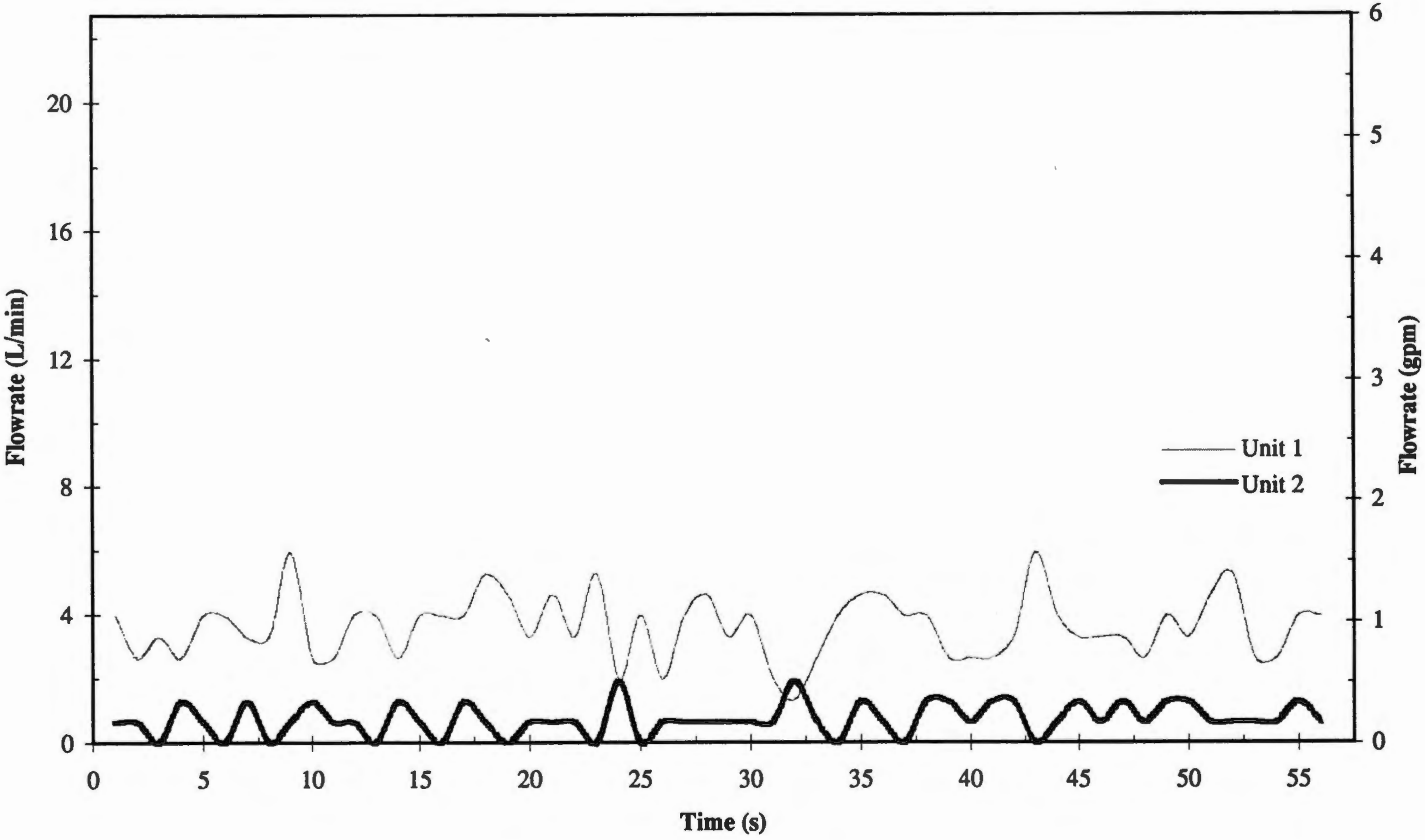
B-13 Flow trace for unit 1 during water-driven injection system operation at high flow with additional hose length configuration.



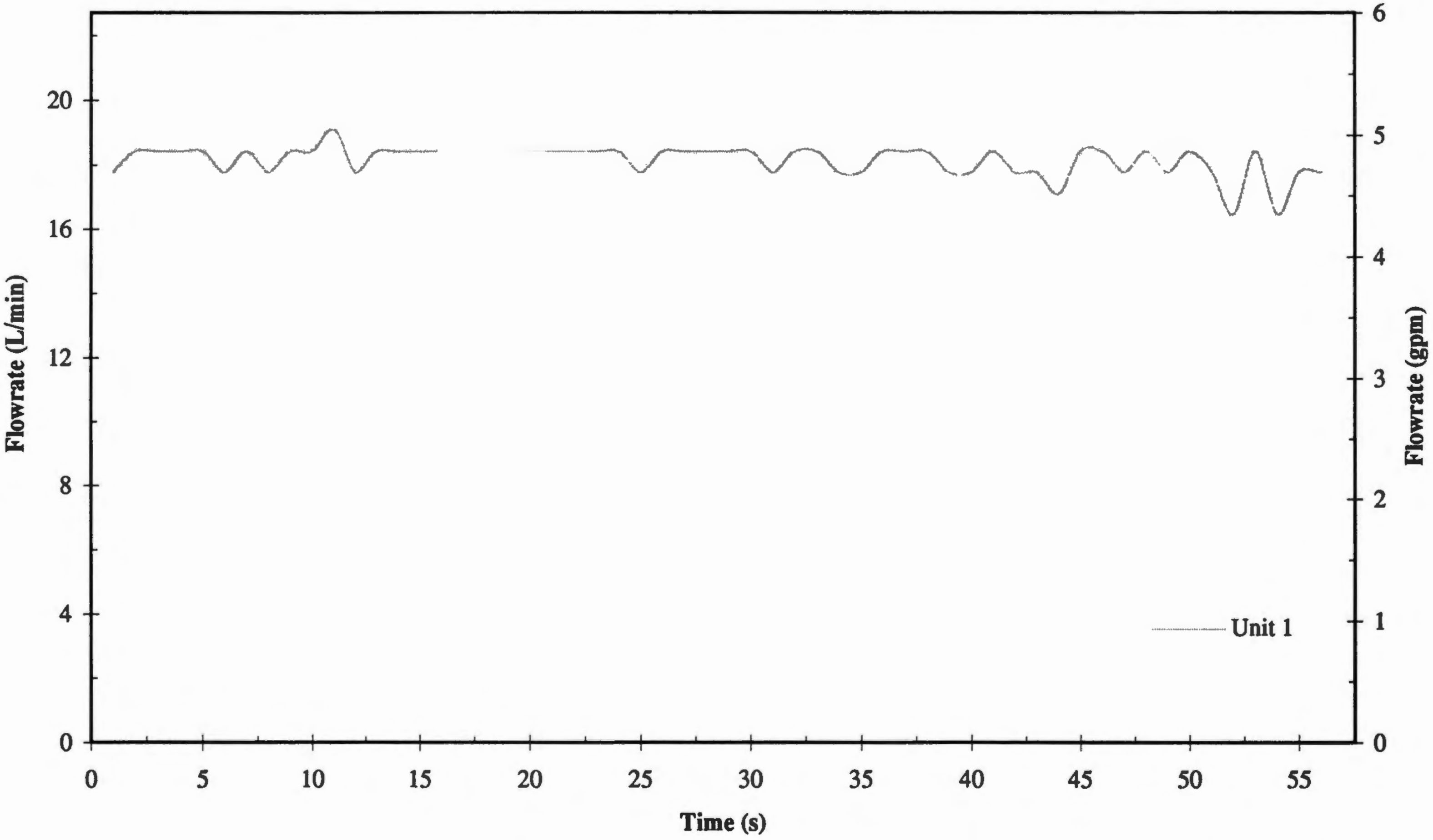
B-14 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with additional hose length configuration.



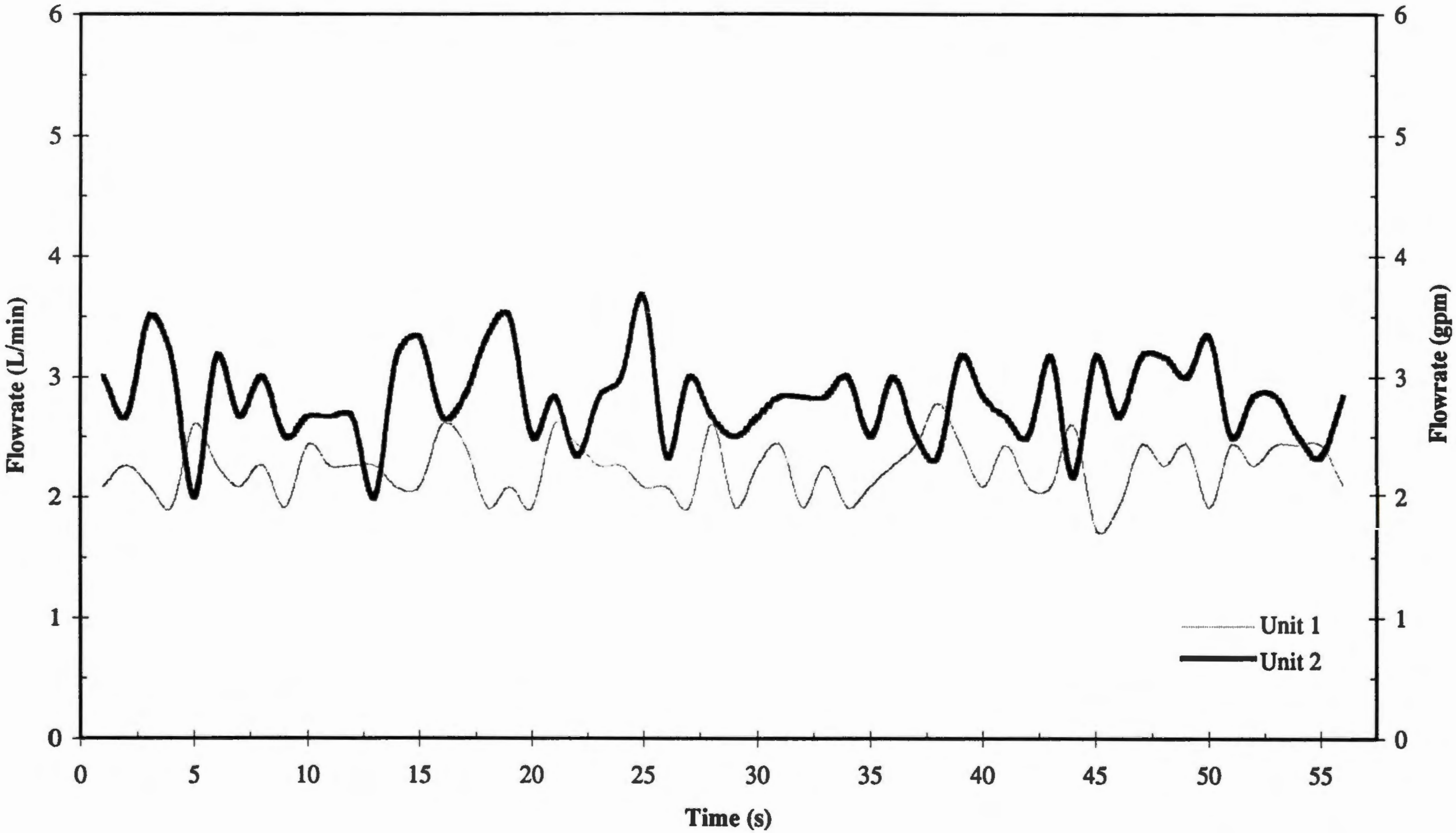
B-15 Flow trace for unit 1 during water-driven injection system operation at low flow with addition hose length configuration.



