PRESSURE TRANSIENTS IN AN AERIAL APPLICATION SYSTEM

By

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PRESSURE TRANSIENTS IN AN

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SYSTEM

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CHAPTER I

INTRODUCTION

The use of aerially applied chemicals has had a substantial impact upon the agricultural industry. Since the early 1920's, airplanes have been applying chemicals to crops in the United States. The agricultural aviation business has grown significantly in the United States and abroad. In 1983, the projected number of agricultural aircraft used worldwide was 32,000; treating 375 million hectares (Hazelrigg, 1978). With the recent advances in monitoring technology, an in depth investigation of the performance of the aerial application equipment can be done, which before, could not. Improved performance of the application equipment could result from this investigation, which would benefit the agricultural aviation sector.

Four categories of chemicals are distributed by aerial application equipment: herbicides, fungicides, defoliants, and insecticides. The physical form of the chemicals may be granular, powder, or liquid. Since most of applied chemicals consist of granular or liquid formulations, the two types of application systems most commonly found on agricultural aircraft are granular and liquid. A liquid application system was used in this study.

The intended purpose of aerial application equipment is to distribute agricultural chemicals evenly at a particular application rate (l/ha) within a target area. If the distribution of the chemical is not fulfilled within certain limits, modification of the equipment may be needed to improve the distribution. An agricultural airplane nominal application speed is 160 km/hr, which corresponds to a ground velocity of 45 m/s. At these speeds, very little deviation in chemical flow rate can be tolerated. If the flow rate is too high, or the plane is flying too slow, a larger volume of chemical is applied than needed. Consequently, both speed and flow rate affect application rate.

A basic liquid aerial application system consists of the following parts and their associated function: a tank to hold the liquid being applied, a centrifugal pump to move the fluid within the system, a control valve to start and stop the spray, booms mounted along the wings of the aircraft to direct the fluid to the nozzles, and nozzles, mounted along the length of booms to produce and distribute the fluid droplets. The pump continually works in the system while the aircraft is in the air. The control valve is under the tank and is manually operated by the pilot. The valve directs the fluid back to the tank, to the booms, or to both the booms and the tank. Since the pump is centrifugal, the application rate can be controlled by boom pressure. The boom pressure is proportional to the opening in the control valve. Whatever fluid is not directed to the booms, returns to the tank to agitate the chemical. Whenever the control valve is turned-off, all of the fluid returns to the tank.

The nozzles are mounted on the booms by a nozzle body. In the nozzled body, a check-valve is incorporated between the booms and the nozzle to isolate the fluid from the nozzle when the booms are not activated. These check-valves keep the nozzles from leaking when the booms are not pressurized.

As the airplane enters and leaves the field, the spraying system must be turned-on or off respectively. If the pilot misjudges his operation of the control valve, he will apply chemicals outside of the field. It takes time for the spraying system to build up or lower pressure in the booms and nozzles following control valve operation. These changes in fluid flow are pressure-transients.

Finding the significance of these pressure-transients would supply the aerial application industry with basic data for use in equipment design, development of new products for aerial applicators, and information as to how this currently used equipment works in the field during these changes in fluid flow.

In some application systems, the nozzle bodies are not mounted at the extreme end of the spray booms. This leaves a small amount of air in the booms during operation. Because air is a compressible fluid and the applied fluid is incompressible, its presence might affect the performance of the system. Determining the significance of the air pocket in the system would supply the aerial application industry with data to understand how the systems works under these conditions.

Objectives

The objectives of this study were:

1. To measure and analyze the time required for the diaphragm check-valves of a liquid aerial application system to open or close and for the nozzle flows to achieve a steady-state condition following turn-on and turn-off of the control valve, with respect to nozzle location on the boom, diaphragm material type, and operating boom pressure.

2. To measure and analyze the time required for diaphragm check-valve operation and for the nozzle flow to achieve steady-state condition during turn-on or

turn-off of the control valve with respect to air volume size at the end of the boom and the operating boom pressure.

CHAPTER II

LITERATURE REVIEW

Water Hammer

The study of hydraulic transient flows in pipes and valves has been done in the past, but none specifically on aerial application equipment. The energy of the fluid at any point along the pipe system will be composed of both kinetic and potential energy. Often, in transient fluid flow, the velocity of the fluid changes suddenly. Due to energy conservation laws, the energy of the system must remain constant. During the time when the fluid velocity changes from one steady-state to another, a phenomenon takes place called water hammer. Water hammer is the mechanism responsible for the changes in steady-state velocities in hydraulic pressure systems.

A description of water hammer is given by Simon (1976, p.69) as follows:

> Any change of discharge in a pipe (valve closer, pipe failure, pump stoppage) results in a change of momentum of flow. By virtue of the impulse-momentum equation, this will cause an impulse force to be created, which is commonly called water hammer.

The water hammer pressure increases proportionally with the rate of closure of the valve (Simon, 1976). These water hammer waves create pressures which are often very large and travel at the speed of sound in water, about 1420 m/s. Water hammer pressures travel throughout the system, bouncing back and forth until they are dampened out by friction (King, 1954).

Monitoring

The monitoring of the steady-state pressure of a spraying system has long been a common practice. Givelet (1981) gives an overview of several monitoring systems on the market in the United States and Europe. These monitoring systems do not record the pressure-transients of the spraying system, but are designed to monitor the system during the application of the spray. These monitoring systems assist the applicators in applying the correct amount of chemical to the crop. Orchard (1979) developed and mounted a monitoring system on an agricultural aircraft that measured boom pressure, flow rate, total flow, elapsed spraying time, and total spray passes. Orchard's monitoring system was limited to steady-state measurement.

Check-Valve

There have been several studies on the action of check-valves during hydraulic transient flow states. Kikai (1976) used computer simulation to predict check-valve movement on valves used on power sprayers used in agriculture. From this information, a valve was designed having the maximum volumetric efficiency. The results obtained from his study of valve movement on the computer simulation correlated well with the experimental results. Provoost (1980) investigated the dynamic behavior of non-return valves somewhat similar to the check-valves mounted on an aerial application system but were very much larger, such as those on large water supply systems. At the time flow reversal occurs, variations in pressure occur. At the instant the closing occurs, the downstream side has a pressure rise, and the upstream side has a pressure drop. Repetitive slamming of the valve will occur if the vapor pressure of the fluid is reached at the initial upstream side of the valve.

Spray Nozzle

Miller and Watt (1980) used high speed photography and an oscilloscope to measure the response time of a solenoid spray valve. The response time of the valve was defined as the time needed for the spray to appear at the nozzle orifice after the start of the control pulse on the solenoid valve. This technique also allowed the analysis of the formation and collapse of a fan spray nozzle. The film recorded pictures of both the oscilloscope screen and the spray nozzle allowing evaluation of the response time of the system. The average time required for spray to be established at a distance of 3 cm from the nozzle was 44.7 ms. The average time required for spray fan collapse was 39.6 ms. The response time of the valve was 20.8 ms.

CHAPTER III

EXPERIMENTAL EQUIPMENT

Pumping Unit

The laboratory aerial spray system used in the experiments is shown in Figure 1. The tank and power supply consisted of a 700 liter Stearman hopper, and a Lincoln, 1745 RPM, three phase, 5.6 kw, electric motor. The power drive used a 1:3 ratio gear box, and a 2:3 ratio pulley drive. The six impeller centrifugal 20783 Transland pump was rated at 379 l/min and operated at 3480 RPM and produced 400 kPa gage pressure.

The control valve of a aerial application system controls the flow of fluid to the booms and thus the boom pressure by the degree of opening (Figure 2). The control valve used in these experiments was an Agrinautics Model 77505. The control valve directs part of the fluid from the pump to the booms; the other portion of the fluid goes back into the tank for agitation. When the valve is closed, all of the pumped fluid is returned to the tank. This action, combined with a venturi incorporated into the top of the control valve, creates a negative pressure in the venturi region of the control valve. This negative

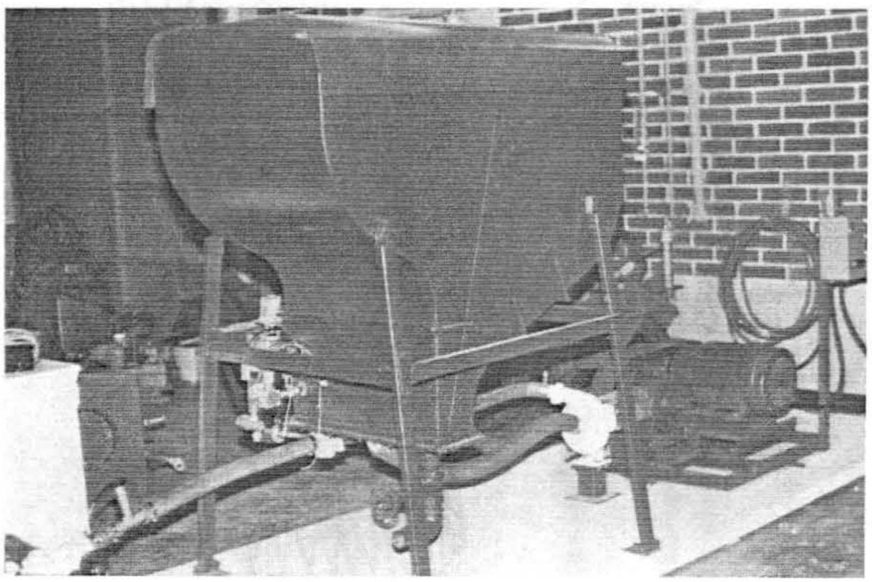

Figure 1. Tank, Power Supply and Pump.

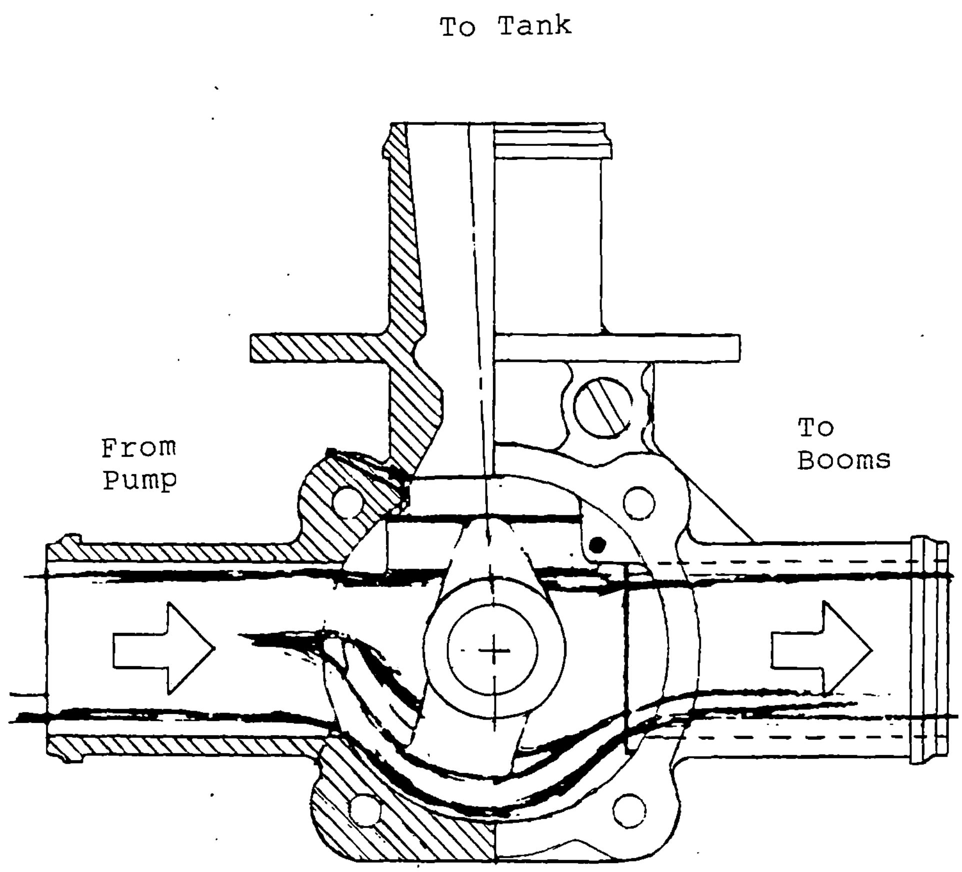

Figure 2. Control Valve Sectional Showing Flow Directed to Booms. (Figure Courtesy Transland, Inc.)

pressure results in rapid closure of the nozzle diaphragm check-valves and helps prevent fluid leakage after the control valve is closed (Figure 3).

The booms were connected to the control valve by a rubber hose and a 20849 Transland y-strainer (Figure 4). The booms were made from 3.2 cm inside diameter aluminum pipe. Each boom was 3.8 meters long and was placed in a 9° dihedral. (A dihedral is the angle between the wing and a horizontal transverse line and 9° being common for agricultural aircraft) (Figure 4). There were fifteen nozzles mounted on each boom at 22.9 cm intervals. A nozzle was not installed at the extreme ends of the booms which forced air pocket to form similar to those normally found on spray aircraft during Test One.

During Test Two, a 0.63 cm x 76.2 cm copper tube was connected as shown in Figure 5. The fourth nozzle from the end was removed and placed at the end of the copper tubing. This nozzle was then mounted back at its former position on the boom with its outlet on the boom blocked off. This installation thus allowed the air pocket to bleed off through the fourth nozzle. The plastic hose mounted on the nozzle bodies helped collect the water flow from the nozzles during the experiments.

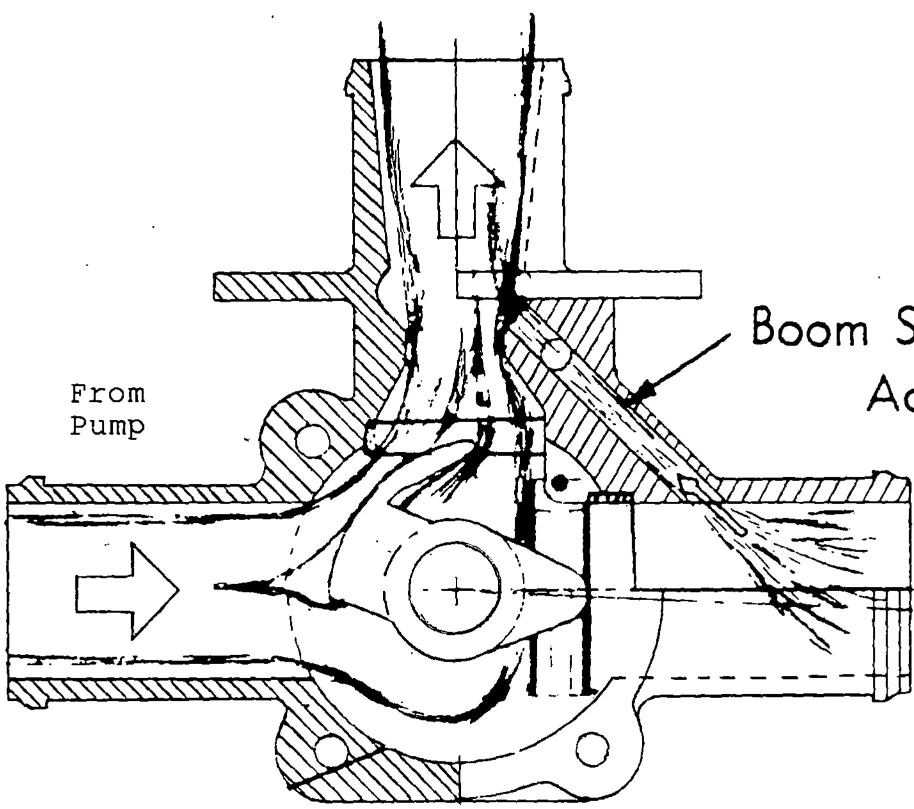

Figure 3. Control Valve Sectional Showing Flow Directed to Tank. (Figure Courtesy Transland, Inc.)