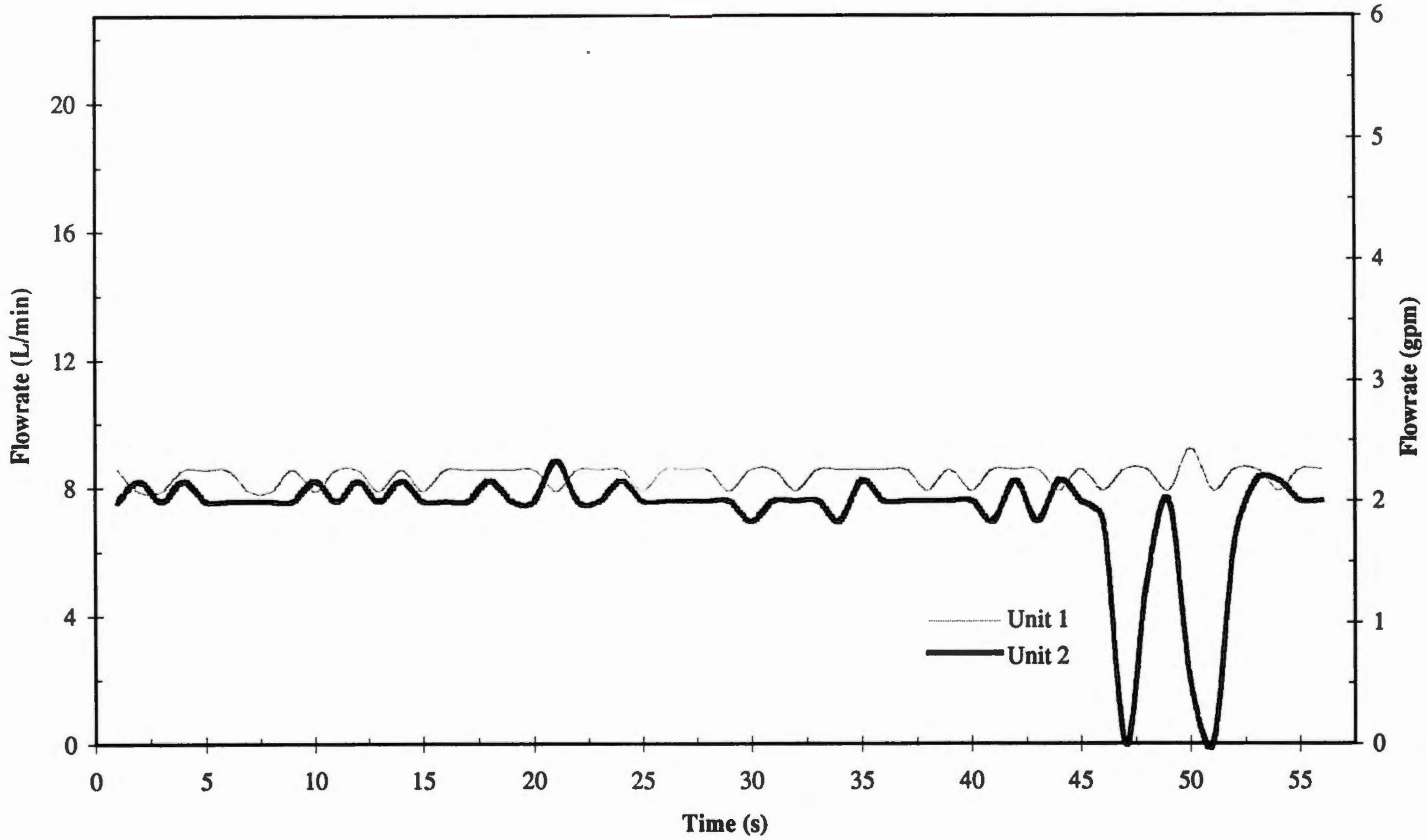
B-16 Flow trace for unit 1 and 2 during water-driven injection system operation at low flow with additional hose length configuration.



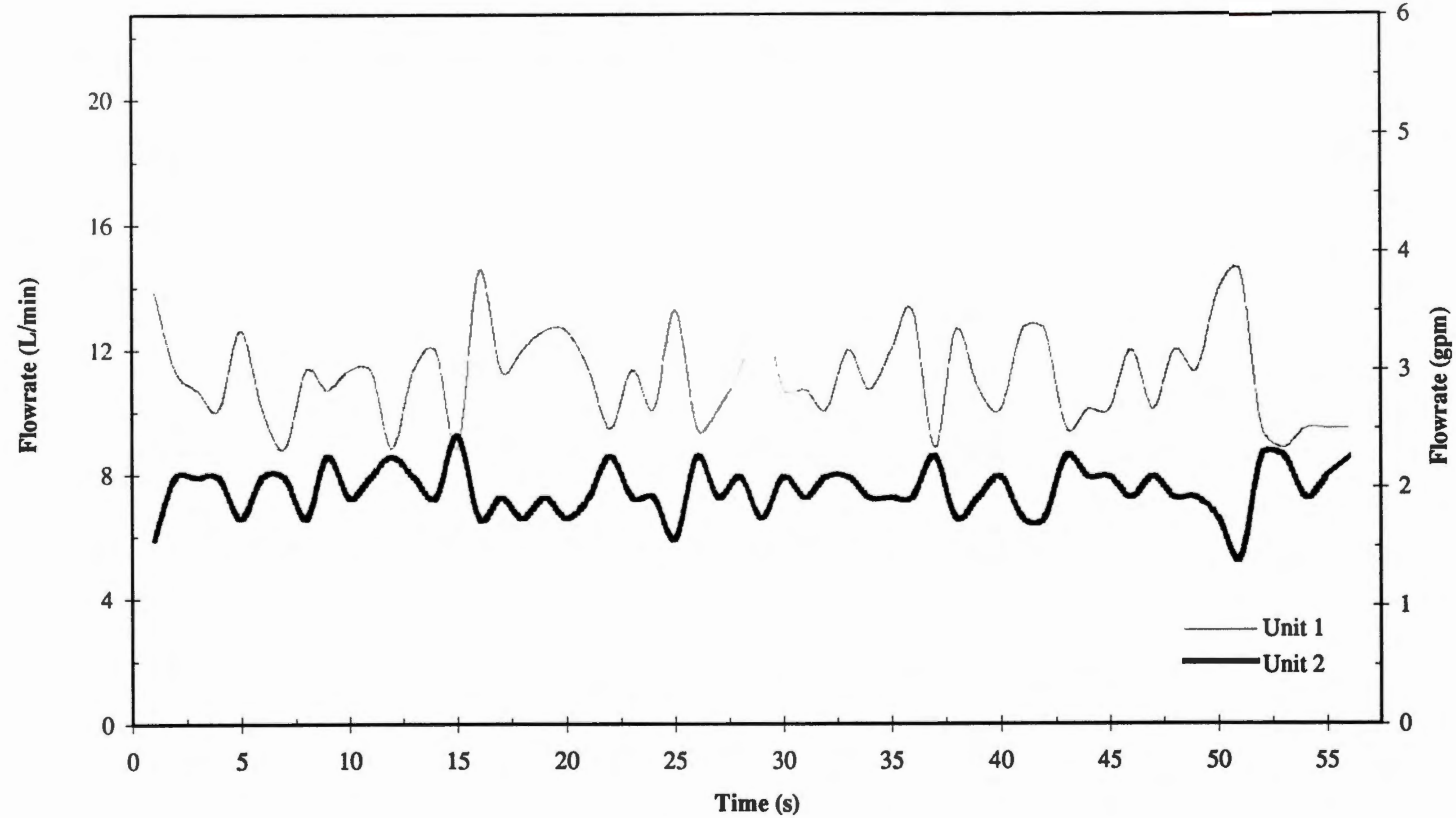
B-17 Flow trace for unit 1 during water-driven injection system operation at high flow with additional hose length configuration.



B-18 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with additional hose length configuration.



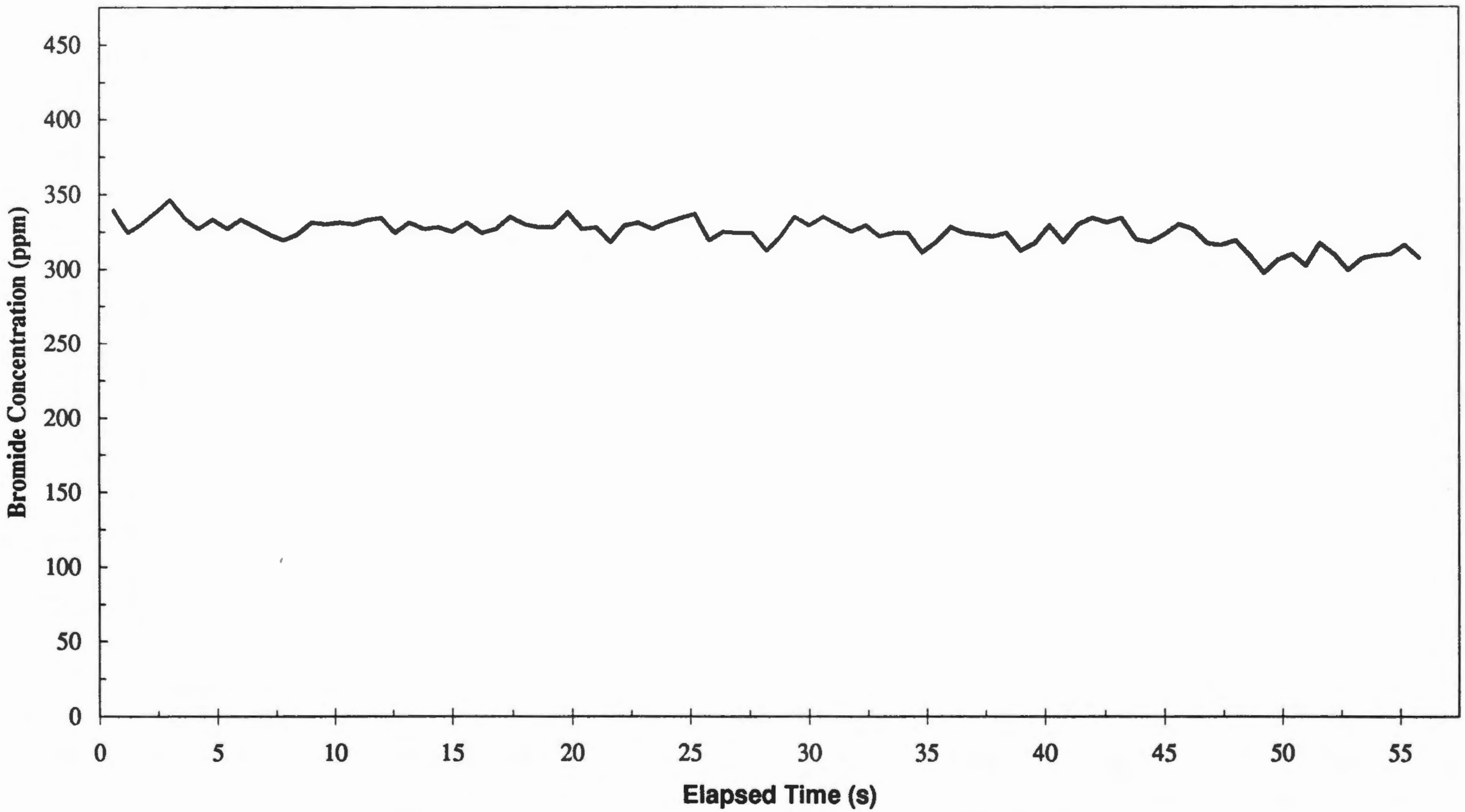
B-19 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with asymmetrical hose configuration.



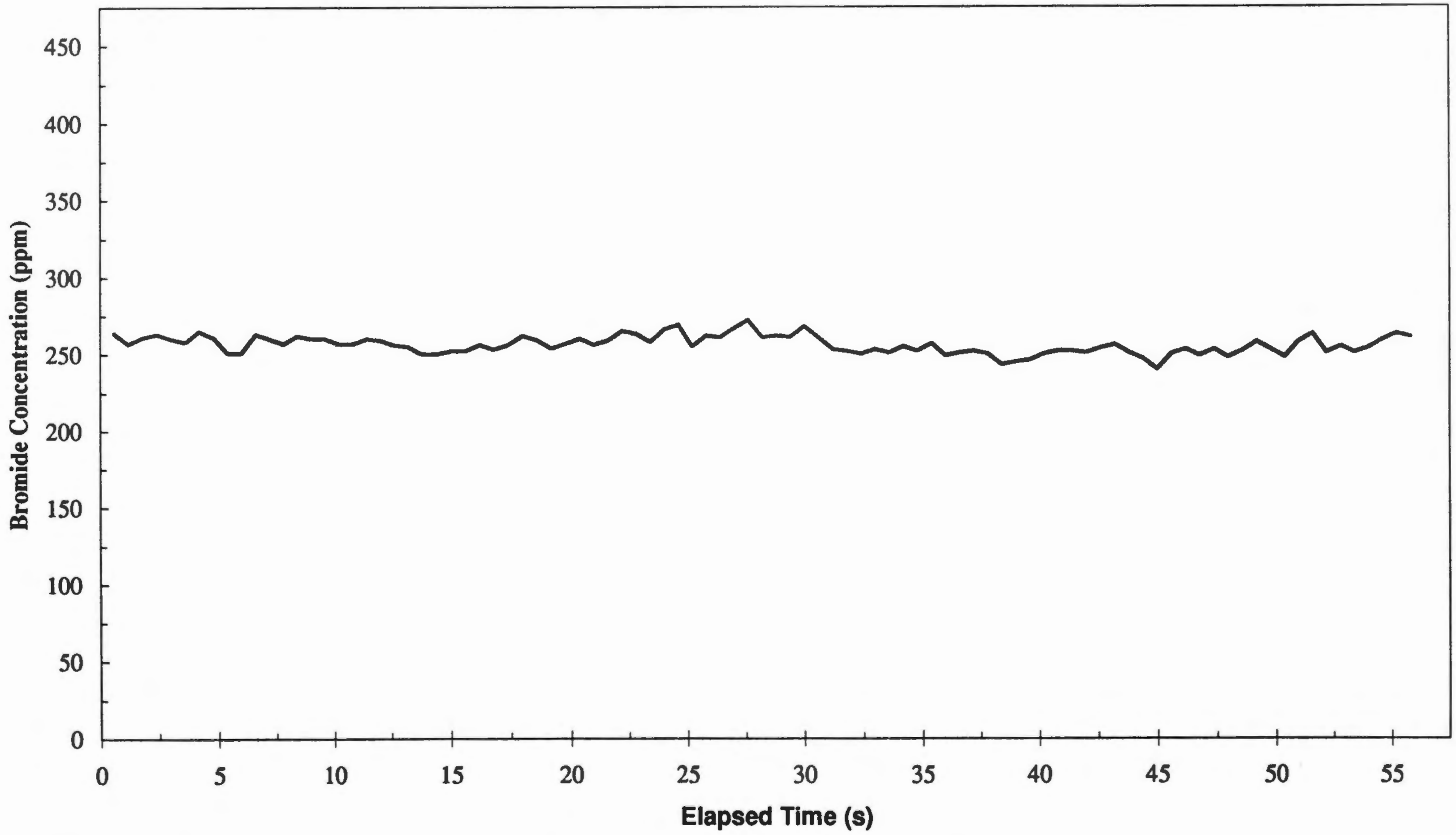
B-20 Flow trace for unit 1 and 2 during water-driven injection system operation at high flow with asymmetrical hose configuration.