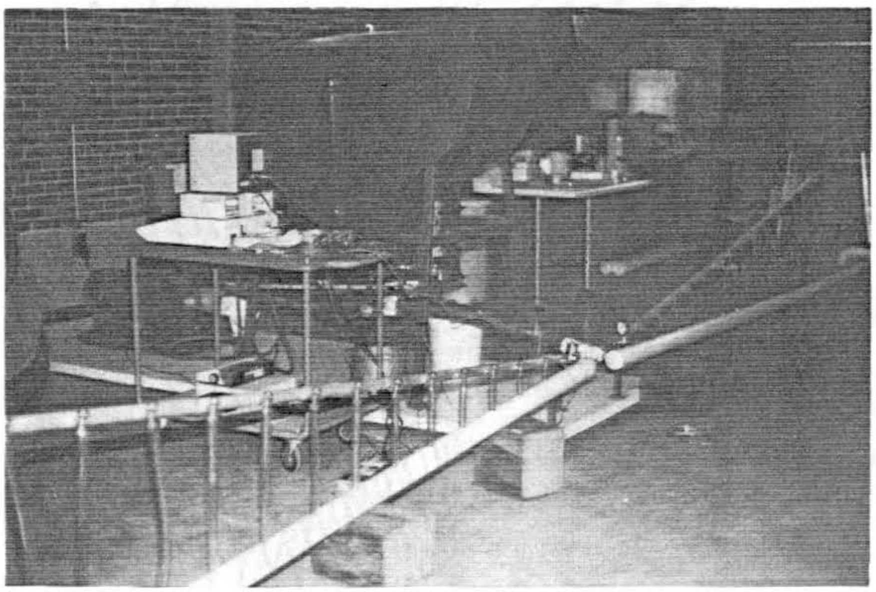

Figure 4. Experimental Equipment System
Showing 9 Degree Dihedral.

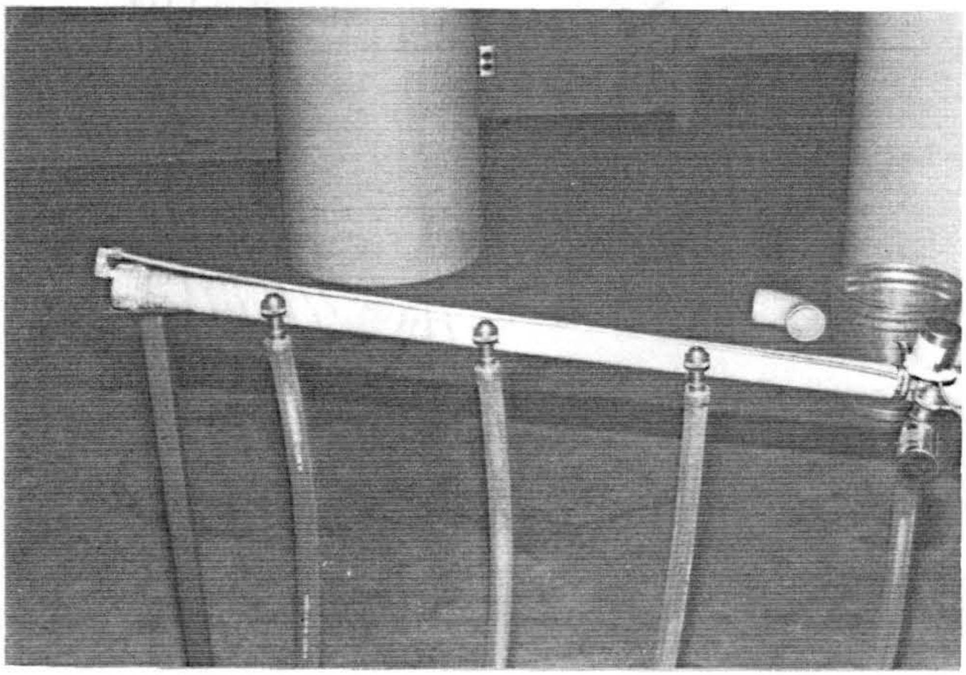

Figure 5. Boom End Air Bleed System.

Nozzle Bodies

The nozzle equipment consisted of two types of brass nozzle bodies. These were Spraying Systems 4664A and the Delevan 34560. Each nozzle body was tested separately, depending upon the experimental design. The Spraying Systems nozzle bodies were outfitted with either Spraying Systems No. 4620 Viton or Fairprene diaphragms. These diaphragms were also combined with or without Spraying Systems No. 6227 Teflon diaphragms, depending upon the test. These diaphragms were kept in place by a Spraying Systems No. 9758 brass end sub assemblies and Spraying Systems No. 4624 brass retainers. The Delevan nozzle bodies were outfitted with Delevan 36042 Viton-A or 34903 Buna-N diaphragms. These diaphragms were kept in place by Delevan 34562 cap assemblies and Delevan 34572 retainers. Nozzle bodies were completed by using Spraying Systems D4 hardened stainless steel orifice disks, brass No. 45 brass disk cores, and 4514-20 brass slotted strainers. These parts fit together as shown in Figure 6.

Diaphragm check-valves are used in aerial application instead of ball type check-valve, because a ball type would be affected by the banking of the airplane due to the inertia of the ball. Several types of diaphragm materials are used in the industry because of the different corrosion resistances needed. Spraying Systems Fairprene diaphragms are made of a special

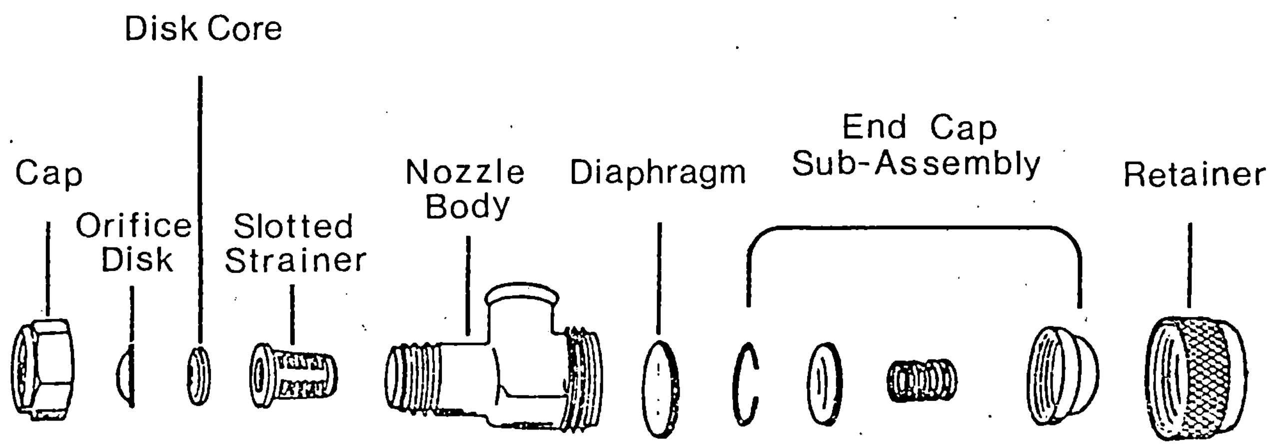

Figure 6. Nozzle Body Assembly. (Figure Courtesy Spraying Systems Co.)

corrosion resistant synthetic rubber compound, polychloroprene, coated on a cotton fabric. Spraying Systems Viton diaphragms are constructed of a synthetic rubber fluorocarbon elastomers coated on fabric cords. Delevan Viton diaphragms are constructed from the same material as the Spraying Systems Viton, but are stiffer. The Delvan Buna-N diaphragm material is constructed from a fabric coated with a nitrile elastomer. The Spraying Systems Teflon insert is used in conjunction with the Spraying Systems Viton and Fairprene diaphragms when more corrosive chemicals are used. This prevents a breaking down of the diaphragms. The Teflon insert fits in the nozzle body according to Figure 7. All five of these diaphragm are relatively soft, make good seals, and will not stick to the metal seat. By choosing the correct diaphragm material, the corrosion problem can be minimized.

The diaphragm check-valves work along with the control valve in assuring the nozzles are not pressurized during turns and ferry. Once the boom pressure drops below the pressure required to open the diaphragm check-valve, it closes, isolating the nozzle from the fluid. The boom pressure continues to drop due to the venturi action of the control valve, and this lower pressure causes the diaphragm to seal even tighter. The

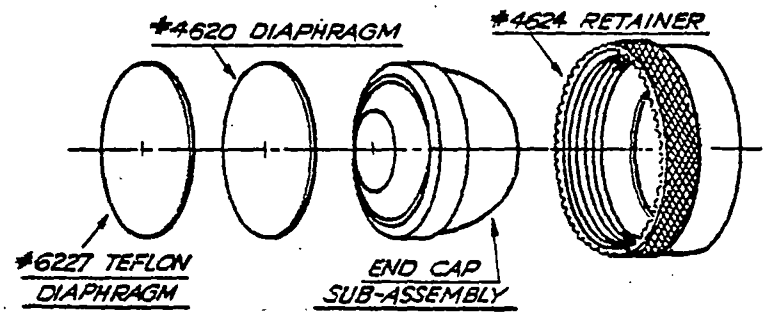

Figure 7. Teflon Insert Assembly. (Figure Courtesy Spraying Systems Co.)

action of the venturi and check-valves reasonably ensures the operator that the nozzles or the booms are not leaking when the control valve is closed.

The orifice disk and disk core work together to break up the fluid into spray droplets. The nozzle tips used were of the same type as those commonly used by aerial application. The core swirls the fluid and without it, the disc would deliver a straight stream spray. This combination delivers a hollow cone spray pattern of relatively consistent particle size that penetrates and covers a leaf canopy evenly. At higher pressures, finer spray particles are produced.

Instrumentation

Various electronic components were used in the experiments. The control valve movement was measured by mounting a 1 kilo-ohm Spectrol Precision potentiometer on the control valve as shown by Figure 8. The potentiometer was connected as a voltage divider with five (5) volts applied across it. The third terminal produced a fraction of the five (5) volts applied proportional to the valve position.

Two micro-switches were used to initialize the test samplings. These micro-switches were mounted at the end of the control valve strokes as shown in Figure 8. When the control valve was opened or closed, one of the switches closed and started the test sampling. At the

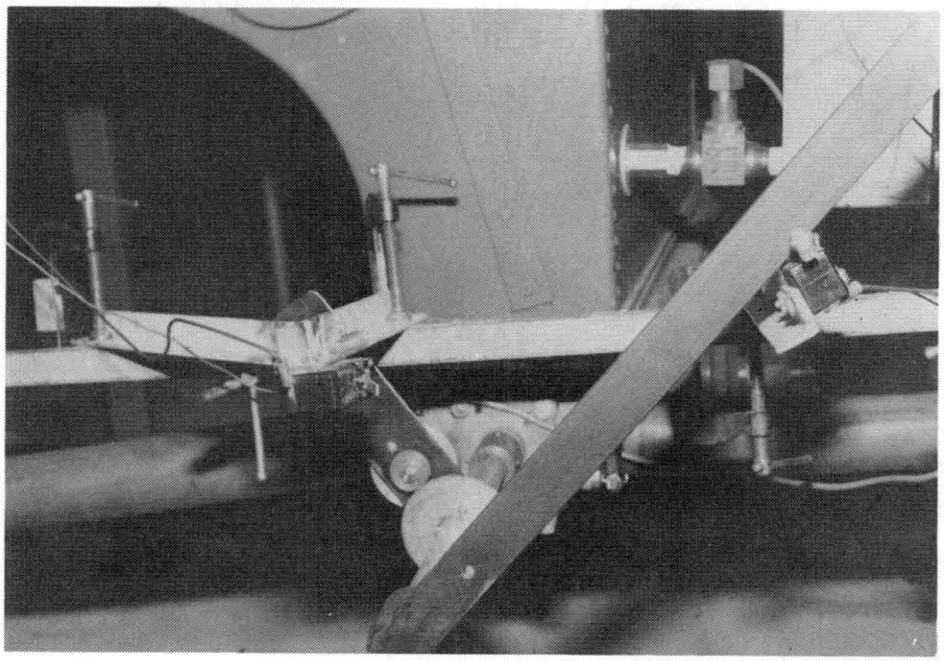

Figure 8. Potentiometer and Micro-Switches Mounted on Control Valve.

open side of the valve, the left side, the micro-switch mounting could be moved back and forth to vary the control valve, which in turn changed the boom pressure. This feature allowed different operating boom pressures to be used during the test.

Sentra Systems 205A pressure transducers were mounted on the nozzled bodies as shown by Figures 9 and 10. Both the boom pressure at the nozzle body mounting and the nozzle pressure within the nozzle body, were measured. The nozzle body pressure was measured between the diaphragm check-valve and the orifice disk. Only one modified nozzle body was used in each experiment. Pressure measurements at these locations monitored the operation of the diaphragm check-valve and indicated when the nozzle had reached steady-state flow. The ports of the pressure transducers were made flush with the walls of the nozzle body so that boundary layer disturbances were minimized. The response time of the Sentra Systems pressure transducers was less than 1 millisecond. This relatively short response time met the requirements necessary for measurement of the dynamic spray pressures. The transducers output a 0 to 5 volt linear response, corresponding to a 0 to 689 kPa absolute reading.

The control valve potentiometer and pressure transducer output signals were connected to an analog to digital (A/D) board which fit inside an Apple II+ computer. Both the potentiometer and the pressure

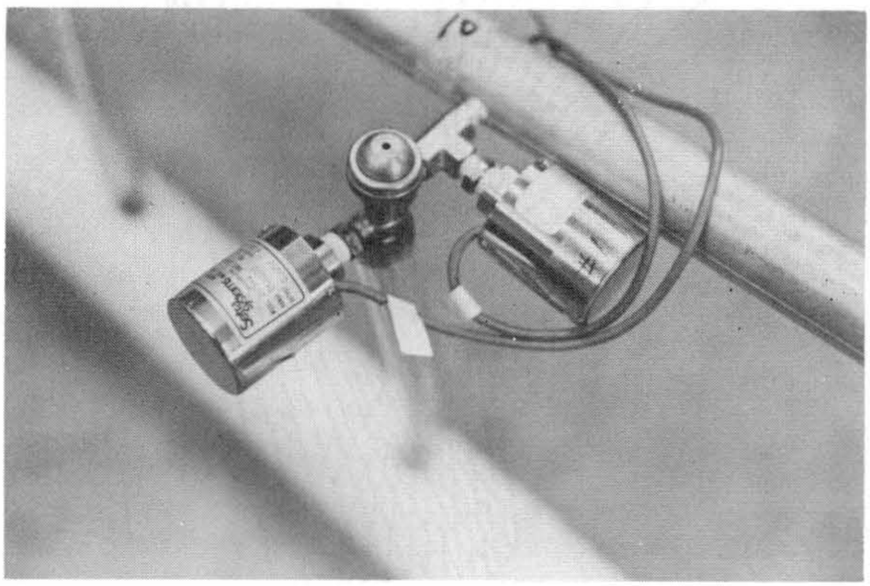

Figure 9. Pressure Transducer Mountings.

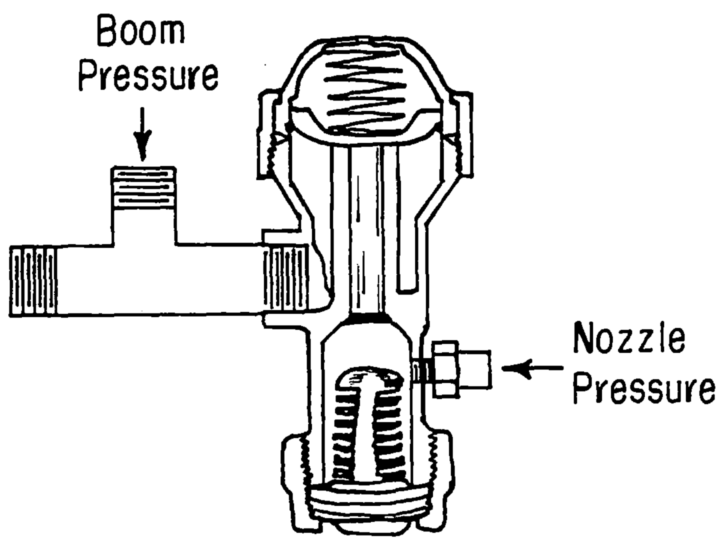

Figure 10. Pressure Transducer Schematic of Mountings.

transducers power supply came from the Apple II+. The output voltage of the pressure transducers corresponded linearly to the pressure reading. These voltage readings were referenced to the ground reference in the Apple II+ through a differential operational amplifier. This amplifier subtracted the difference in voltage of the output leads from the ground of the Apple II+ computer.

An A/D converter changes voltage readings from an analog voltage to a digital output, which can then be stored and/or processed by a computer. The A/D used in these experiments was a AI13 board with a miltiplexer built by Interactive Systems, Inc. for use with an Apple II+. The multiplexer allowed the sampling of sixteen separate channels. Controlling the A/D board and multiplexer was an ADALAB Data Aquisition System. The system provided the operator the flexibility to sample the channels at various voltage gains, sampling rates, and sampling time. The system was controlled by the software supplied by the company along with additional program development to sample the data as required in the experiment. An overall view of the A/D board, multiplexer, ADALAB board, conditioning board, and computer, can be seen in Figure 11.

Figure 11. Apple II+ Computer and Assorted Hardware for Data Aquisition.

CHAPTER IV

EXPERIMENTAL DESIGN AND PROCEDURE

Test One

An experimental design was needed to determine what effects boom pressure, diaphragm check-valve material type, and nozzle boom position had upon the performance of the application system. This experiment was identified as Test One. Dependent variables measured were 1) the time required for the diaphragm check-valves to open, 2) the time required for steady-state flow to be established in the nozzle, relative to the initial control valve opening time, 3) the time required for the diaphragm check-valve to close, and 4) the time required for the flow to stop, relative to the control valve closing time. Independent variables were operating pressure (203, 276, and 345 kPa absolute), check-valve diaphragm materials (Spraying Systems Viton, Viton with Teflon, Fairprene, Fairprene with Teflon, Delevan Viton-N, and Buna-N), and boom nozzle position (1, 2, 3, 4, 5, and 6). The control valve movement was measured to give an initiation time and its opening time or closing time.

In Test One the control valve was moved to initiate the sampling. This part of the test measured check-valve opening time and the steady-state flow time. After the sampling was recorded, the control valve position would be reversed, initiating another sampling. This part of the experiment measured the check-valve closing times and steady-state flow stoppage time. Therefore, two collections of data would be made during the variable settings. An experimental design was needed to achieve these objectives and still take into consideration that only one modified nozzle body was available. Due to time constraints, some randomization of the experiment was sacrificed to speed up the experimental procedures. Also, duplication would be done while the variables remained at one setting in the experiment.

There are fifteen nozzle positions on each boom. Three were chosen on each boom to vary during Test One and are shown in Figure 12.

In the experimental design, the diaphragm check-valve materials were chosen in an ordered procedure, due to the nature of the test, and the operating pressure and boom nozzle position were chosen randomly. The experimental plan was a 3 x 6 x 6 factorial and is shown in Table I.

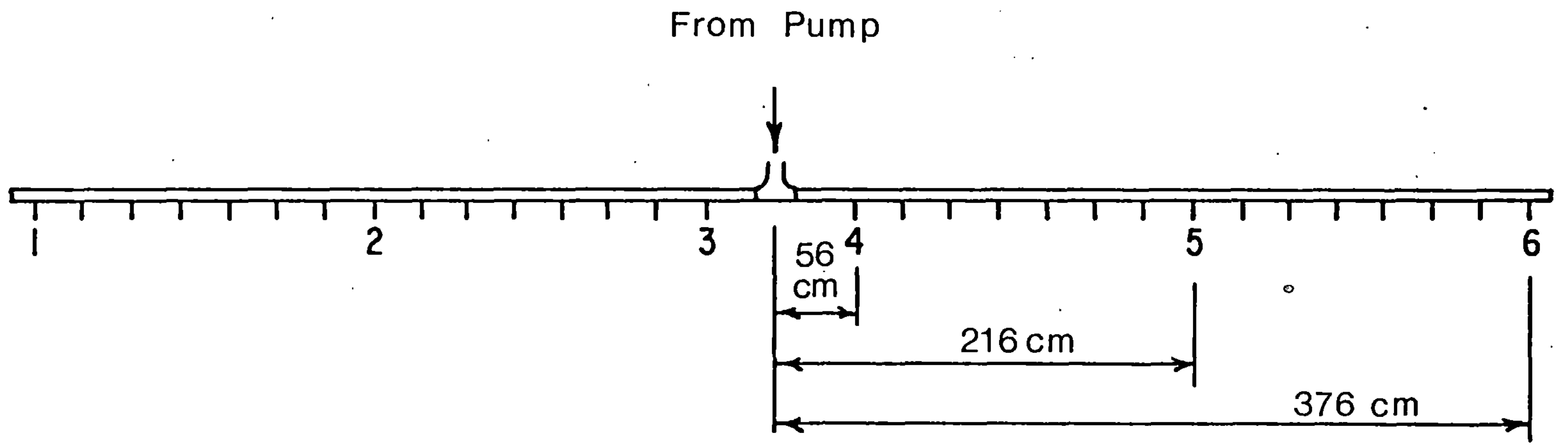

Figure 12. Nozzle Positions on Booms.

TABLE I

EXPERIMENTAL PLAN FOR TEST ONE

Operating Boom kPa absolute	Diapragm Material Type	Boom Position
207	Spraying Systems Viton	6 5 2 4 1 3
	Spraying Systems Viton Teflon	6 4 1 5 3 2
	Spraying Systems Fairprene	6 4 1 5 3 2
	Spraying Systems Fairprene Teflon	6 4 2 5 1 3
	Delevan Viton-A	4 6 2 5 3 1
	Delevan Buna-N	4 3 2 6 1 5
276	Spraying Systems Viton	6 1 3 5 4 2
	Spraying Systems Viton Teflon	6 3 1 5 2 4
	Spraying Systems Fairprene	1 6 2 4 3 5
	Spraying Systems Fairprene Teflon	6 2 3 1 5 4
	Delevan Viton-A	1 5 3 6 2 4
	Delevan Buna-N	1 3 6 4 2 5
345	Spraying Systems Viton	1 2 3 5 6 4
	Spraying Systems Viton Teflon	1 2 4 3 6 5
	Spraying Systems Fairprene	4 2 6 1 5 3
	Spraying Systems Fairprene Teflon	2 4 1 3 5 6
	Delevan Viton-A	6 4 3 5 1 2
	Delevan Buna-N	5 3 2 6 4 1

Experimental Procedure

All experiments used water as the fluid. During the running of the test, the tank was filled with water and kept at approximately the same level throughout the whole series of experiments. This level was held constant because the water height in the tank could add head pressure to the booms during the test. The 9 degree dihedral was maintained on the booms, and an air volume cavity was present and remained constant, above the last nozzle positions in the booms, during Test One. The pump was turned-on and the boom pressure was set by varying the control valve opening position to the proper pressure as outlined in the experimental plan.

The micro-switched stops were put in place and secured. The pump was turned-off and the correct nozzle bodies were placed on the booms. The prescribed diaphragm check-valves materials were placed in the nozzles bodies, as selected according to the experimental plan. The boom position was selected as specified, and the modified nozzle body was placed in that position. The pump was turned-on and the air was bled from the booms. The control valve was closed and a negative boom pressure was allowed to build. Finally, the control valve was turned-on, initializing test sampling.

The ADALAB DATA AQUISITION SYSTEM was programmed to read three channels at 600 Hz for length of 1.25 seconds for the operating pressures of 345 and 276 kPa absolute. For the 207 kPa absolute operating pressure, a sampling length of 3.00 seconds was used because it took longer for the diaphragm check-valves to open at this lower pressure. During the test, the two pressure transducers on the modified nozzle body and the potentiometer connected to the control valve were monitored. Once the sampling was completed, the data was stored. Then, the control valve was reversed, and the sampling began during the turn-off of the system.

This procedure was repeated until all of the boom nozzle positions were tested. Then the diaphragms were changed according to the experimental plan, and the procedure outlined above was repeated. Once all of the diaphragms were tested, the operating boom pressure was changed to the required pressure. The procedure was repeated until all of the operating pressures were sampled.

This test was designed to measure what effects, boom operating pressure, diaphagm check-valve material and boom nozzle position had upon the performance of the application system. The control valve movement was also measured during the test.

Test Two

Test Two was designed to measure the effect that air volume at the end of the booms and operating pressure had upon the performance of the application system. Independent variables for Test Two included air volume size in the boom ends (0, 180, 345, and 540 ml) and operating boom pressure (207, 276, and 345 kPa absolute). Dependent variables were the time required for the check-valve to open or close and the time required for steady-state flow to develop or stop in the nozzle, relative to the control valve initial movement time. The control valve movement was also measured during Test Two. The modified check-valve remained in the same boom position throughout the test at four nozzle positions up from the y-strainer. All of the nozzle bodies were Spraying System 4664A with Fairprene diaphragms. A completely random 3 x 4 factorial experimental plan was used in the experiment as shown in Table II.

Experimental Procedure

The correct boom pressure was chosen and the control valve was adjusted accordingly. The micro-switched stops were put in place and the correct boom position, according to the experimental plan, was chosen. The nozzle positions were configured as shown in Figure 13. When the boom position needed in the experimental plan

TABLE II

EXPERIMENTAL PLAN FOR TEST TWO

Operating Boom Pressure kPa	Air Pocket Size			
207	3	2	1	4
276	2	1	3	4
345	4	3	2	1

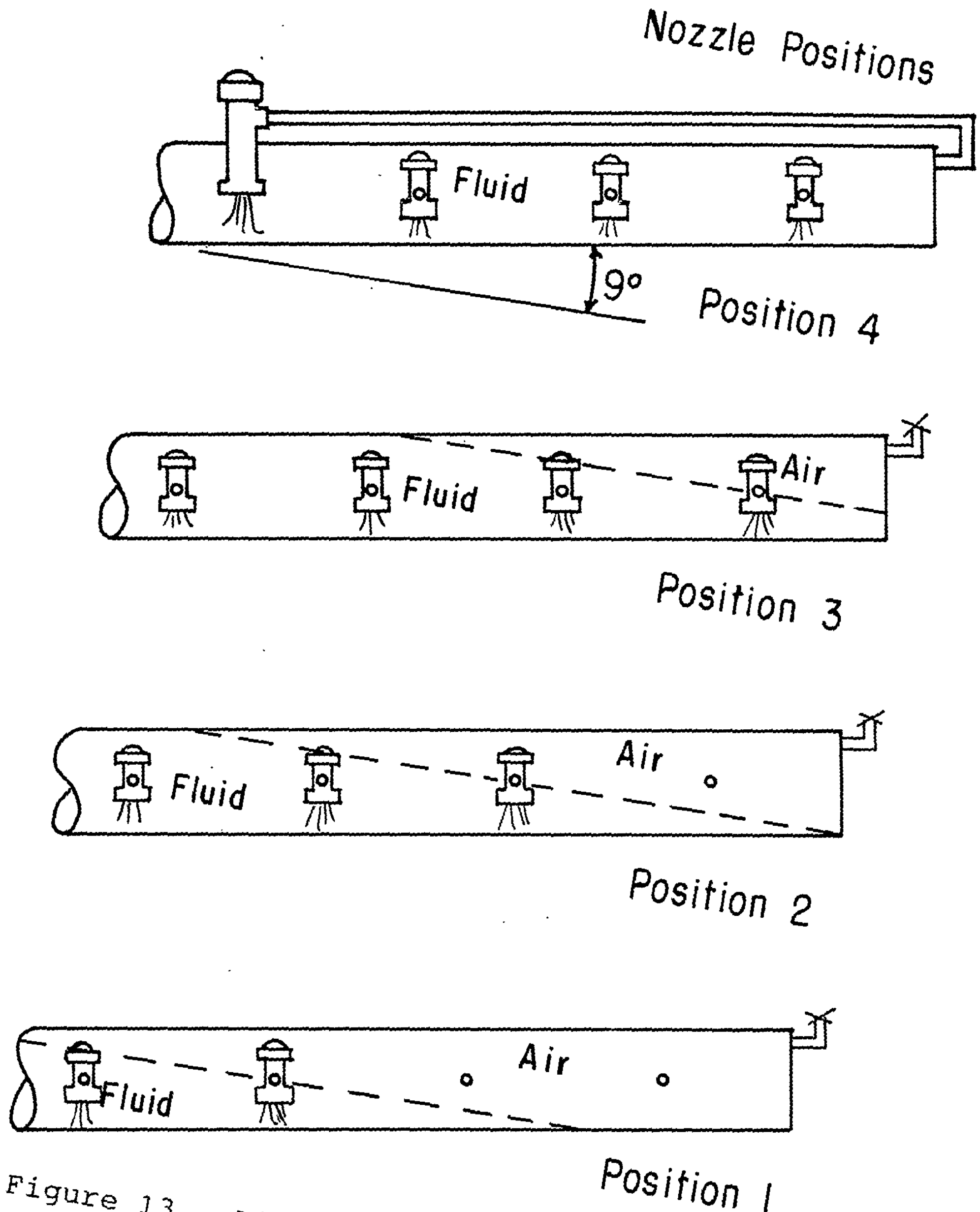

Figure 13. Air Volume Cavities for Each Position.

was 4, the air pocket was bled out of the boom. Whenever the boom position was 1, 2, or 4, the nozzle or nozzles were removed and plugs were placed in their position. Air was introduced into the end of booms until it reached the last nozzle location on the boom at the time. This procedure was done on both booms to ensure the pressure reactions were balanced. The control valve was closed and a negative pressure was allowed to build in the booms. The control valve was opened and the test sampling was initiated, completed and stored. The sampling length was 3.00 seconds at 600 Hz. The control valve was reversed and sampling of the turn-off performance was completed and stored. The next boom position was chosen and the procedure outlined above was repeated until all the boom positions were sampled. Then the boom operating pressure was changed to the one prescribed. The above procedure was repeated until all the operating pressures were sampled.

The valve movement, nozzle pressure, and boom pressure were sampled in this experiment as in the experiment before. This test was designed to measure the pressure transients of the system during turn-on and off of the control valve with changes in air pocket size and operating boom pressures.

Analysis Procedure

Once all the tests were completed, this data was transferred to the Oklahoma State University IBM 3081 mainframe computer. The data from each test was plotted using a Tektronics 4662 plotter, the IBM 3081 computer and Statistical Analysis Systems software (SAS Institute, 1982). These plots all looked similar to the plots in Figures 14 and 15. The following variables were read from the plots for Test One and Two: control valve opening or closing time, initial boom pressure, the time needed for the diaphragm check-valve to open or close, and the time needed for the nozzle to achieve a steady-state flow or stoppage condition. When the response time of a variable was read, time zero was when the control valve first moved, the time the micro-switches initiate the sampling.

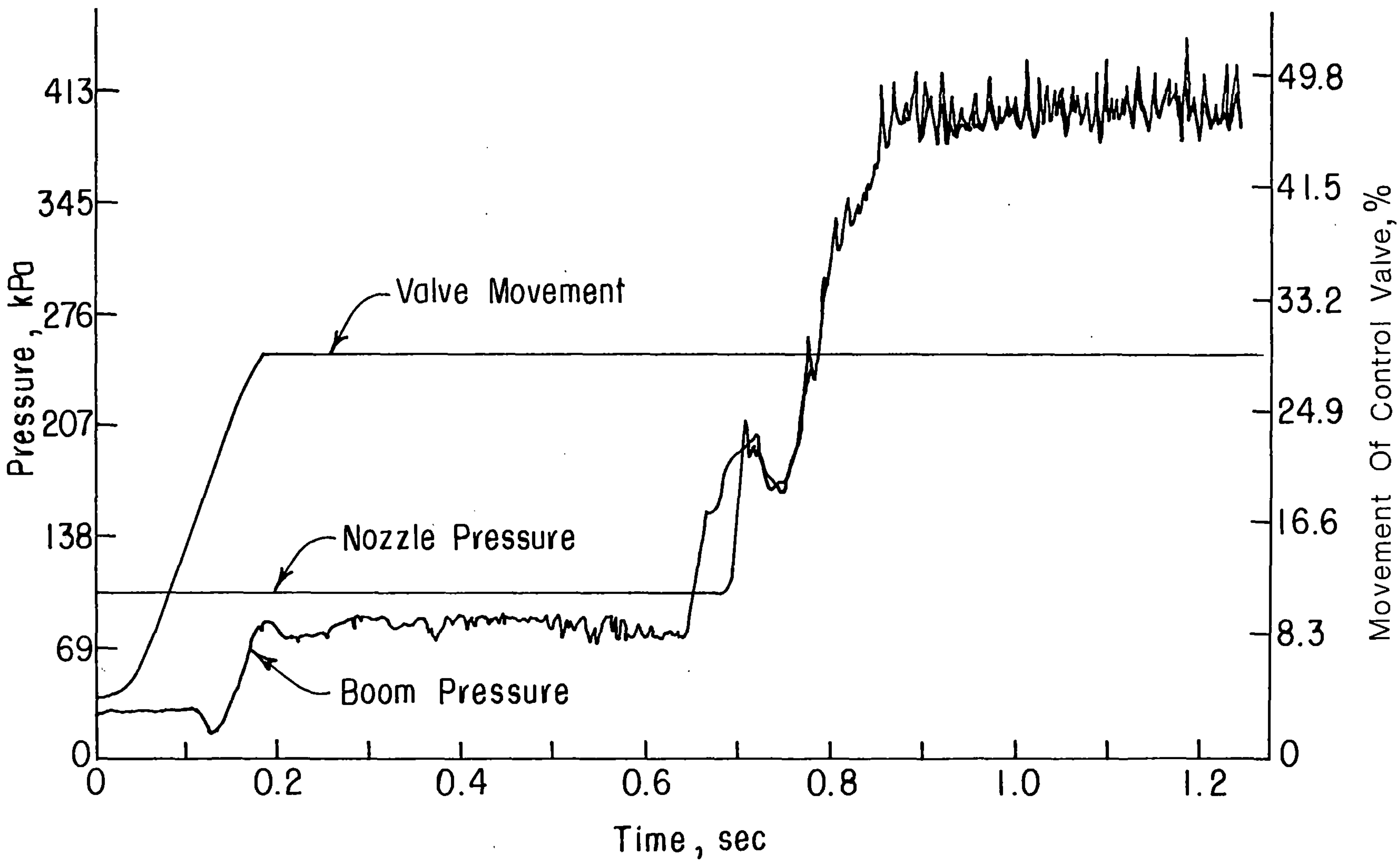

Figure 14. Sample of Plotted Data During Turn-On.