APPENDIX C

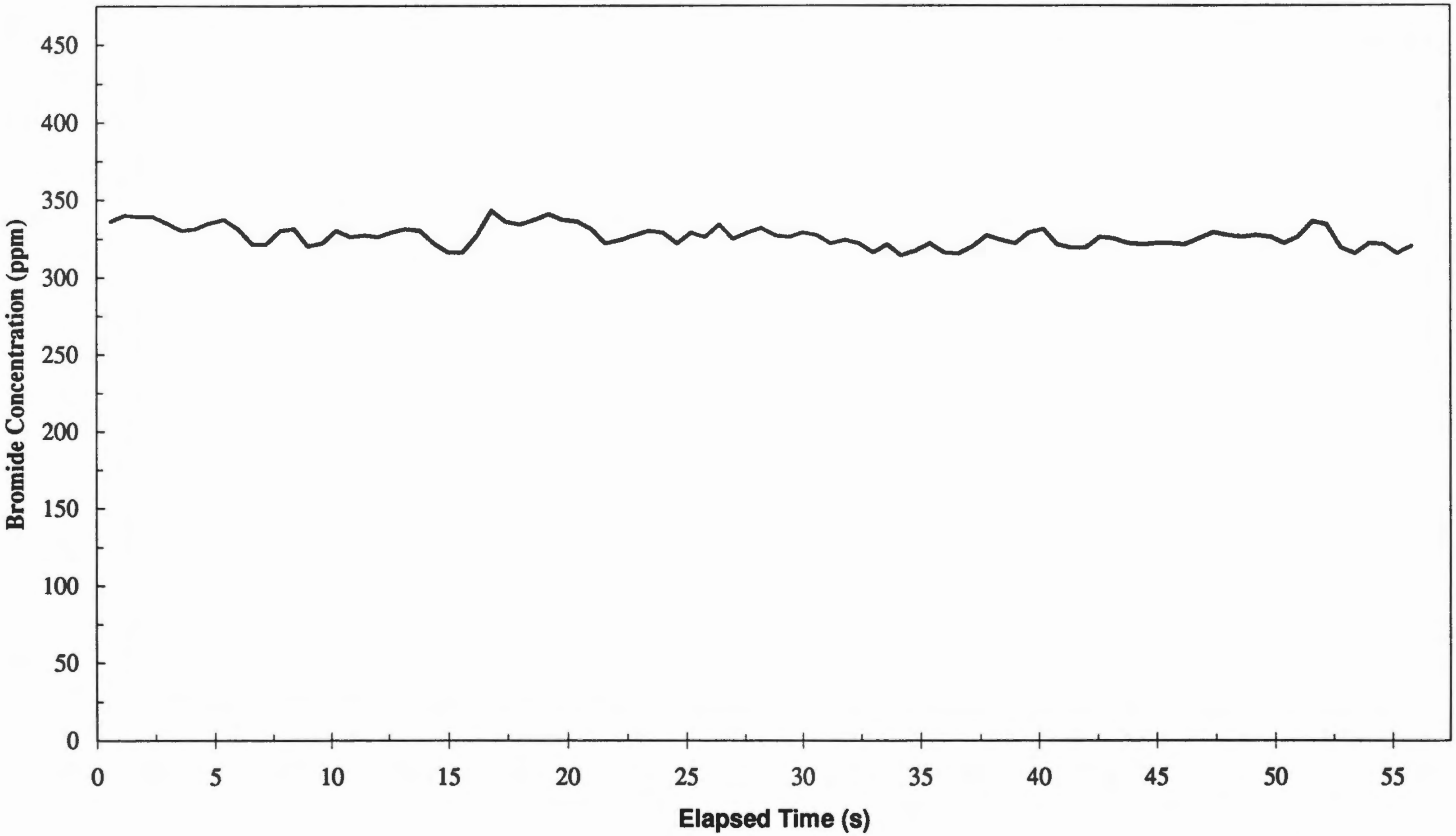
WATER-DRIVEN UNIT CHEMICAL TRACES



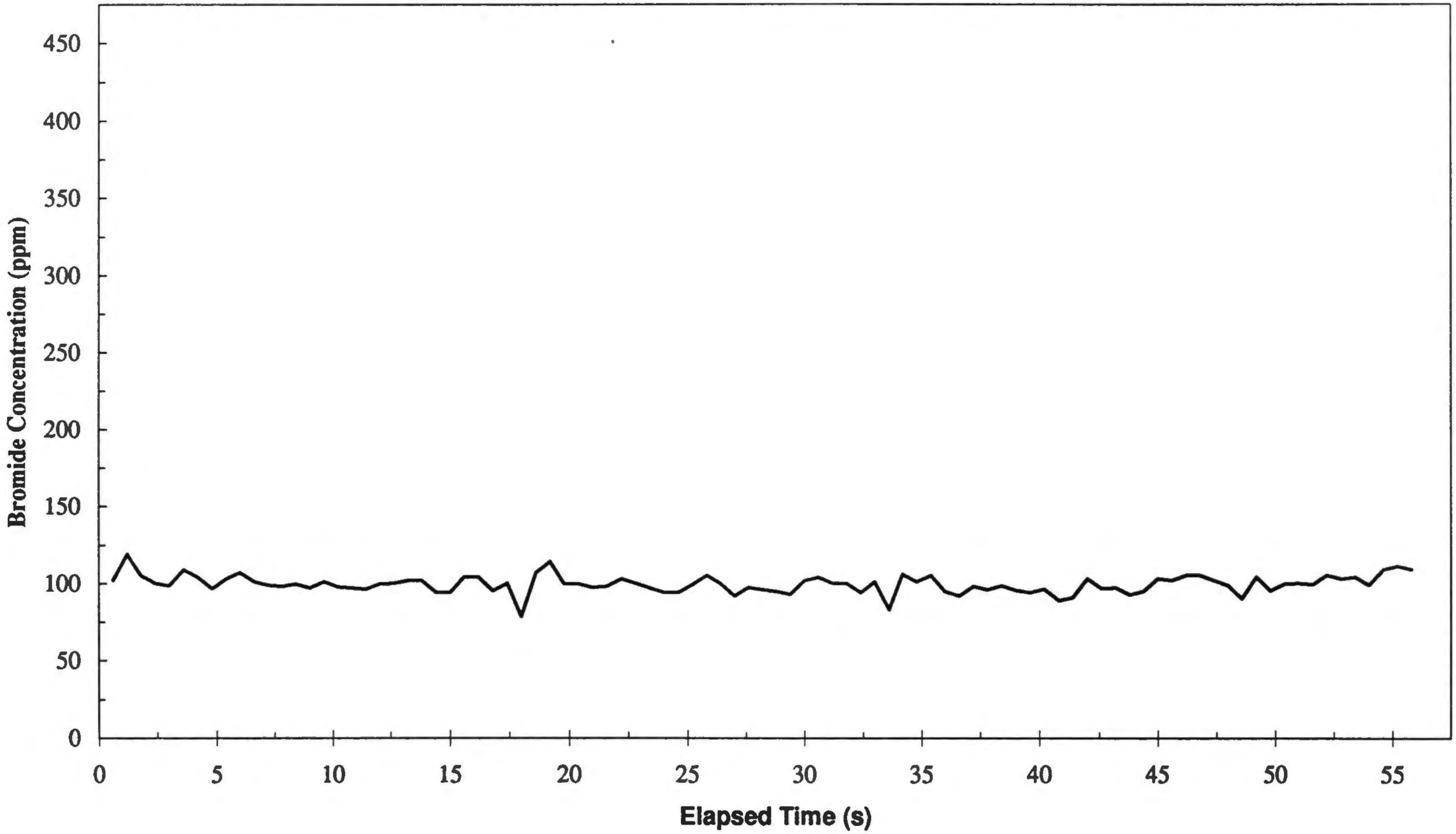
C-1 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 at low flow with symmetrical hose configuration.



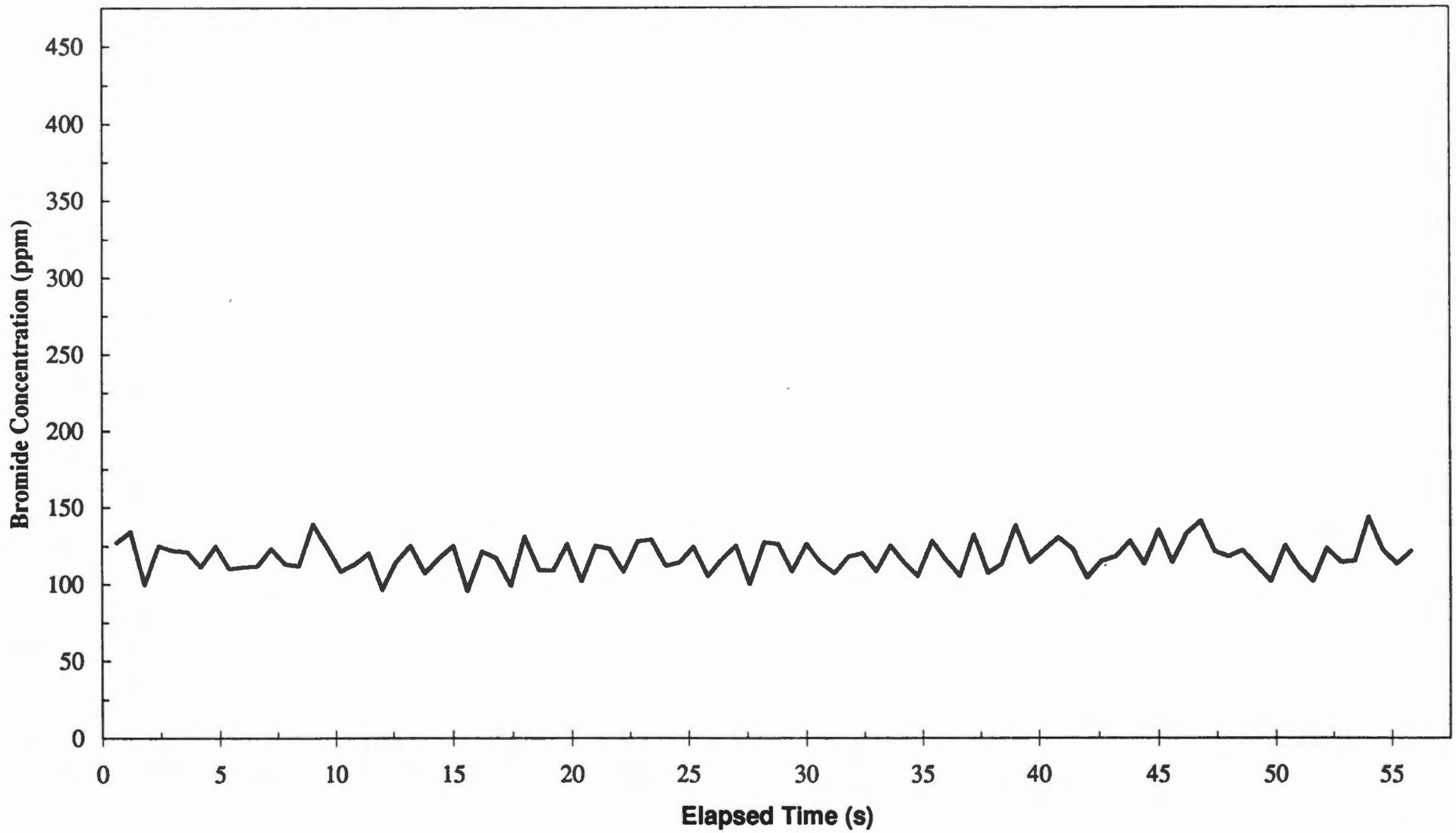
C-2 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 2 at low flow with symmetrical hose configuration.