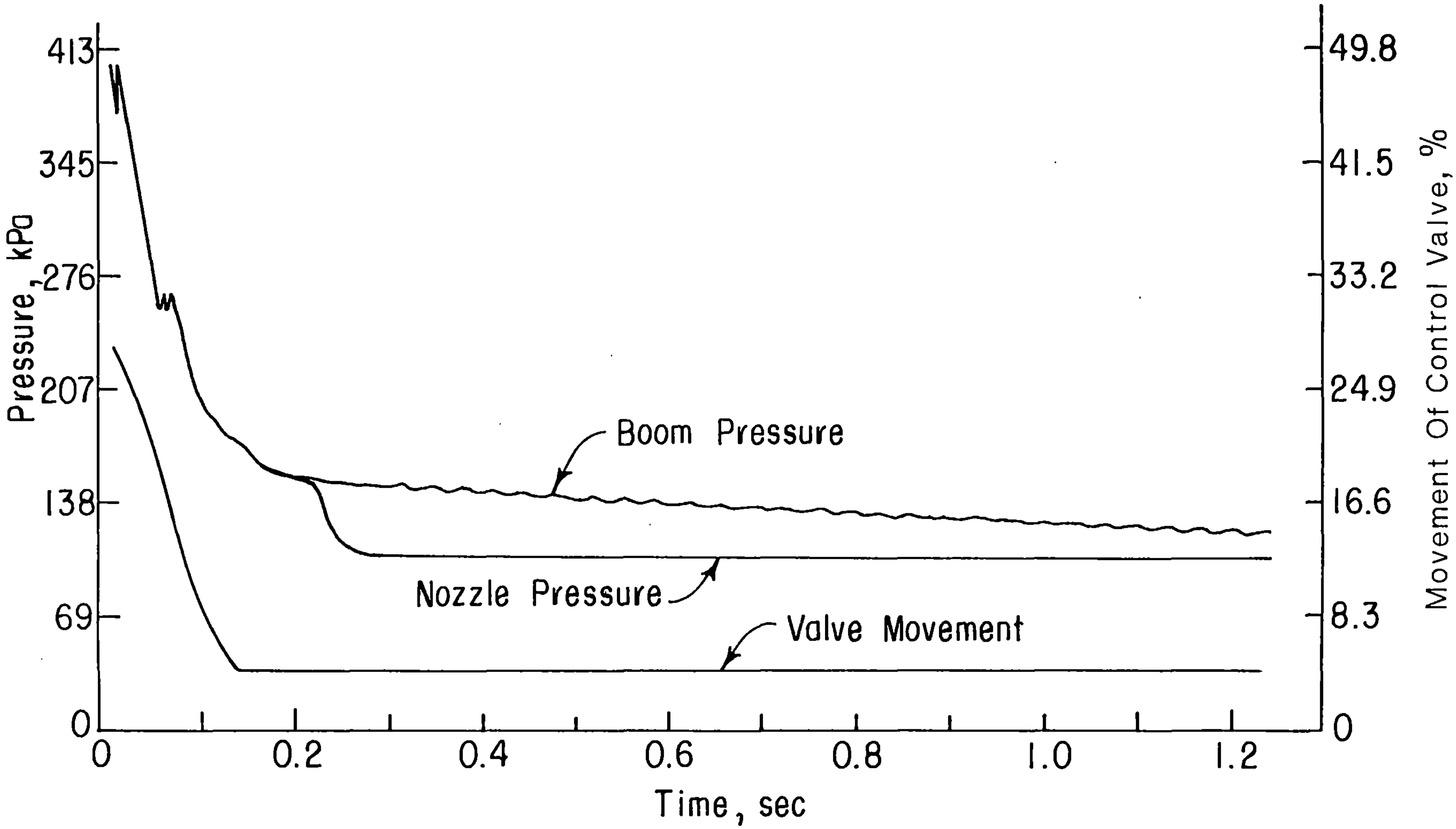

Figure 15. Sample of Plotted Data During Turn-Off.

CHAPTER V

RESULTS AND DISCUSSION

The data from the experiments are presented in Appendix A. An Analysis of Variance (AOV) was performed for all of the measured responses of the test with SAS on Procedure General Linear Model (GLM), because of the unbalanced data set. The AOV was performed to determine the significance of the variables in the models. In some experiments, extra variables which were not varied to an experimental design, were included in the models to find their significance. Their inclusion proved to be meaningful in some instances, and removal of these variables would give misleading results in some cases. Stepwise Regression was not performed on Test One data, because physical differences in the variables were hard to describe.

Test One

In Test One, the three variables were: operating boom pressure, diaphragm check-valve material type, and boom nozzle position. Two more variables were included in the model in order to determine their significance: initial boom pressure and control valve movement time.

Diaphragm Check-Valve Opening Time

The AOV and statistical explanation of the response time for the diaphragm check-valve to open in presented in TABLE III. The data fit the model with a correlation coefficient (R^2) of .914. The variables significant at α = .05 in the model according to Type III Sum of Squares were: operating boom pressure, diaphragm check-valve material type, and initial boom pressure. There was some interaction of the variables in the model, which indicated that some of the variables did not affect the model independently. Therefore, these variables must be presented together in the means of the opening times of the check-valves to get a better representation of their effects on the system performance. These interacting variables were: operating boom pressure x diaphragm check-valve material type, and operating boom pressure x diaphragm check-valve material type, and operating boom pressure x diaphragm check-valve material type x boom nozzle position. According to Least Square means (LSmeans), the means which have the most significance to the model is operating pressure x diaphragm check-valve material type. A plot of this is shown in Figure 16.

Generally, as the operating pressure was increased, the check-valves opened sooner. At 207 kPa it took about 1.6 seconds to open versus 0.4 seconds for 345 kPa. There was a difference between the diaphragms with the Buna-N

TABLE III

ANALYSIS OF VARIANCE FOR TEST ONE
CHECK-VALVE OPENING TIME

Source	DF	SS	MS	F	R^2
Model	107	68.8704	0.6436	8.68	0.914
Error	87	6.4543	0.0742		
Corrected Total	194	75.3247			

Check-Valve Opening Mean Time = 0.951 seconds

Source	DF	Type III SS	F	PR< F
P	2	32.1224	216.50	0.0001
D	5	1.0804	2.91	0.0177
PxD	10	2.1668	2.92	0.0034
N	5	0.3191	0.86	0.5128
PxN	10	0.4937	0.67	0.7532
DxN	25	2.1288	1.15	0.3112
PxDxN	48	5.4940	1.54	0.0398
IP	1	3.0675	41.35	0.0001
CV	1	0.1213	1.64	0.2043

where

P = Operating Boom Pressure

D = Diaphragm Check-Valve Material Type

N = Boom Nozzle Position

IP = Initial Boom Pressure

CV = Control Valve Movement Time

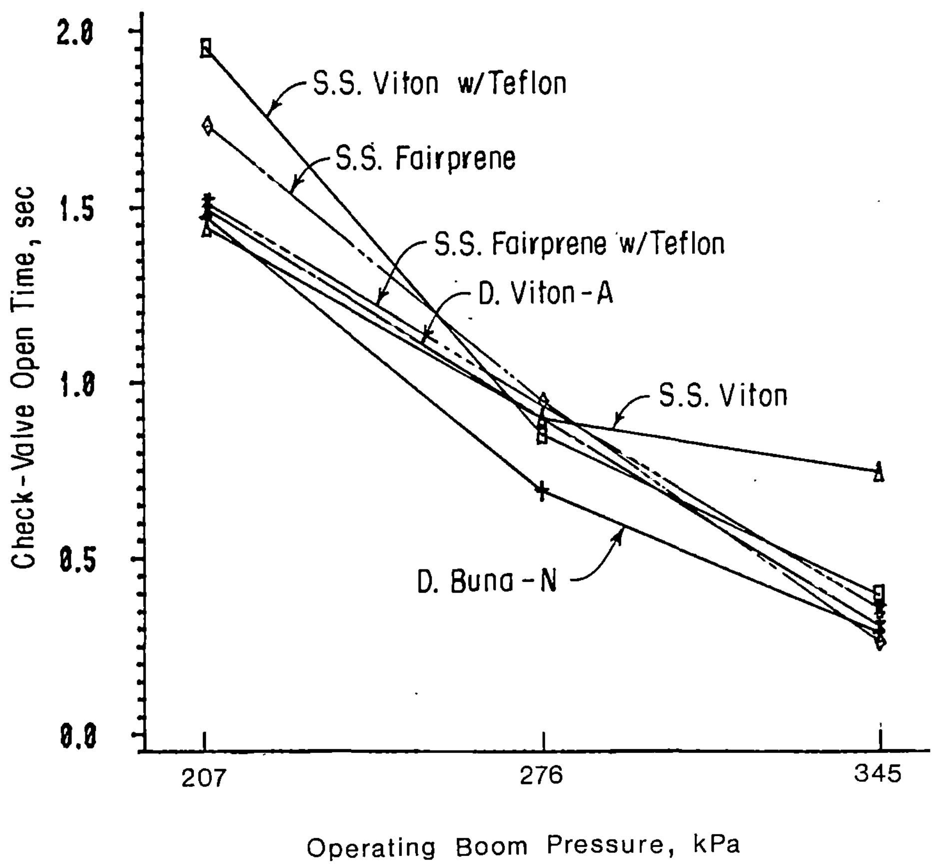

Figure 16. Influence of Diaphragm Material and Operating Boom Pressure on Check-Valve Opening Time.

consistently opening sooner than the other diaphragms. Some opening times were 0.5 seconds later, due to different diaphragm materials. Virtually no differences in the opening times were found for different nozzle positions on the boom.

Steady-State Flow Time

The next measured response time analyzed was the time needed for the nozzles to establish a steady-state flow. The AOV for this model is found in TABLE IV. The same variables were used as above and the data fit the model with a R^2 of .978. The Type III Sum of Squares indicated that operating boom pressure, diaphragm check-valve material type, and initial boom pressure were significant at $\alpha = .05$ to the model. The variables that interacted significantly at $\alpha = .05$ were: operating boom pressure x diaphragm check-valve material type and operating boom pressure x diaphragm check-valve material type x boom nozzle position. The LSmeans that is most significant to the model is the operating boom pressure x diaphragm check-valve material type. Figure 17 presents the means of the steady-state flow times showing this interaction.

Generally, as the operating boom pressure increased, the time to reach steady-state flow decreased. For 207 kPa it took about 2.9 seconds to establish flow versus 0.9 seconds for 395 kPa. The diaphragm check-valve

TABLE IV

ANALYSIS OF VARIANCE FOR TEST ONE
STEADY-STATE FLOW TIME

Source	DF	SS	MS	F	R^2
Model	106	94.9953	0.8961	24.39	0.978
Error	59	2.1680	0.0367		
Corrected Total	165	97.1633			

Steady-State Flow Mean Time = 1.47 seconds

Source	DF	Type III SS	F	PR > F
P	2	52.8002	718.47	0.0001
D	5	1.5353	8.36	0.0001
PxD	10	2.4112	6.56	0.0001
N	5	0.2730	1.49	0.2072
PxN	10	0.3381	0.92	0.5214
DxN	25	1.0893	1.19	0.2900
PxDxN	47	3.2923	1.91	0.0096
IP	1	1.4925	40.62	0.0001
CV	1	0.0302	0.82	0.3682

where

P = Operating Boom Pressure

D = Diaphragm Check-Valve Material Type

N = Boom Nozzle Position

IP = Initial Boom Pressure

CV = Control Valve Movement Time

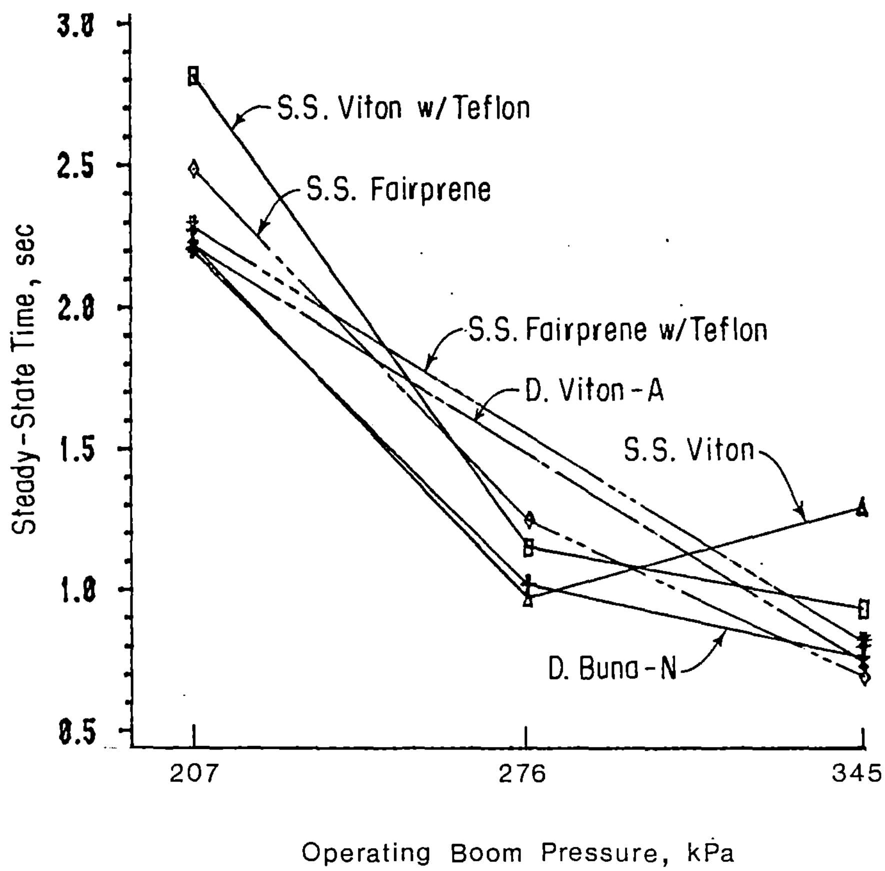

Figure 17. Influence of Diaphragm Material and Operating Boom Pressure on Time to Reach Steady-State Flow.

material type that consistently allowed faster flow establishment in the nozzle was Buna-N. The nozzle position on the boom variations did not effect the steady-state flow time.

Check-Valve Closing Time

In this analysis, the variables included in the model to describe the time needed for the diaphragm check-valves to close were: operating boom pressure, diaphragm check-valve material type, and boom nozzle position. The two variables, initial boom pressure and control valve closing time, were also included in the model as before. The AOV can be found in TABLE V and the R^2 value was .946. The Type III Sum of Squares indicated that the significant variables at $\alpha = .05$ in the model were: operating boom pressure, diaphragm check-valve material type, boom nozzle position, and control valve movement time. The significant interaction variables were: operating boom pressure x diaphragm check-valve material type, operating boom pressure x boom nozzle position, and diaphragm check-valve material type x boom nozzle position, and operating boom pressure x diaphragm check-valve material type x boom nozzle position. The LSmeans that best describes the model of check-valve closing time is operating boom pressure x diaphragm check-valve material type x boom nozzle position. Plots times of the check-valve closing time can be found in

TABLE V

ANALYSIS OF VARIANCE FOR TEST ONE
CHECK-VALVE CLOSING TIME

Source	DF	SS	MS	F	R^2
Model	109	0.9736	0.0089	16.62	0.946
Error	103	0.0554	0.0005		
Corrected Total	212	1.0290			

Check-Valve Closing Mean Time = 0.264 seconds

Source	DF	Type III SS	F	PR > F
P	2	0.1197	111.33	0.0001
D	5	0.2212	82.29	0.0001
PxD	10	0.1454	27.05	0.0001
N	5	0.0292	10.85	0.0001
PxN	10	0.0179	3.25	0.0011
DxN	25	0.0367	2.73	0.0002
PxDxN	50	0.1016	3.78	0.0001
IP	1	0.0002	0.46	0.4997
CV	1	0.0025	4.71	0.0322

where

P = Operating Boom Pressure

D = Diaphragm Check-Valve Material Type

N = Boom Nozzle Position

IP = Initial Boom Pressure

CV = Control Valve Movement Time

Figures 18, 19, 20 and 21. These plots indicate that each variable contributes to the closing time of the valves. The check-valve material type significantly contributed to the closing time, but in field situations their difference is small, since no more than 0.1 of a second difference exist between diaphragm materials. The boom nozzle positions close at the end of the booms first, but only 0.1 of a second sooner than the inside positions. The operating boom pressures are significant contributors at $\alpha = .05$, but again, very little difference in time exist between them. The 276 kPa boom pressure closed sooner than the 207 kPa and the 345 kPa operating pressures, but not more than 0.1 second. The interaction of the operating boom pressure x diaphragm check-valves materials types indicates some interaction of the variables. Buna-N and Viton-A consistently close sooner than other diaphragm materials. Very little time difference in the closure time of the valves is present in field situations due to the variations of: boom operating pressure, diaphragm check-valve material type, and boom nozzle position.

Nozzle Flow Stoppage Time

The next model fitted to the data is the time needed for the nozzle flow to stop. The R^2 is .917 and the AOV can be found in TABLE VI. The Type III Sum of Squares indicates that the significant variables at $\alpha = .05$ in the

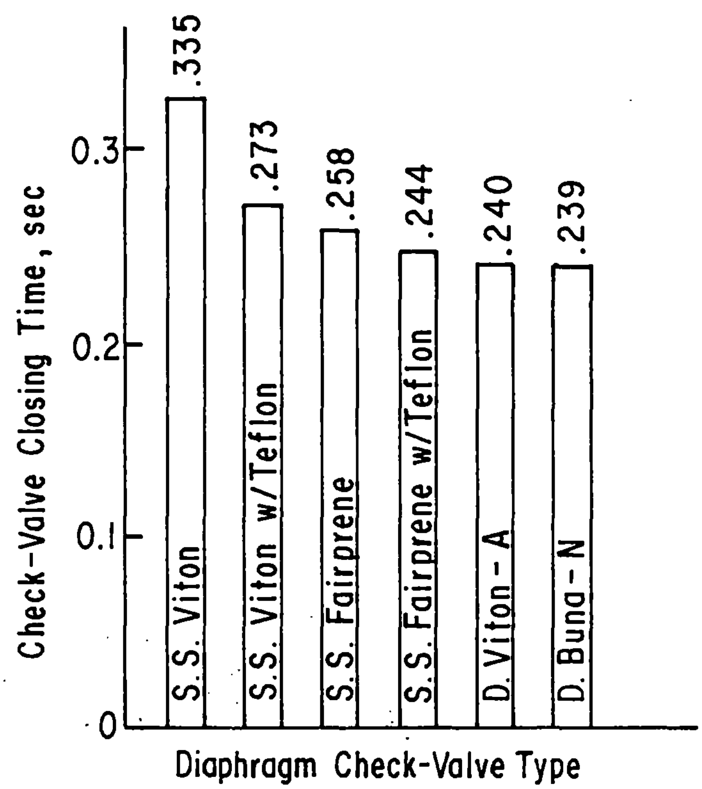

Figure 18. Effect of Diaphragm Material on Check-Valve Closing Time.

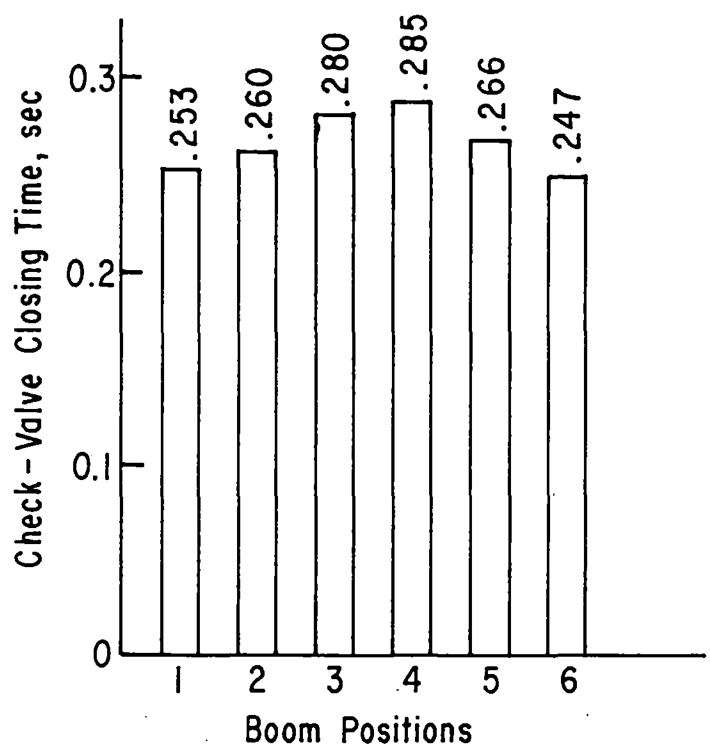

Figure 19. Boom Nozzle Position Effect on Check-Valve Closing Time.

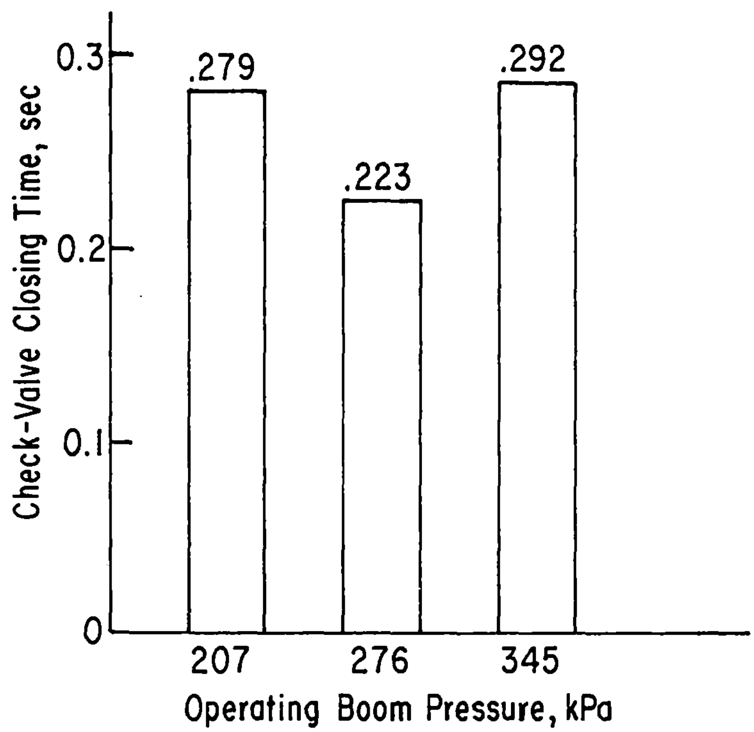

Figure 20. Operating Boom Pressure Effect on Check-Valve Closing Time.

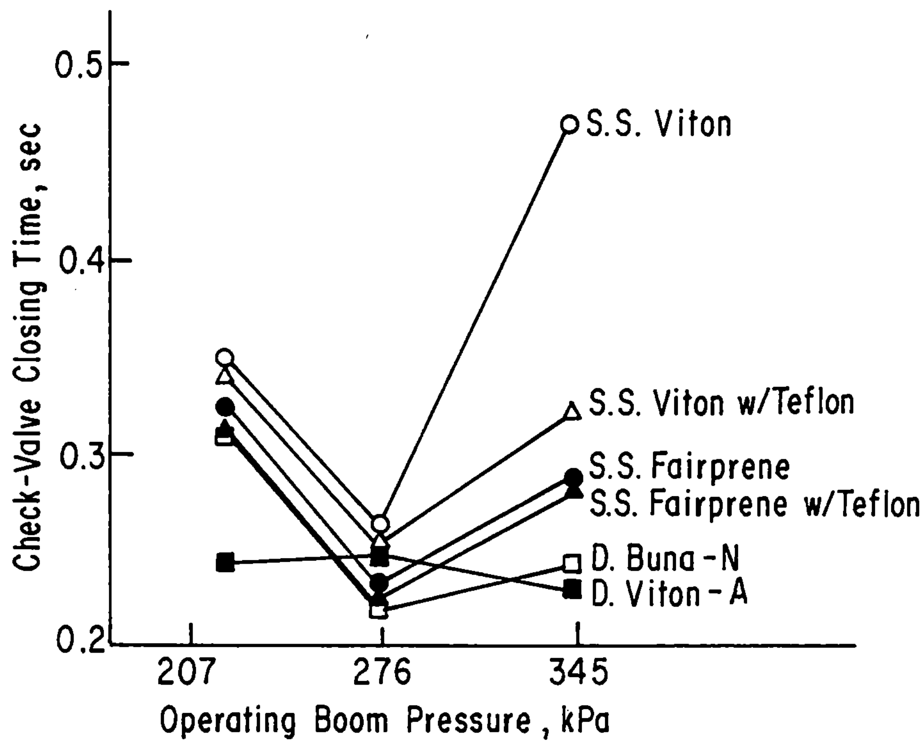

Figure 21. Influence of Diaphragm Material and Operating Boom Pressure on Check-Valve Closing Time.

TABLE VI

ANALYSIS OF VARIANCE FOR TEST ONE
STEADY-STATE FLOW STOPPAGE TIME

Source	DF	SS	MS	F	R^2
Model	109	1.6819	0.0154	10.46	0.917
Error	103	0.1519	0.0015		
Corrected Total	212	1.8338			

Steady-State Flow Stoppage Mean Time = 0.401 seconds

Source	DF	Type III SS	F	PR > F
P	2	0.2112	71.59	0.0001
D	5	0.4246	57.56	0.0001
PxD	10	0.3200	21.69	0.0001
N	5	0.0503	6.82	0.0001
PxN	10	0.0525	3.56	0.0004
DxN	25	0.0731	1.98	0.0089
PxDxN	50	0.1882	2.55	0.0001
IP	1	0.0023	1.57	0.2126
CV	1	0.0074	5.01	0.0274

where

P = Operating Boom Pressure

D = Diaphragm Check-Valve Material Type

N = Boom Nozzle Position

IP = Initial Boom Pressure

CV = Control Valve Movement Time

model to describe nozzle flow stoppage time were: operating boom pressure, diaphragm check-valve material type, boom nozzle position, and control valve closure time. The significant interactions at α = .05 were: operating boom pressure x diaphragm check-valve material type, and operating boom pressure x diaphragm check-valve material type x boom nozzle position. The best means indicated by the LSmeans is operating boom pressure x diaphragm check-valve material type x boom nozzle position. The Figures 22, 23, 24, and 25, show the means for the nozzle flow to stop with the various variable effects. The boom nozzle positions close from outside to inside, with a maximum of 0.1 second difference. The Spraying Systems Fairprene with Teflon diaphragms closed first with the Spraying Systems Viton closing last. These differences in time of less than 0.2 of a second will not make a significant difference in the field. The 276 kPa operating boom pressure closed first. In the field, the effect of operating boom pressure on nozzle flow stoppage is negligible. From Figure 25, operating boom pressure and the check-valve material type indicates that some interaction exists between the variables. The Spraying Systems Fairprene with Teflon consistently closed sooner than the other diaphragm materials, but in most cases less than 0.1 second sooner.

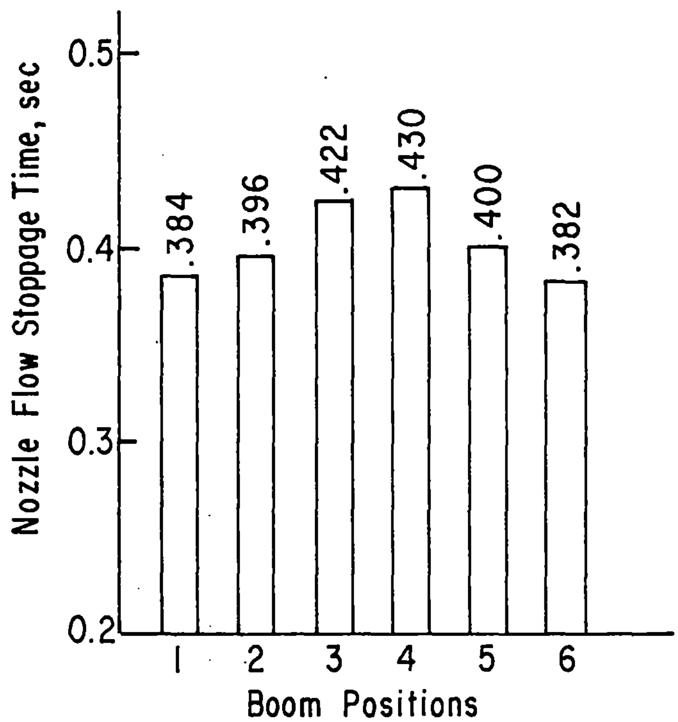

Figure 22. Boom Nozzle Position Effect on Nozzle Flow Stoppage Time.

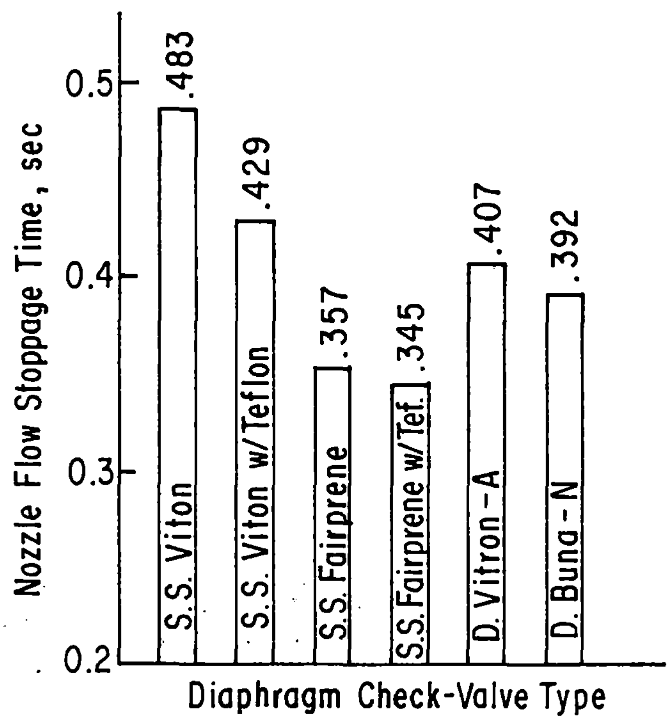

Figure 23. Effect of Diaphragm Material on Steady-State Flow Stoppage Time.

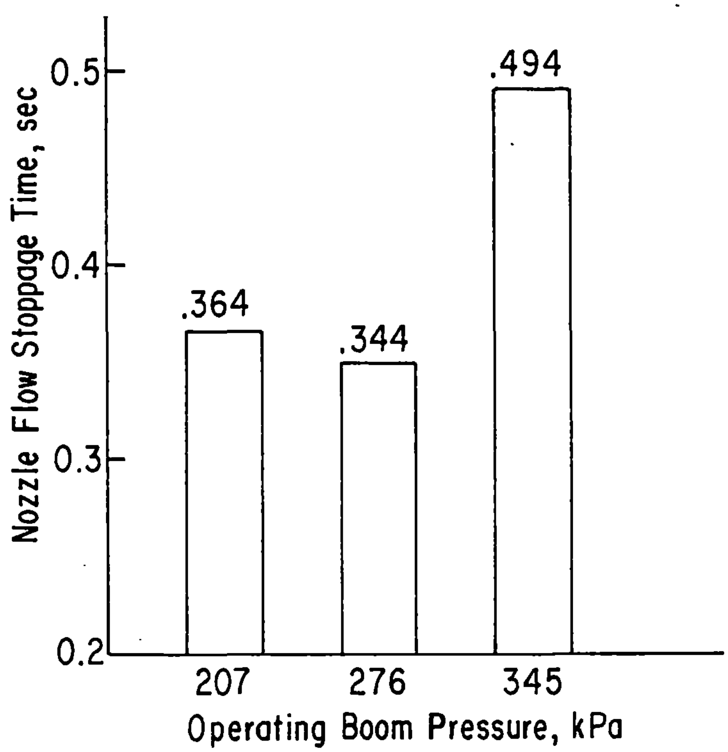

Figure 24. Operating Boom Pressure Effect on Steady-State Flow Stoppage Time.