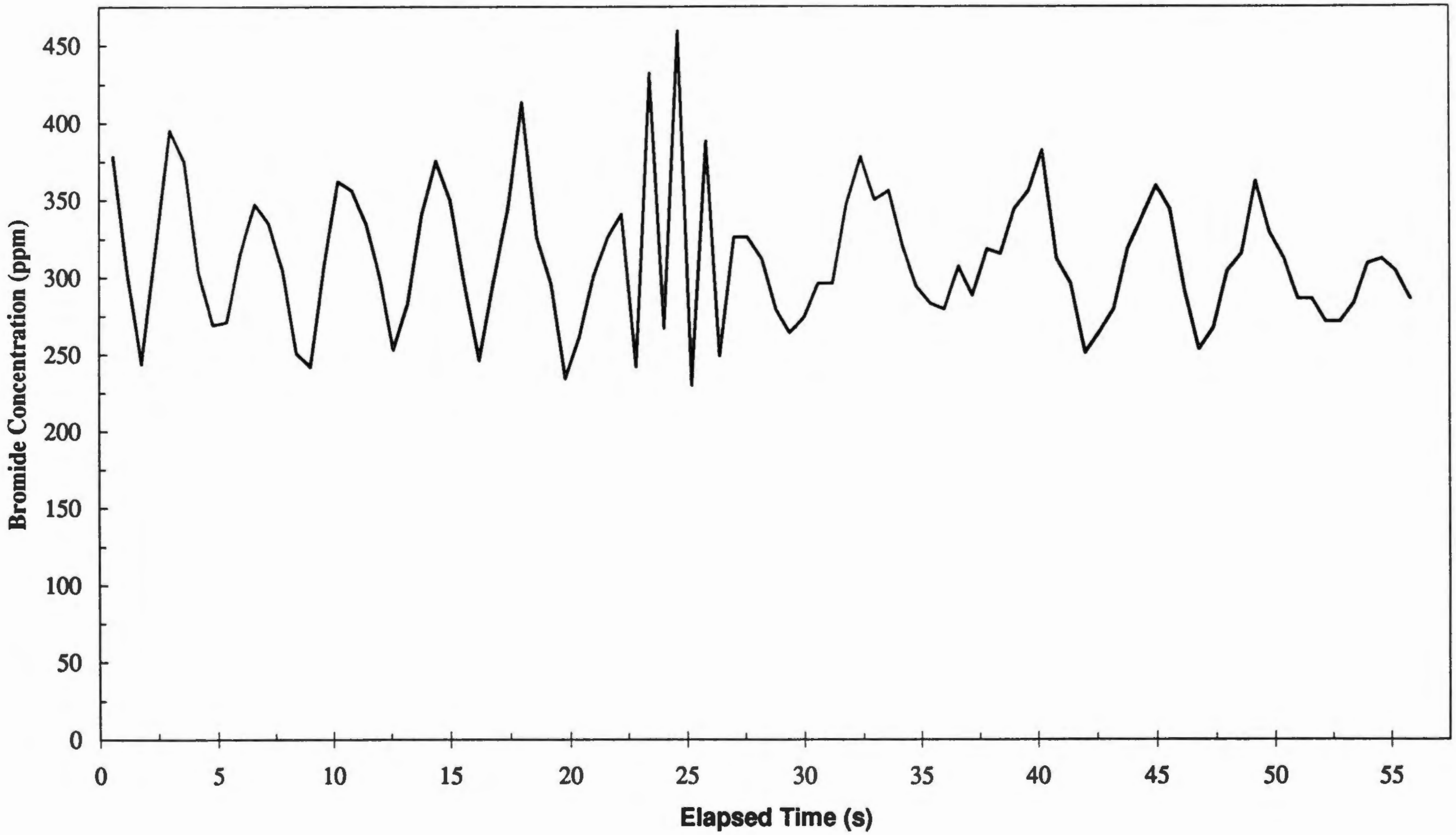
C-3 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and 2 at low flow with symmetrical hose configuration.



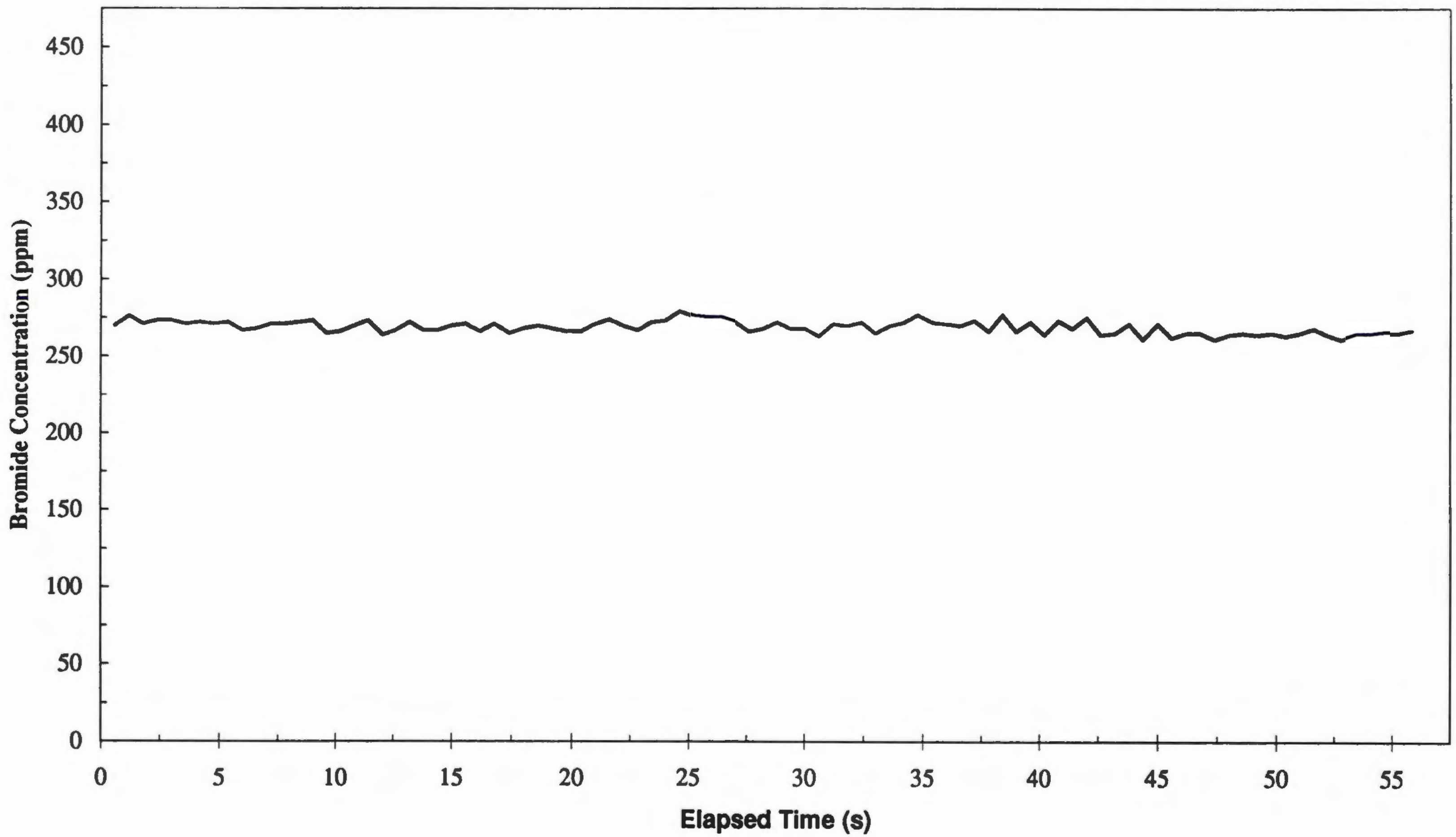
C-4 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and bypass at low flow with symmetrical hose configuration.



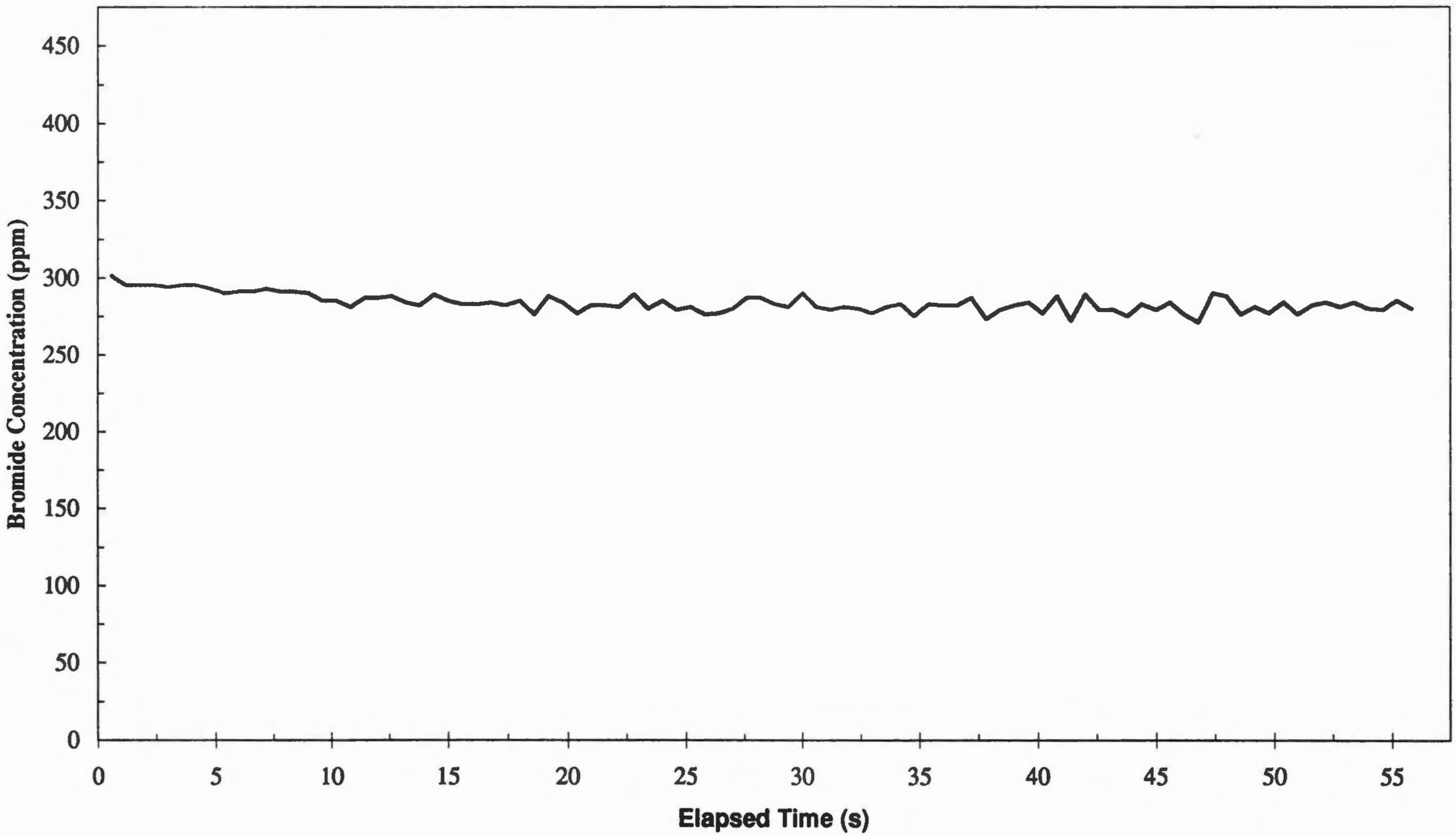
C-5 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 2 and bypass at low flow with symmetrical hose configuration.



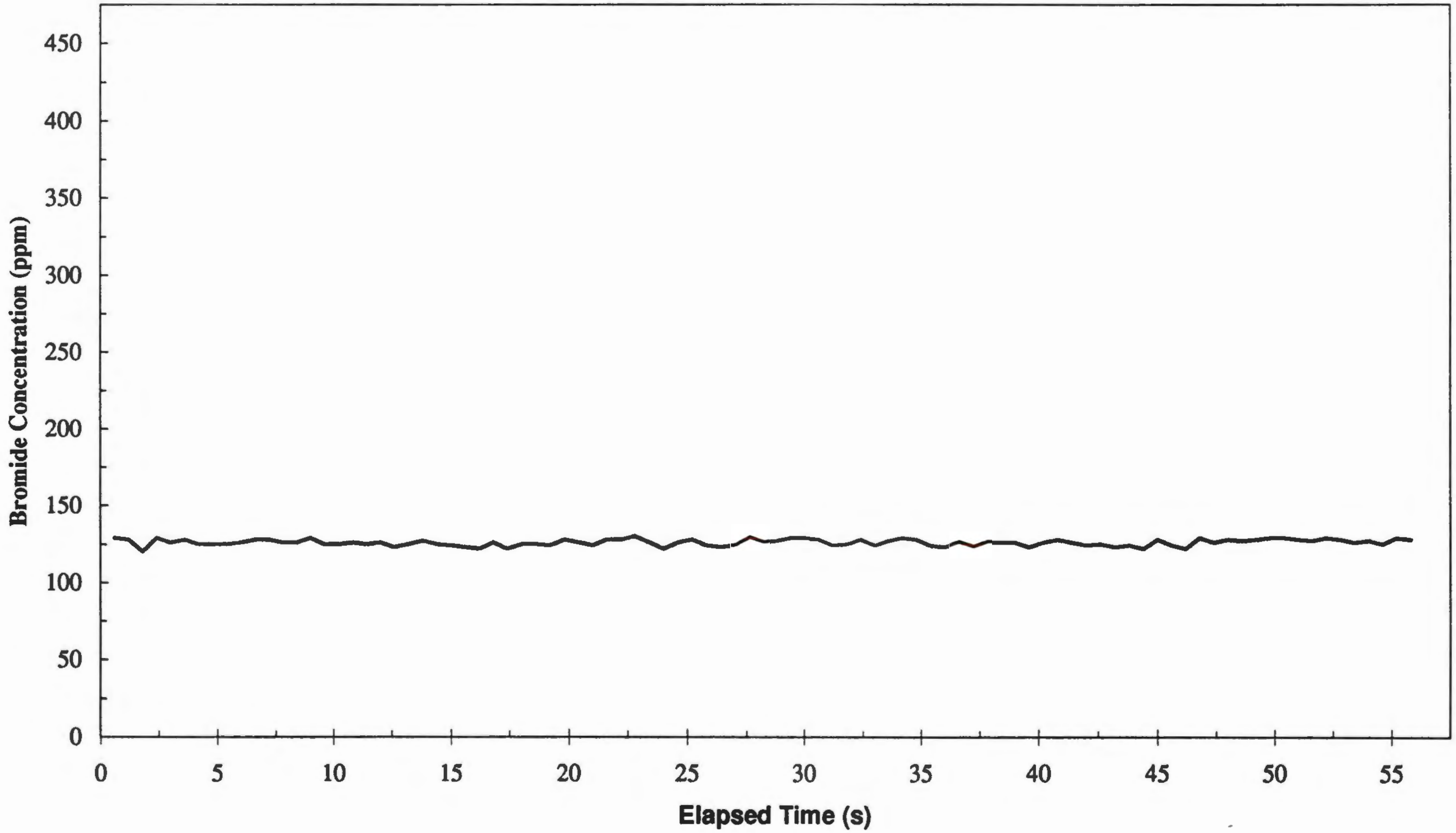
C-6 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1, 2, and bypass at low flow with symmetrical hose configuration.



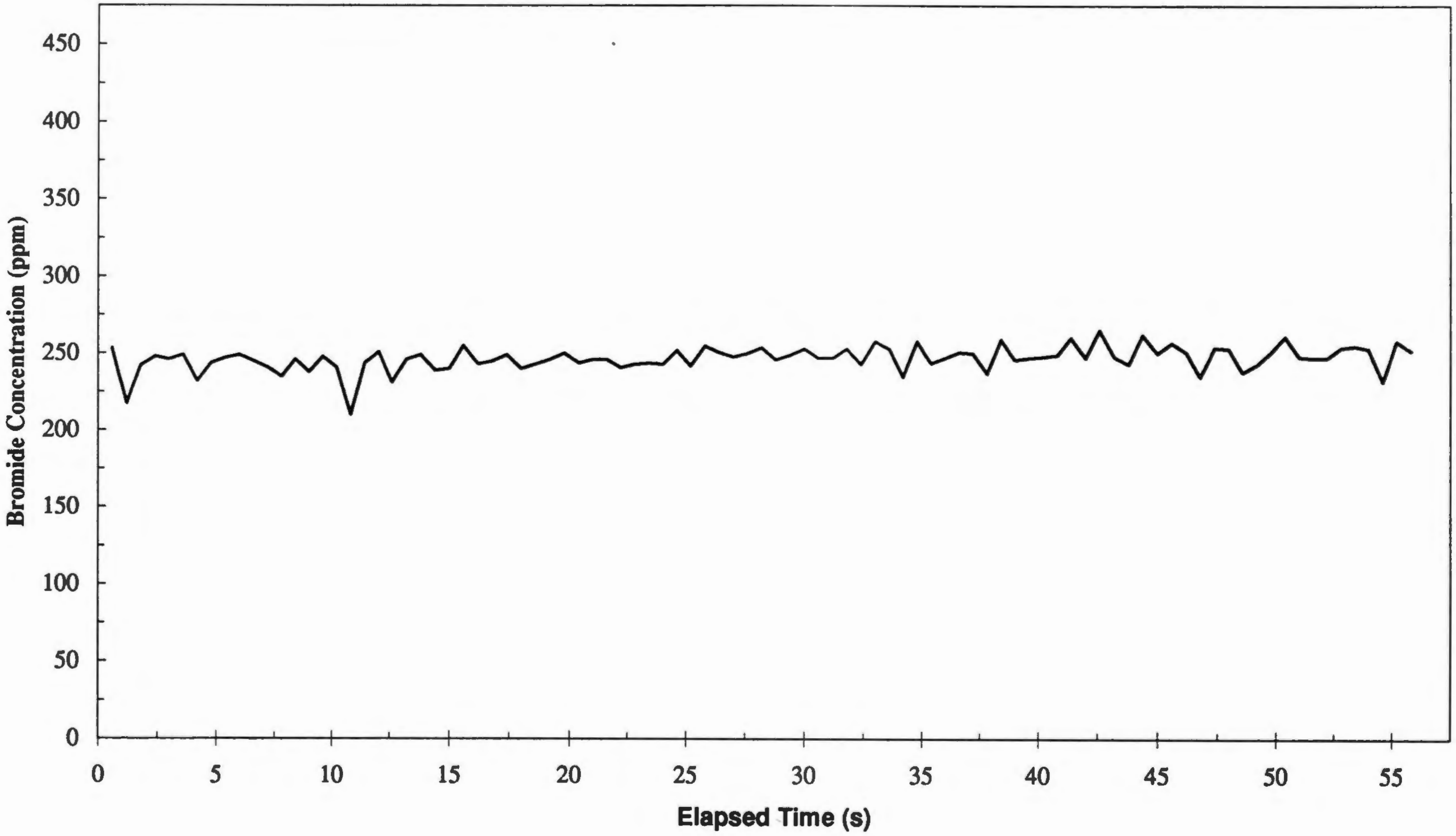
C-7 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 at high flow with symmetrical hose configuration.