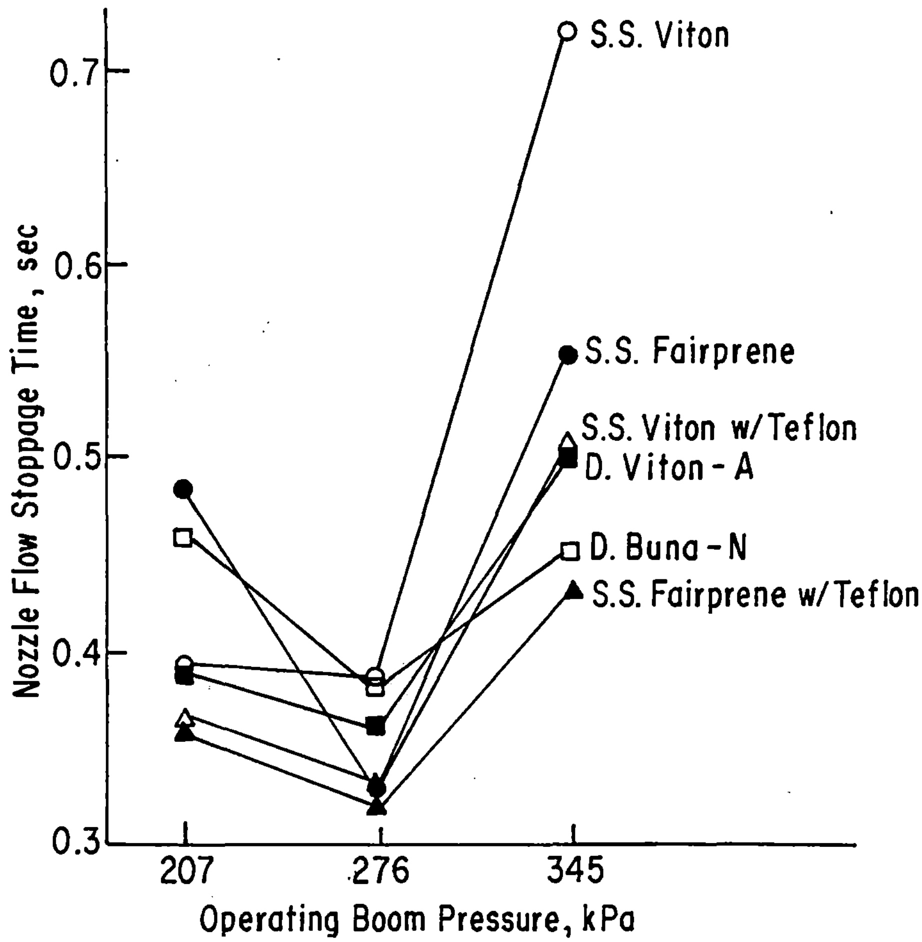

Figure 25. Influence of Diaphragm Material and Operating Boom Pressure on Steady-State Flow Stoppage Time.

Test Two

The data for Test Two are found in Appendix A. Analysis of Variance was performed on the variables to find its significance to the times needed for the check-valves to open and close and establish steady-state flow or stoppage. The variables fit to the model were: operating boom pressure and boom end volume. The variable, control valve movement time, was included in the model and because of pressure transducer failure, initial boom pressure was not included. The AOVs were done on SAS with the GLM because of the unbalanced nature of the data. Stepwise Regression was performed on the data because of the physical nature of the variables used and provided an equation to fit the model.

Check-Valve Opening Time

The AOV for the model of the check-valve opening time with respect to air volume size and operation boom pressure can be found in TABLE VII. The R^2 is .977 and the significant variables at $\alpha = .05$ in the model according to the LSmeans are: air volume size and boom operating pressure. The interaction of these two variables is the most significant representation of the model. Figure 26 indicates that as the air volume size increased, the valve opening time increased. Figure 27 shows two plots which indicate how the air volume size

TABLE VII

ANALYSIS OF VARIANCE FOR TEST TWO
CHECK-VALVE OPENING TIME

Source	DF	SS	MS	F	R^2
Model	12	8.112	0.6760	39.18	0.977
Error	11	0.190	0.0172		
Corrected Total	23	8.302			

Check-Valve Opening Mean Time = 0.948 seconds

Source	DF	Type III SS	F	PR > F
P	2	0.3770	10.92	0.0024
A	3	3.4415	66.49	0.0001
PxA	6	0.6701	6.47	0.0040
CV	1	0.0065	0.38	0.5523

where

P = Operating Boom Pressure

A = Air Volume Size

CV = Control Valve Movement Time

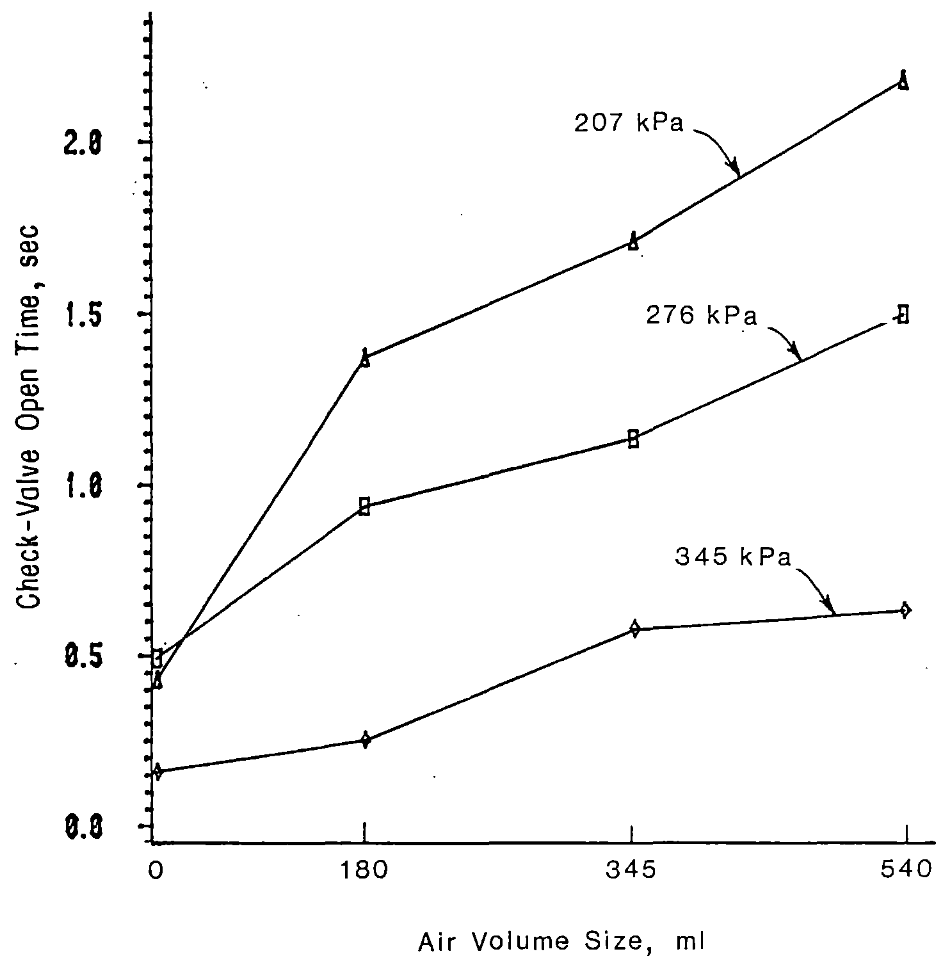

Figure 26. Air Volume Size and Operating Boom Pressure Effect on Check-Valve Opening Time.

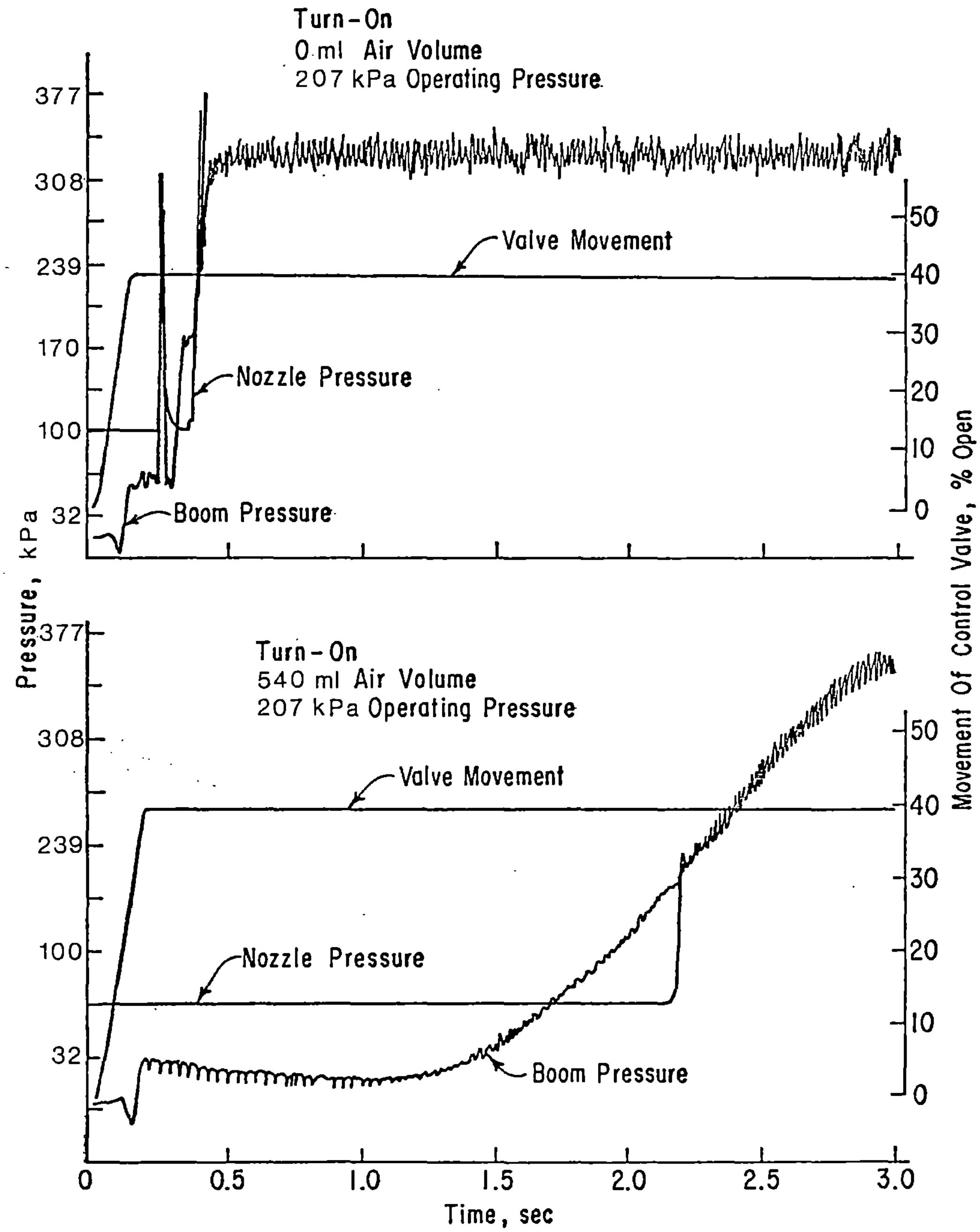

Figure 27. The Influence of Air Volume Size on Performance of the System During Turn-On of the Control Valve.

effects the system during turn-on of the control valve. The reaction time of the valves decreased as the operating pressure increased. The regression equation for this model is:

$$CVO = (-.00826)P + (0.00208)AV + (1.68)CV \quad \text{(Eq 1)}$$

where

CVO = check-valve opening time (sec)

P = operating boom pressure (kPa)

AV = air volume at end of boom (ml)

CV = control valve opening time (sec)

The R^2 for this regression model is .854. This regression model indicated that the air volume size affected the operating time the most, followed by operating boom pressure, and then control valve movement time.

Nozzle Steady-State Flow

There was not enough collected data because of equipment failure to provide a significant model for the nozzle steady-state flow.

Check-Valve Closing Time

An AOV was performed on the data to find the significant variables in the check-valve closing time model and can be found in TABLE VIII. The R^2 for this model was .948 and the variable that contributed significantly at $\alpha = .05$ to the model by using Type III Sum of Squares was: air volume size. The result of the LSmeans is shown in Figure 28. As the air volume increased, the closure time of the valve increased. Figure 29 shows what effects air volume size had upon the closing times of the check-valves.

A Stepwise Regression was performed on the data and the R^2 was .822. The equation was:

$$CVC = (.00189)P + (.00176)AV \quad \text{(Eq 2)}$$

where

CVC = the check-valve closing time (sec)

P = the operating boom pressure (kPa)

AV = the air volume size (ml) at the end of the booms.

The air volume size contributed the most to the model, with the operating boom pressure second. The control valve did not contribute significantly at $\alpha = .05$ to be included in the model.

TABLE VIII

ANALYSIS OF VARIANCE FOR TEST TWO
CHECK-VALVE CLOSING TIME

Source	DF	SS	MS	F	R^2
Model	13	2.8700	0.2208	9.79	0.948
Error	7	0.1579	0.0226		
Corrected Total	20	3.0278			

Check-Valve Closing Mean Time = 0.497 seconds

Source	DF	Type III SS	F	PR > F
P	2	0.0113	0.25	0.7855
A	3	0.6565	9.70	0.0069
PxA	6	0.2990	2.21	0.1616
IP	1	0.0143	0.63	0.4519
CV	1	0.0113	0.50	0.5022

where

P = Operating Boom Pressure

A = Air Volume Size

IP = Initial Boom Pressure

CV = Control Valve Movement Time

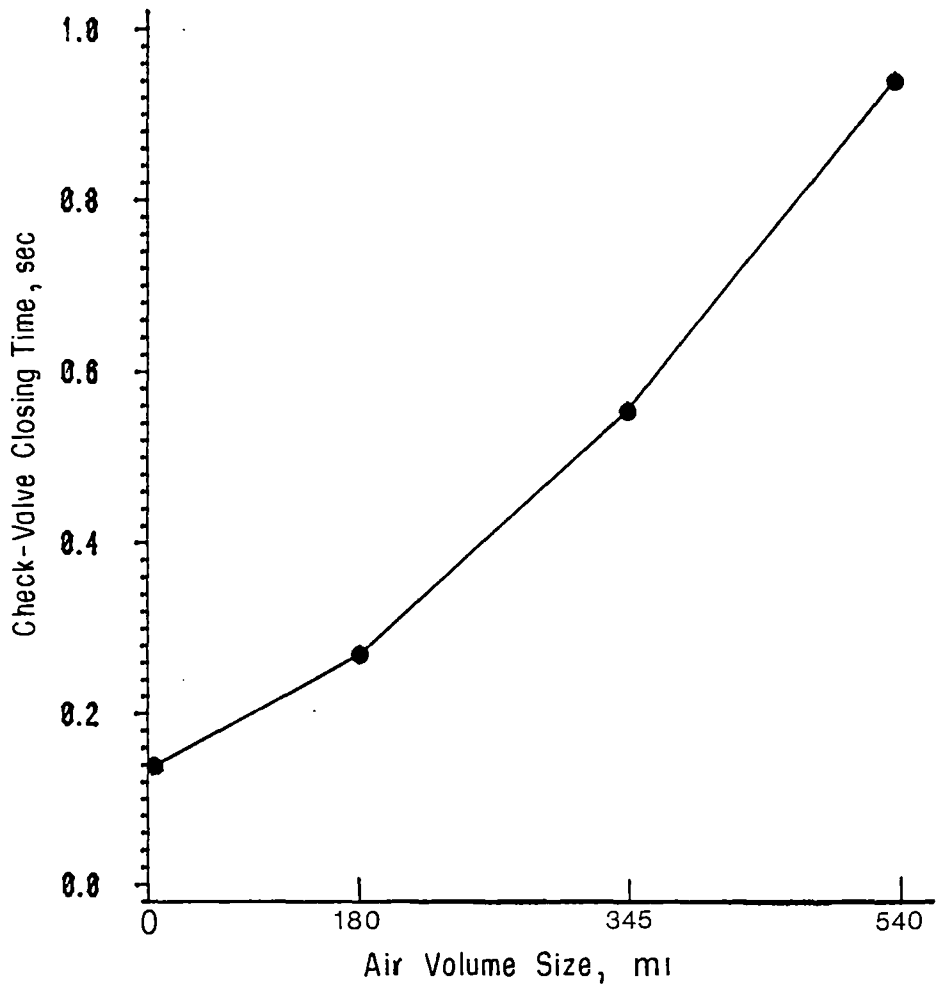

Figure 28. The Influence of Air Volume Size on Check-Valve Closing Time.

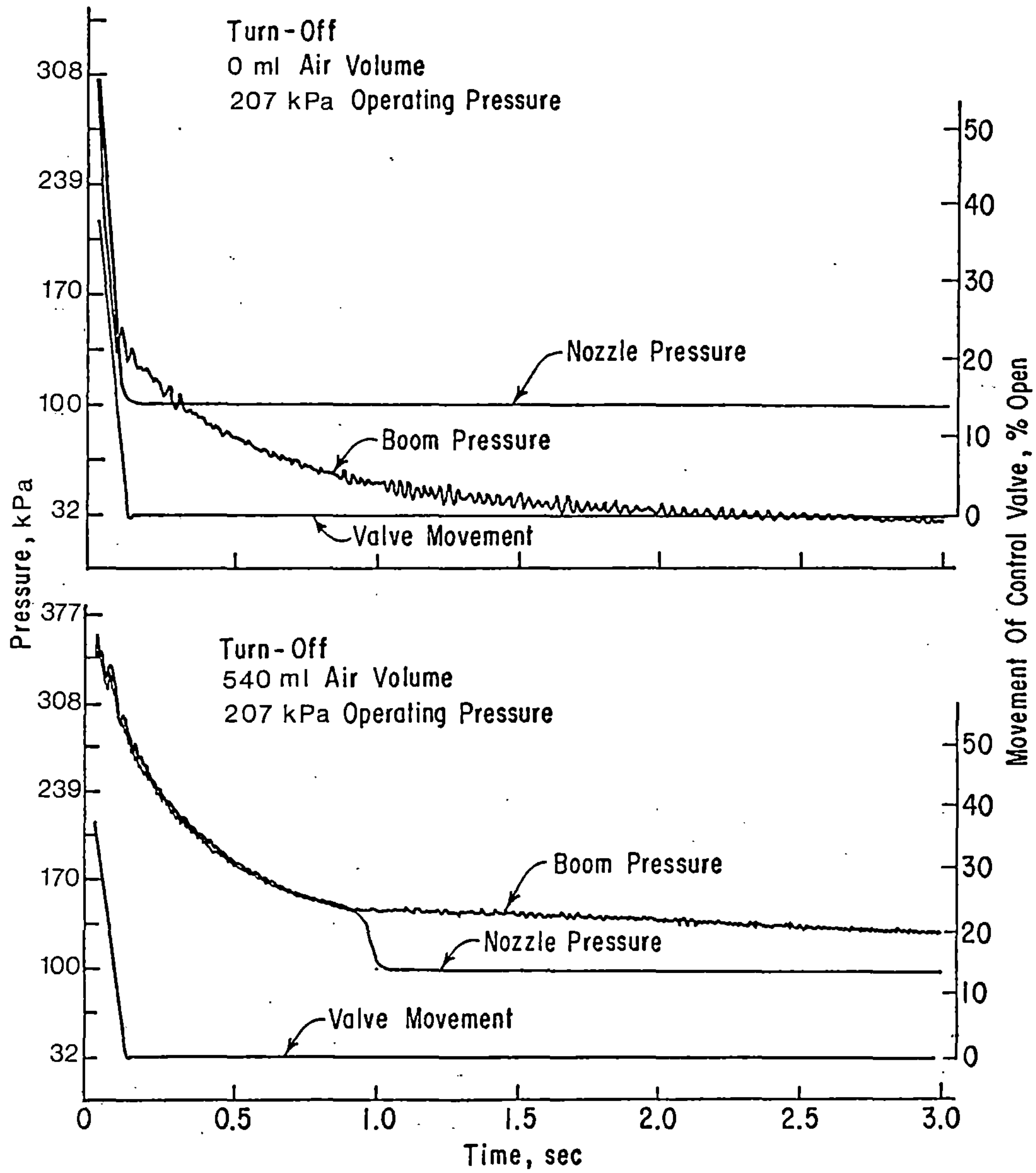

Figure 29. The Influence of Air Volume Size on Performance of the System During Turn-Off of the Control Valve.

Nozzle Flow Stoppage Time

The data for finding the time needed for the nozzle flow to stop was fitted to a model and the AOV is shown in TABLE IX. The R^2 was .986. The variable that is significant at $\alpha = .05$ in the Type III Sum of Squares to the model is: air volume size. The LSmeans that described the model is shown in Figure 30. The operating boom pressure x air volume size interacts significantly, in the model. As the air volume increased, the check-valve closing time increased and as the operating boom pressure increased, the check-valve closing time decreased.

The Stepwise Regression was performed on the data and the equation had a R^2 of .906. The variable that contributed to the regression equation the most was air volume size, with operating pressure second. Control valve time did not contribute significantly enough to be included the model. The regression equation is:

$$SS = (.00197)P + (.00222)AV \quad \text{(Eq 3)}$$

where

SS = the steady-state stoppage time (sec)

P = the operating boom pressure (kPa)

AV = the air volume size at the end of the booms (ml).

TABLE IX

ANALYSIS OF VARIANCE FOR TEST TWO
STEADY-STATE FLOW STOPPAGE TIME

Source	DF	SS	MS	F	R^2
Model	13	4.1998	0.3231	37.79	0.986
Error	7	0.0598	0.0085		
Corrected Total	20	4.2596			

Steady-State Stoppage Mean Time = 0.670 seconds

Source	DF	Type III SS	F	PR > F
P	2	0.0441	2.58	0.1446
A	3	1.0217	39.84	0.0001
PxA	6	0.2220	4.33	0.0381
IP	1	0.0295	3.46	0.1054
CV	1	0.0118	1.38	0.2781

where

P = Operating Boom Pressure

A = Air Volume Size

IP = Initial Boom Pressure

CV = Control Valve Movement Time

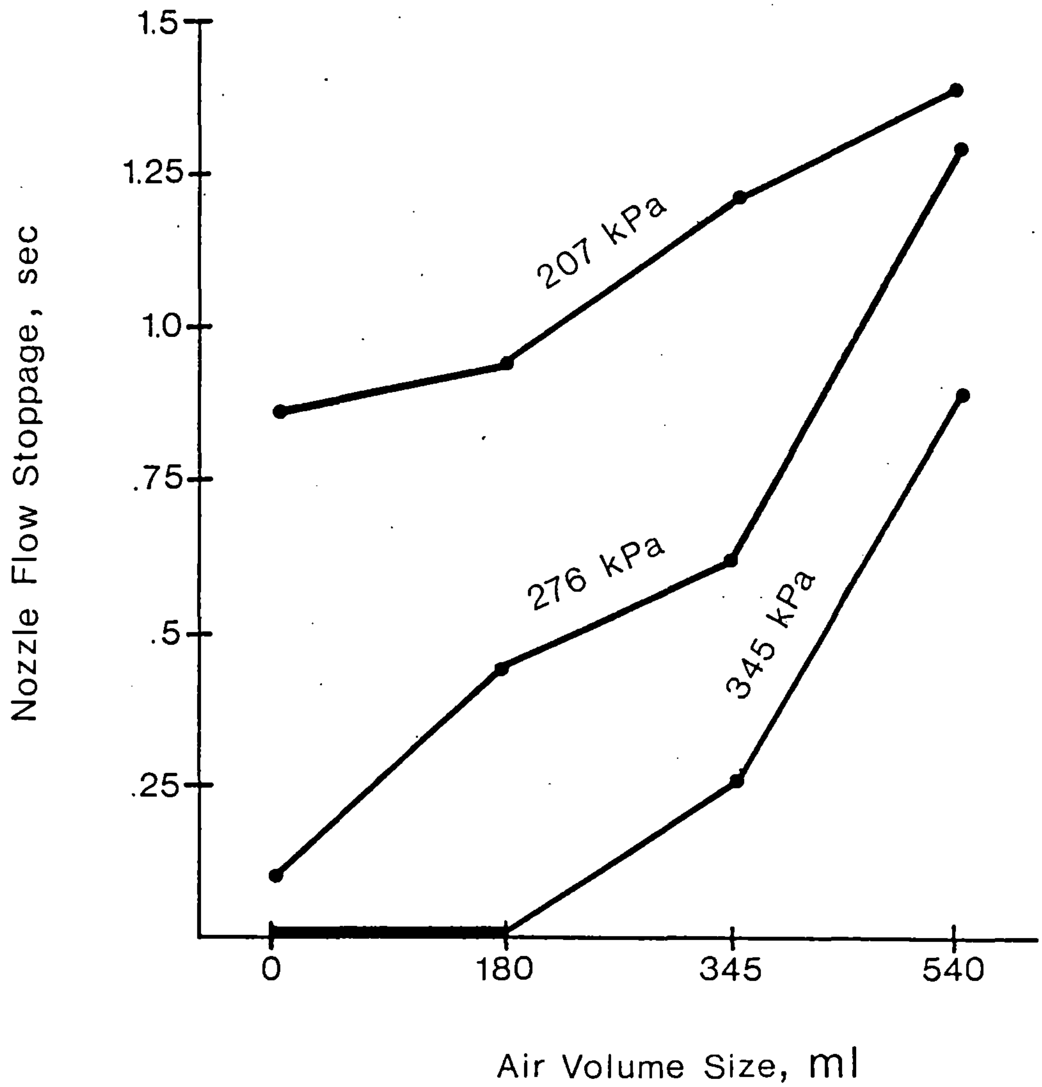

Figure 30. The Influence of Air Volume Size on Steady-State Flow Stoppage Time.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

A laboratory aerial application system was analyzed during the turn-on and turn-off operation to find the response times of the system. The parameters, operating boom pressure, diaphragm check-valve material type, boom nozzle position, and air volume size at the end of the boom were varied in order to find their significance in affecting the performance of the system during turn-on and turn-off. The measured responses of the system were the time needed for the diaphragm check-valve to open or close and the time needed for the nozzle flow to be established or stopped.

Conclusions

The most significant factor affecting the performance of the aerial application system was air volume size at the end of the boom. Any air in the booms was detrimental to diaphragm check-valve opening time, nozzle flow establishment time, diaphragm check-valve opening time, and nozzle flow stoppage time. As more air was introduced into the boom, slower reaction times resulted. Since air is compressible, its presence made the venturi takes more of the fluid out of the booms to lower the pressure. During turn-on, the pressure rise was slower because more fluid had to be pumped into the booms to raise the pressure. Therefore, keeping the air out of the booms is very beneficial to the performance of the system with respect to opening and closing times of the check-valves. Using the boom end modification from Test Two would fulfill this recommendation.

The aerial application system performance was affected by the operating boom pressure in that as it increased, the check-valve opening time and the steady-state flow time decreases. The faster the fluid was pumped into the booms, the faster the pressure increased, which explained that result. The closing of the check-valves and the nozzle flow stoppage times were not affected by the operating boom pressure enough to change current application practices which is an indication that the flow reversal and the venturi action take time to develop.

The diaphragm check-valve material type did not affect the performance of the aerial application system enough to warrant a dramatic change in the current practices of the industry. The Delevan Buna-N consistently gave the best overall performance during Test One. But the main purpose of the various materials used is to control the corrosion causing characteristics of the application chemicals. Therefore, their main purpose, corrosion resistance, is more important than their effects on opening and closing times of the check-valves.

The boom nozzle positions have little affect upon the system performance. During turn-on and nozzle flow establishment, the nozzle positions engage at relatively the same time. During turn-off, the outer nozzle positions close first and the inside nozzle positions close last. The differences the boom nozzle positions contribute to the performance of the aerial application system, during turn-on and turn-off of the control valve, is not great enough to change the current practices of the aerial application field.

The control valve movement and initial boom pressure were not investigated enough to make much conclusion. The initial boom position contributed enough to tell that if the boom pressure is lowered too much during turns and ferry, the time needed to raise the boom pressure and open the check-valve is increased. Either keeping the air out of the booms or setting the venturi action to keep the booms at a reasonable pressure, about 70 kPa absolute, would improve the performance of the system, with respect to opening and closing times of the check-valves.

Recommendations for Future Work

More tests need to be done to duplicate this data at other operating pressures. The operating pressures should be done at more numerous pressures, since lower and higher pressures, along with those used in the experiments, are used in the aerial application industry.

The effects of other types of nozzles and fluids needs to be analyzed. Only one nozzle type and one fluid was used in these experiments. This analysis would benefit the industry since many different types of nozzles and several effluents are used in the aerial application field.

Varying the two variables, control valve movement time and initial boom pressure, would help to establish a better model of the response time of the aerial application system. Since these variables proved to be valuable to the models, a better analysis of these variables is needed in order to have understanding of their contributing significance.

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APPENDIX A

EXPERIMENTAL DATA

TEST ONE

TURN-ON

EXPERIMENT	CTIME	IBKPAA	CVOTIME	SSTIME
E111A	.170	62	.220	.70
E111B	.167	86	.180	.84
E112A	.180	99	.154	.84
E112C	.190	33	.527	
E113A	.192	99	.135	.72
E113C	.164	49	.464	1.2
E114A	.160		.120	.80
E114C	.192	34	.144	.64
E115A	.152	101	.343	1.10
E115C	.200	37	.696	1.20
E116A	.166	57	.2	.8
E116C	.160	19	.480	1.20
E121A	.200	48	.244	.78
E121C	.160	17	.510	1.10
E122A	.200	36	.260	.65
E122C	.200	17	.532	1.06
E123A	.254	21	.574	1.00
E123C		73		
E124A	.210	69	.152	.64
E124C	.210	23	.560	1.02
E125A	.180	33	.280	.96
E125C	.145	23	.393	1.18
E136A	.206	40	.264	.76
E126C	.220	21	.467	1.20
E131A	.216	26	.306	.90
E131C	.234	17	.466	.94
E132A	.254	38	.245	.56
E132C	.240	22	.344	.70
E133A	.160	38	.156	.54
E133C	.236	19	.486	.82
E134A	.254	36	.200	.64
E134C	.204	19	.472	.92
E135A	.184	29	.284	.60
E135C	.210	17	.484	.98
E136A	.225	36	.265	.68

E136C	.220	21	.508	.92
E141A				
E141C	.206	19	.408	1.00
E142A	.234	28	.376	.76
E142C	.194	21	.500	.86
E143A	.216	33	.194	.62
E143C	.226	22	.456	1.00
E144A	.252	36	.194	.54
E144C	.210	21	.480	.84
E145A	.216	72	.204	.52
E145C	.194	22	.542	1.02
E146C	.176	22	.548	
E151A	.230	41	.416	.82
E151C	.204	17	.418	1.08
E152A	.260	33	.264	.76
E152C	.206	19	.406	.88
E153A	.220	36	.182	.52
E153C	.234	21	.484	.92
E154A	.206	29	.188	.60
E154C	.188	21	.475	.82
E155A	.186	34	.274	.70
E155C	.256	19	.554	1.00
E156A	.256	50	.328	.66
E156C	.216	17	.525	.94
E161A	.196	34	.224	.70
E161C		14		
E162A	.206	38	.220	.70
E162C	.194	19	.472	.92
E163A	.190	36	.148	.56
E163C	.196	21	.420	.92
E164A	.210	34	.176	.70
E164C	.218	21	.462	1.02
E165A	.200	38	.240	.58
E165C	.182	19	.506	.92
E166A	.284	38	.338	.66
E166C	.220	17	.520	1.24
E211A	.198	19	1.058	1.25
E211C	.174	30	4.40	
E212A	.156	34	.526	.76
E212C	.152	19	1.26	
E213A	.200	42	.538	.80
E213C	.200	23	1.228	
E214A	.144	34	.576	.80
E214C	.180	20	1.250	
E215A	.16	30	.596	1.08
E215C	.134	20	1.146	
E216A	.172	23	.788	1.10
E216C	.160	19	.196	