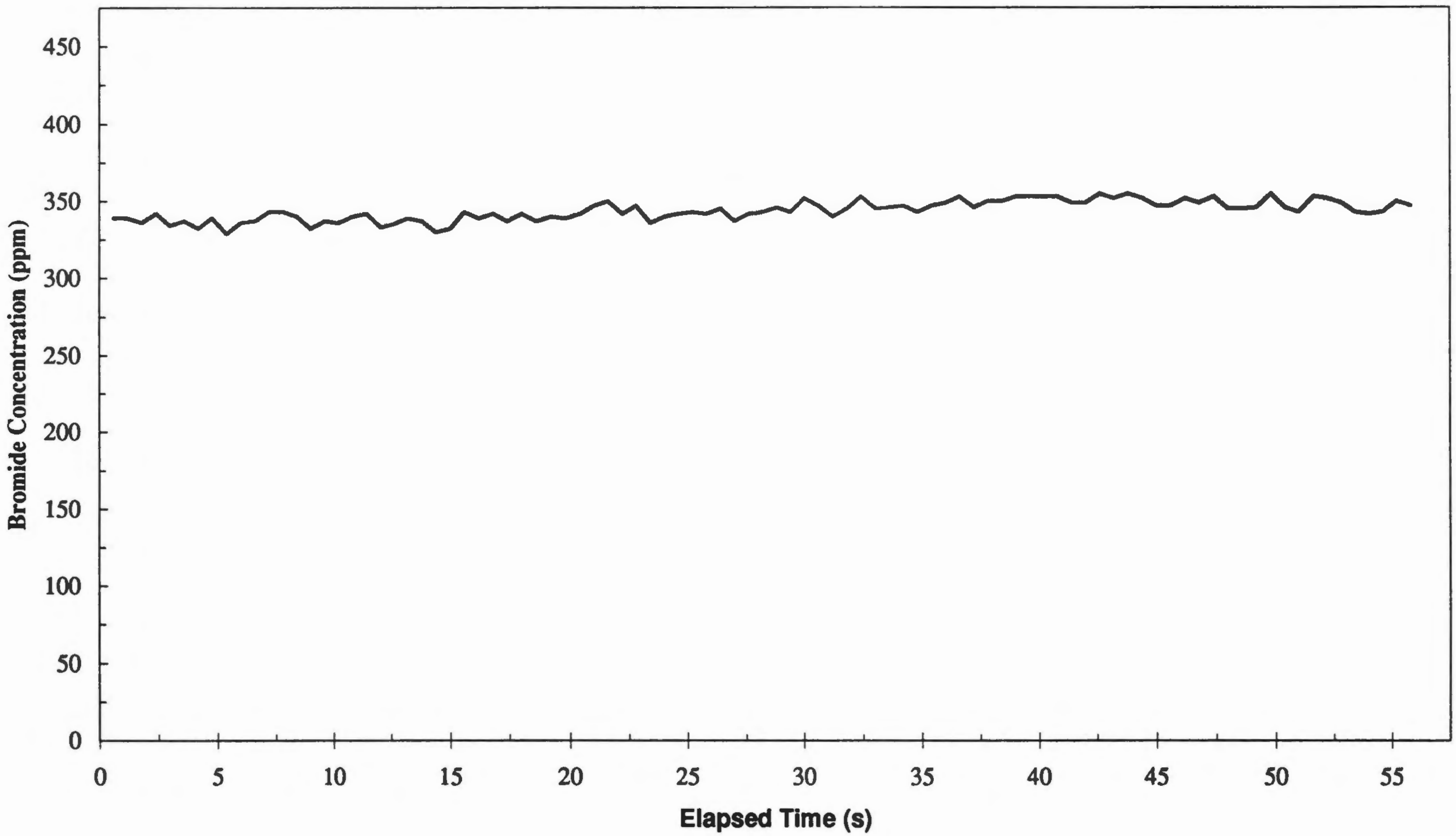
C-8 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and 2 at high flow with symmetrical hose configuration.



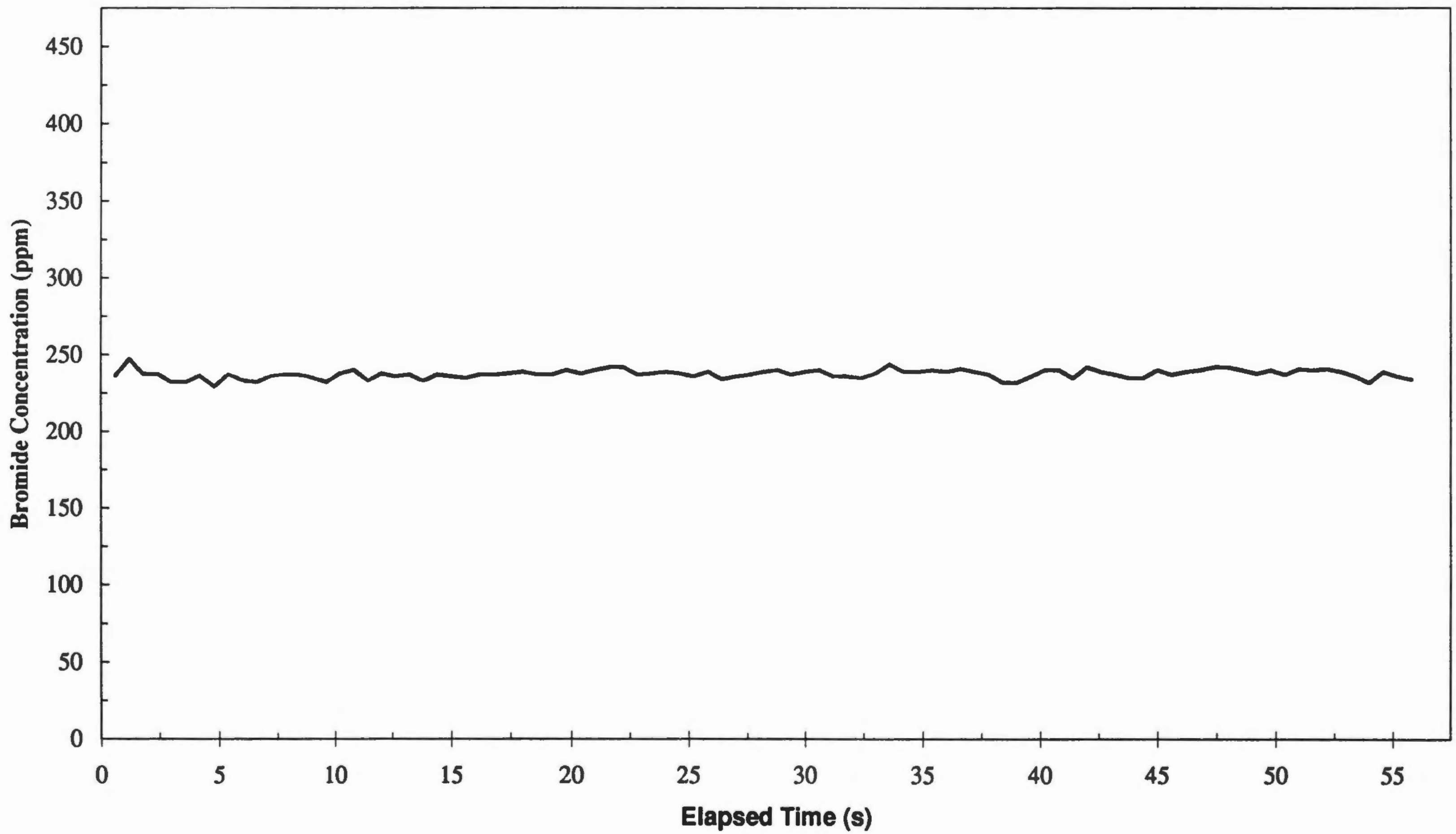
C-9 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and bypass at high flow with symmetrical hose configuration.



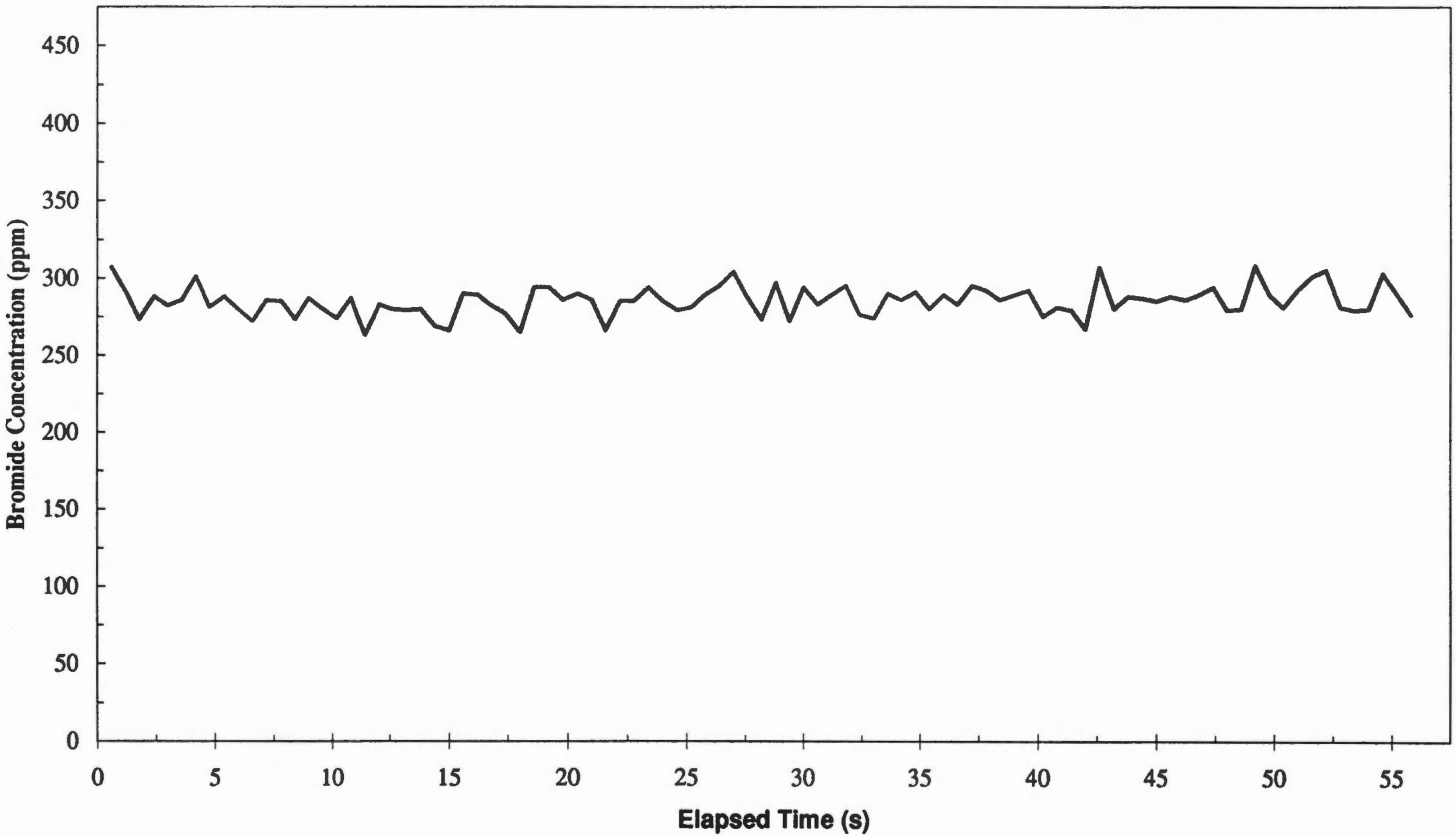
C-10 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1, 2, and bypass at high flow with symmetrical hose configuration.