E221C	.162	19	1.148	1.27
E221A	.204	25	.644	1.05
E222A	.216	33	.560	1.08
E222C	.148	19	1.132	
E223A	.146	29	.676	.90
E223C	.180	22	1.112	
E224A	.152	32	.676	1.40
E224C	.224	22	1.25	
E225A	1.80	21	.944	1.25
E225C	.164	24	.778	1.21
E226A	.160	30	.636	1.16
E226C	.152	19		
E231A	.168	28	.658	1.20
E231C	.148	39	.436	.92
E232A	.128	30	.534	1.04
E232C	.148	18	1.214	
E233A	.116	52	.732	1.25
E233C	.146	25	1.26	
E234A	.168	28	.674	1.02
E234C	.136	39	.734	1.08
E235A	.166	50	.836	1.25
E335C	.158	43	1.26	
E236A	.186	28	.652	1.18
E236C	.146	19	1.14	
E241A	.156	26	.570	1.12
E241C	.176	16	1.182	
E242A	.182	30	.702	1.18
E242C	.178	18	1.227	
E243A	.186	28	.684	.90
E243C	.144	7	1.048	1.26
E244A	.204		.824	1.10
E244C	.174		1.058	1.27
E245A	.170	28	.588	.76
E245C	.166	19	1.118	
E246A	.156		.746	1.12
E246C	.136	19	1.280	
E251A	.168	26	.856	1.25
E251C	.138	21	1.134	
E252A	.180	30	.546	.84
E252C	.176	19	1.200	
E253A	.212	29	.430	.94
E253C	.148	28	.875	1.18
E254A	.180		.468	.68
E254C	.162		1.008	1.28
E255A	.186		.656	1.00
E255C	.166	25	.976	1.20
E256A	.170	28	.692	1.20
E256C	.132	19	1.088	
E261A	.200	28	.616	1.08

E261C	.196	19	1.164	
E262A	.228	29	.548	.96
E262C	.210	19		
E263A	.210	29	.648	.98
E263C	.186	20		
E264A	.166	26	.826	1.12
E264C	.162		1.048	
E265A	.212	28	.768	1.19
E265C	.148	20	1.084	
E266A	.190	28	.676	1.10
E266C	.176		1.084	
E311A	.160	23	1.510	2.70
E311C	.156	28	1.285	2.65
E312A	.235	29	1.430	2.15
E312C	.170	33	1.335	2.05
E313A	.205	37	1.130	1.90
E313C	.205	28	1.700	2.35
E314A	.165	32	1.415	2.20
E314C	.255	34	1.365	2.15
E315A	.140	35	1.025	1.75
E315C	.230	36	1.190	1.85
E316A	.145	30	1.340	2.45
E316C	.150	19	2.44	
E321A	.200	25	2.04	2.90
E321C	.175	21	2.470	
E322A	.135	23	1.965	2.70
E322C	.125	23	1.935	2.90
E323A	.140	26	1.810	2.60
E323C	.185	26	2.185	3.00
E324A	.175	29	2.09	3.00
E324C	.165	30	1.945	2.90
E325A	.170	26	2.100	2.80
E325C	.110	26	1.80	2.80
E326A	.130	24	1.480	2.90
E326C	.160	22	1.830	2.90
E331A	.190	21	2.101	2.80
E331C	.145	20	2.530	
E332A	.170	23	1.885	2.70
E332C	.155	22	2.170	3.00
E333A	.155	35	1.085	1.90
E333C			1.905	
E334A	.165	27	1.705	2.50
E334C	.165	26	2.165	2.16
E335A	.150	28	1.50	2.10
E335C	.180	27	1.65	2.40
E336A	.140	25	1.46	2.70
E336C	.160	23	1.69	2.60
E341A	.180	28	.980	1.90
E341C	.135	21	1.235	2.30

E342A	.125		1.02	1.90
E342C	.170	23	1.830	2.70
E343A	.135	25	1.92	2.60
E343C	.200	23	1.860	2.50
E344A	.175	36	1.03	1.70
E344C	.210	22	2.385	3.00
E345A	.210	22	1.55	2.30
E345C	.160	23	1.375	2.00
E346A	.135	28	1.04	1.90
E346C	.150	22	1.64	2.50
E351A	.180	29	1.185	2.10
E351C	.230	35	1.235	2.30
E352A	.190	26	1.785	2.50
E352C	.240	18		
E353A	.200	33	1.22	2.10
E353C	.245	32	1.65	2.60
E354A	.160	33	.960	1.70
E354C	.200	18	2.90	
E355A	.185	39	1.04	1.80
E355C	.205	32	1.475	2.40
E356A	.155	23	1.420	2.50
E356C	.180	19		
E361A	.200	22	1.735	2.60
E361C	.130	29	1.270	2.30
E362A	.185	43	.855	1.90
E362C	.125	29	1.215	2.10
E363A	.170	34	1.210	1.90
E363C	.215	19		
E364A	.160	30	1.30	2.00
E364C	.150	33	1.260	2.00
E365A	.145	23	2.185	2.90
E365C	.155	18	3.050	
E366A	.170	36	.885	1.90
E366C	.210		2.80	

CTIME = Control Valve Opening Time (sec)
IBKPAA = Initial Boom Pressure (kPa absolute)
CVOTIME = Check-Valve Opening Time (sec)
SSTIME = Steady-State Flow Time (sec)

TEST ONE

TURN-OFF

EXPERIMENT	CTIME	IBKPAA	CVCTIME	SSTIME
E111B	.158	455	.452	.546
E111D	.164	455	.470	.662
E112B	.150	455	.442	.600
E112D	.140	455	.490	.604
E113B	.226	448	.520	.668
E113D	.174	455	.516	.636
E114B	.172	448	.526	.730
E114D	.174	455	.454	.614
E115B	.164	462	.480	.610
E115D	.184	462	.510	.626
E116B	.178	455	.416	.560
E116D	.166	455	.366	.540
E121B	.180	448	.280	.434
E121D	.176	455	.258	.398
E122B	.164	455	.268	.402
E122D	.180	455	.288	.414
E123B	.192	455	.372	.528
E123D	.182	448	.392	.560
E124B	.212	448	.320	.492
E124D	.192	455	.376	.548
E125B	.206	455	.334	.566
E125D	.166	448	.424	.686
E126B	.162	448	.316	.452
E126D	.180	441	.346	.578
E131B	.214	455	.292	.364
E131D	.222	441	.276	.346
E132B	.180	448	.286	.406
E132D	.200	455	.292	.372
E133B	.214	455	.272	.384
E133D	.200	448	.276	.340
E134B	.194	441	.318	.580
E134D	.178	441	.300	.372
E135B	.214	455	.260	.348
E135D	.204	448	.264	.334
E136B	.212	441	.254	.334

E136D	.176	441	.244	.334
E141B	.176	448	.272	.378
E141D	.204	448	.300	.372
E142B	.182	448	.276	.374
E142D	.190	441	.250	.344
E143B	.216	448	.328	.426
E143D	.186	441	.320	.428
E144B	.168	455	.246	.374
E144D	.180	441	.360	.386
E145B	.180	448	.300	.412
E145D	.188	448	.306	.396
E146B	.200	455	.348	.440
E146D	.156		.314	.456
E151B	.196	448	.280	.380
E151D	.200	448	.280	.374
E152B	.176	441	.268	.386
E152D	.174	448	.264	.372
E153B	.196	448	.264	.438
E153D	.158	448	.248	.406
E154B	.200	448	.260	.486
E154D	.380	441	.292	.526
E155B	.182	448	.260	.410
E155D	.184	441	.256	.424
E156B	.216	441	.256	.540
E156D	.158	455	.240	.326
E161B	.202	448	.268	.368
E161D	.174	441	.254	.358
E162B	.174	441	.252	.404
E162D	.210	455	.280	.414
E163B	.192	455	.252	.410
E163D	.208	448	.272	.420
E164B	.246	441	.286	.432
E164D	.188	448	.252	.416
E165B	.206	448	.244	.386
E165D	.196	441	.238	.392
E166B	.192	448	.228	.358
E166D	.214	441	.248	.368
E211B	.152	373		
E211D	.146	386	.386	.600
E212B	.126	379	.242	.368
E212D	.184	379	.226	.364
E213B	.142	386	.254	.472
E213D	.146	379	.214	.400
E214B	.166	379	.266	.404
E214D	.136	373	.248	.378
E215B	.178	386	.234	.352
E215D	.134	386	.246	.356
E216B	.146	386	.220	.374
E216D	.136	393	.212	.428

E221B	.1343	386	.180	.248
E221D	.136	386	.174	.266
E222B	.108	379	.196	.296
E222D	.140	386	.206	.306
E223B	.124	386	.234	.346
E223D	.124	379	.216	.326
E224B	.172	386	.252	.320
E224D	.164	373	.256	.354
E225B	.154	386	.260	.294
E225D	.144	386	.204	.286
E226B	.166	379	.200	.280
E226D	.144	386	.212	.326
E231B	.130	393	.186	.260
E231D	.132	393	.206	.284
E232B	.148	400	.200	.282
E232D	.140	393	.200	.268
E233B	.140	386	.234	.324
E233D	.160	386	.272	.366
E234B	.132	373	.192	.290
E234D	.154	379	.262	.372
E235B	.128	386	.284	.354
E235D	.120	386	.336	.388
E236B	.140	393	.206	.286
E236D	.148	393	.206	.286
E241B	.152	400	.182	.264
E241D	.134	386	.174	.254
E242B	.132	386	.214	.332
E242D	.120	393	.204	.300
E243B	.132	379	.222	.312
E243D	.138	386	.224	.314
E244B	.144	379	.216	.320
E244D	.144	393	.220	.306
E245B	.146	393	.204	.288
E245D	.136	386	.212	.306
E246B	.172	393	.214	.288
E246D	.140	393	.216	.310
E251B	.146	393	.186	.314
E251D	.142	393	.160	.330
E252B	.126	393	.180	.352
E252D	.132	393	.216	.352
E254B	.134	379	.174	.314
E253D	.164	379	.220	.366
E254B	.134	386	.248	.348
E254D	.148	379	.252	.360
E255B	.122	386	.172	.328
E255D	.142	386	.180	.340
E256B	.156	393	.180	.302
E256D	.128	393	.200	.382
E261B	.154	393	.242	.380

E261D	.132	386	.248	.436
E262B	.166	379	.184	.328
E262D	.156	386	.190	.330
E263B	.156	379	.194	.386
E263D	.190	386	.252	.396
E264B	.172	386	.202	.388
E264D	.158	386	.206	.376
E265B	.146	386	.194	.330
E265D	.154	386	.194	.326
E266B	.158	386	.198	.360
E266D	.126	393	.194	.328
E311B	.160	324	.246	.368
E311D	.204	324	.246	.394
E312B	.126	311	.276	.410
E312D	.180	311	.292	.434
E313B	.120	311	.254	.408
E313D	.188	304	.284	.426
E314B	.156	304	.324	.456
E314D				
E315B	.140	317	.254	.388
E315D	.142	317	.276	.402
E316B	.118	324	.246	.346
E316D	.132	317	.256	.368
E321B	.148	311	.308	.616
E321D	.144	317	.216	.400
E322B	.168	311	.268	.460
E322D	.152	311	.286	.464
E323B	.134	311	.254	.464
E323D	.144	317	.272	.476
E324B	.152	311	.272	.536
E324D	.140	311	.356	.546
E325B	.142	304	.240	.472
E325D	.160	317	.254	.432
E326B	.130	324	.242	.426
E326D	.122	324	.256	.434
E331B	.160	311	.240	.362
E331D	.126	317	.244	.386
E332B	.152	311	.264	.396
E332D	.126	317	.294	.406
E333B	.140	311	.286	.400
E333D	.148	317	.308	.434
E334B	.148	311	.290	.400
E334D	.156	324	.312	.434
E335B	.140	324	.244	.376
E335D	.186	311	.252	.382
E336B	.164	317	.232	.330
E336D	.138	311	.226	.342
E341B	.180	311	.166	.278
E341D	.144	311	.176	.264

E342B	.146	331	.266	.396
E342D	.120	311	.200	.316
E343B	.122	304	.196	.320
E343D	.142	317	.226	.336
E344B	.120	311	.274	.400
E344D	.148	317	.300	.416
E345B	.122	311	.186	.278
E345D	.124	324	.178	.282
E346B	.116	331	.214	.326
E346D	.124	338	.228	.334
E352B	.114	317	.266	.480
E352D	.149	317	.314	.568
E353B	.146	304	.270	.512
E351B	.146	324	.222	.356
E351D	.152	317	.254	.428
E353D	.156	311	.314	.546
E354B	.128	324	.200	.386
E354D	.140	324	.240	.470
E355B	.138	324	.252	.486
E355D	.140	317	.308	.556
E356B	.162	331	.228	.390
E356D	.132	331	.272	.320
E361B	.128	324	.196	.344
E361D	.186	331	.238	.380
E362B	.106	304	.226	.424
E362D	.146	324	.236	.416
E363B	.140	304	.314	.486
E363D	.150	324	.346	.520
E364B	.174	317	.254	.474
E364D	.126	331	.334	.536
E365B	.144	311	.278	.446
E365D	.140	331	.272	.320
E366B	.134	311	.206	.352
E366D	.126	317	.200	.436

CTIME = Control Valve Opening Time (sec)
IBKPAA = Initial Boom Pressure (kPa absolute)
CVCTIME = Check-Valve Closure Time (sec)
SSTIME = Steady-State Flow Stoppage Time (sec)

TEST TWO

TURN-ON

EXPERIMENT	CTIME	IBKPAA	CVOTIME	SSTIME
E411A	.304	455	.645	
E411C	.350	455	.782	
E412A	.238	455	.484	
E412C	.236	448	.678	
E413A	.150		.170	
E413C	.224		.254	
E414A	.514	441	.382	
E414C	.460	448	.380	
E421A	.220	386	1.610	
E421C	.235	386	1.380	
E422A	.250	386	1.355	
E422C	.260	393	.960	
E423A	.235	386	.940	
E423C	.210	393	.915	
E424A	.160	386	.480	
E424C	.220	393	1.590	
E431A	.165	317	2.150	3.00
E431C	.165	324	2.100	3.00
E432A	.200	331	1.750	2.80
E432C	.160	324	1.586	2.70
E433A	.165	324	.175	2.20
E433C	.185	324	1.470	2.40
E434A	.130	317	.355	0.70
E434C	.130	331	.325	0.70

CTIME = Control Valve Opening Time (sec)
IBKPAA = Initial Boom Pressure (kPa absolute)
CVTIME = Check-Valve Opening Time (sec)
SSTIME = Steady-State Flow Time (sec)

TEST TWO

TURN-OFF

EXPERIMENT	CTIME	IBKPAA	CVCTIME	SSTIME
E411B	.190	441	1.25	1.25
E411D	.212	441	1.25	1.25
E412B	.270	441	1.25	1.25
E412D	.194	441	.732	.954
E413B	.214	441	.180	.296
E413D				
E414B	.196	428	.136	.254
E414D	.294	441	.190	.300
E421B	.170	393	1.25	1.765
E421D	.220	393	1.06	1.38
E422B	.180	400	.620	.885
E422D	.145	386	.605	.795
E423B	.160	386	.450	.615
E423D	.185	386	.420	.555
E424B	.180	379	.120	.200
E424D	.160	386	.110	.215
E431B	.130	331	.890	1.04
E431D	.150	331	.335	.970
E432B	.150	317	.565	.680
E432D	.180	331	.620	.705
E433B	.180	317	.250	.400
E433D	.130	317	.250	.335
E434B	.115	304	.075	.135
E434D	.190	304	.085	.165

CTIME = Control Valve Closure Time (sec)
IBKPAA = Initial Boom Pressure (kPa absolute)
CVCTIME = Check-Valve Closure Time (sec)
SSTIME = Steady-State Stoppage Time (sec)

APPENDIX B

LIST OF COMPANIES SUPPLYING EQUIPMENT

Agrinautics
1333 Patric Lane
Las Vegas, NV 89119

Apple Computer, Inc.
20525 Mariani Avenue
Cupertino, CA 95014

Delevan Corporation
811 Fourth Street
West DesMoines, IA 50265

Interactive Microwave, Inc.
P.O. Box 771
State College, PA 16801-0771

Interactive Structures, Inc.
146 Montgomery Ave.
P.O. Box 404
Bala Cynwyd, PA 19004

International Business Machines Corporation
Boca Raton, FL 33432

Lincoln Electric Company
Cleveland, OH 44117

SAS Institute Inc.
P.O. Box 10066
Raleigh, NC 27605

Sentra Systems, Inc.
45 Nagog Park
Acton, MA 01720

Spectrol Electronics
17070 East Gate Avenue
City of Industry, CA 91342

Spraying Systems Co.
N. Avenue at Schmale Road
Wheaton, IL 60187

Tektronics, Inc.
P.O. Box 500, V#-314
Beaverton, OR 97077

Transland, Inc.
24511 Frampton Avenue
Harbor City, CA 90710

VITA

Cam Pekrul

Candidate for the Degree of

Master of Science

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Major Field: Agricultural Engineering

Biographical:

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