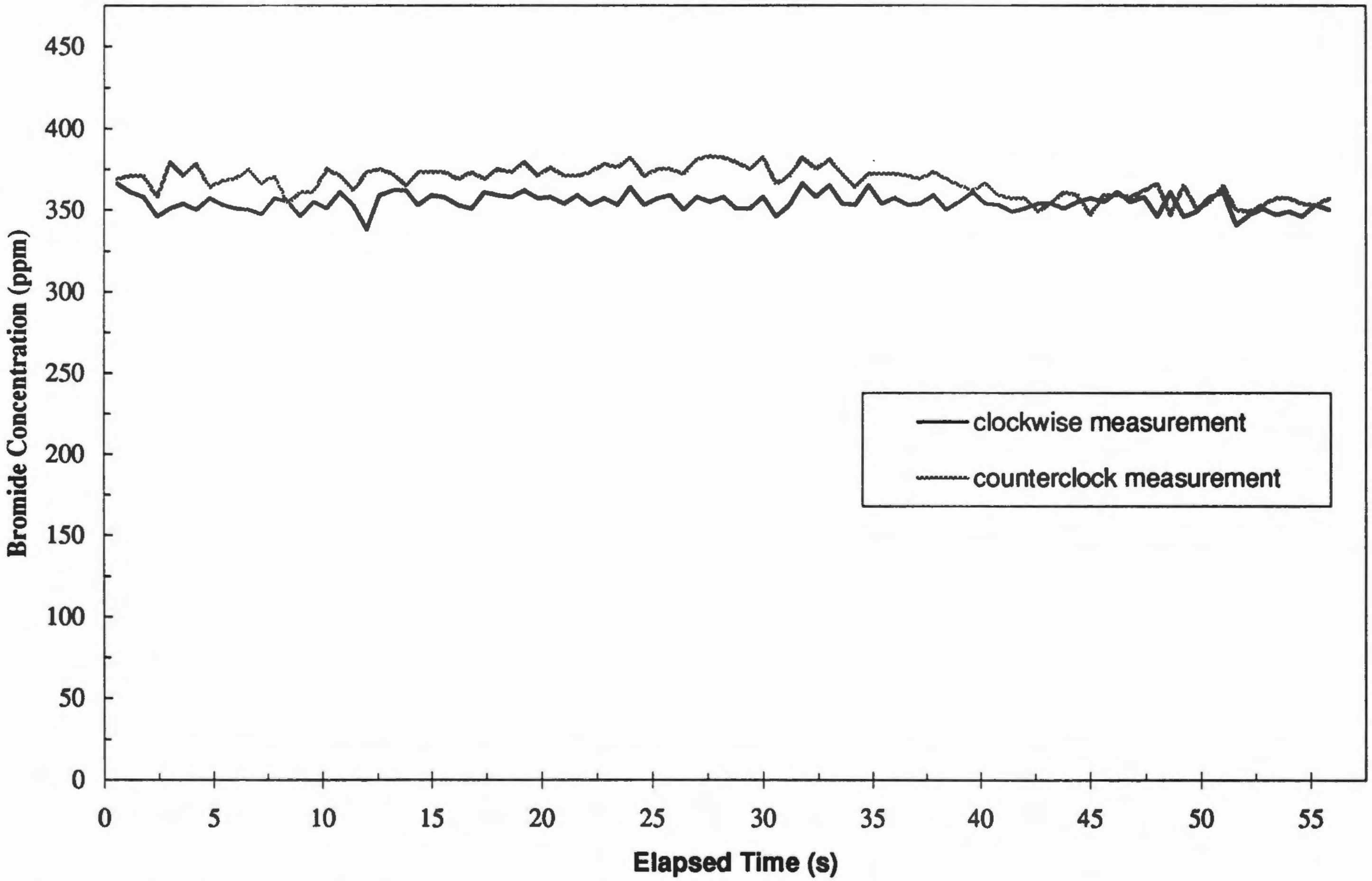
C-11 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and 2 at high flow with symmetrical hose configuration.



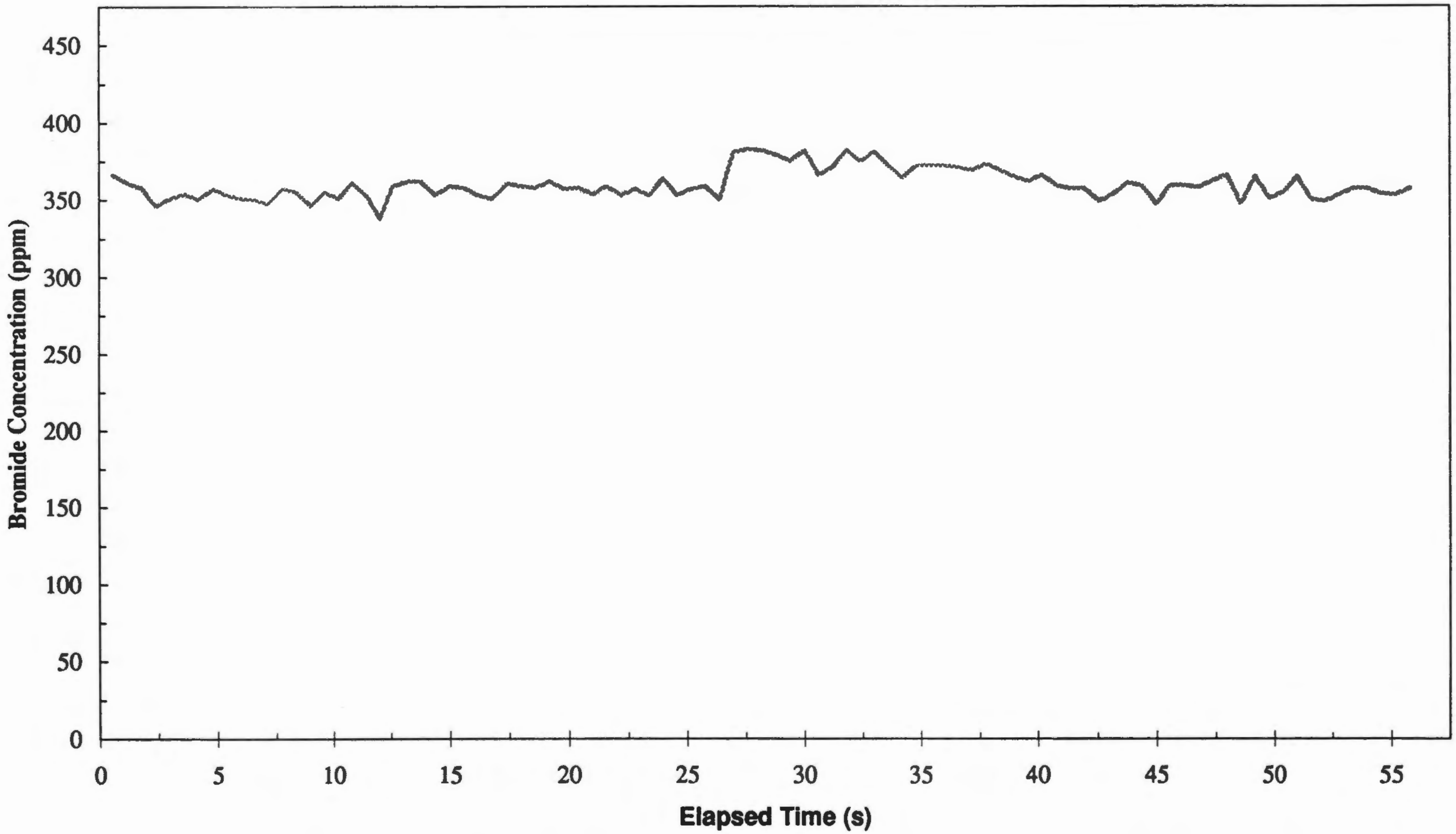
C-12 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 at high flow with additional hose length configuration.



C-13 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 at high flow with additional hose length configuration.



C-14 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and 2 at high flow with asymmetrical hose configuration. KBr samples were measured twice and matched to test for sensor drift.



C-15 KBr trace for nozzle discharge samples from water-driven injection system operation using unit 1 and 2 at high flow with asymmetrical hose configuration.

VITA

Ray Allen Maynard II was born March 15, 1971 in Kansas City, Missouri. He resided in East Tennessee, South Dakota, and Middle Tennessee before he graduated from White County High School in Sparta, Tennessee in May of 1989.

The author entered The University of Tennessee, Knoxville in August 1989 and received the Bachelor of Science Degree with a major in Agricultural Engineering in December 1993. He entered The Graduate School at The University of Tennessee, Knoxville in January 1994. He received the Master of Science degree with a major in Agricultural Engineering in May 1997. The author plans to immediately enter Southern Theological Seminary to pursue the Master of Divinity degree.