BRAKE FLUID IN ANTI-LOCK BRAKE SYSTEM EVALUATOR, RIG DESIGN

INTERIM REPORT
GVSC No. 493

By
Kira L. Turner

GVSC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

For
Zackery Schroeder

Force Projection Technologies,
Warren, Michigan

Contract No. W56HZV-15-C-0030 (WD24)

March 2020

Disclaimers

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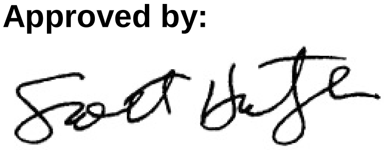

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Southwest Research Institute

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14. ABSTRACT

This task developed a method to determine the compatibility of brake fluid in an anti-lock braking system under different environments. A laboratory based test rig was designed and built to mimic an anti-lock braking system environment and to provide a close approximation to field testing. The test rig was tested and proved to have the ability to simulate an anti-lock braking event at 200 °C and ambient (25 °C) temperatures. The test rig was not able to produce the braking event at -55 °C, but was functional at -40 °C.

15. SUBJECT TERMS

Hydraulic Power Brake, Anti-lock, Brake Fluid

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FOREWORD/ACKNOWLEDGMENTS

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The authors would like to acknowledge the contribution of the GFLRF technical and administrative support staff.

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

Figure **Page**

List of Figures from Appendices

Figure **Page**

LIST OF TABLES

Tables **Page**

ACRONYMS AND ABBREVIATIONS

ABS	Anti-lock Brake System
°C	Degrees Celsius
HCU	Hydraulic Control Unit
CCDC	Combat Capabilities Development Command
GFLRF	GVSC Fuels and Lubricants Research Facility
GVSC	Ground Vehicle Systems Center
HPB	Hydraulic Power Brake
Hz	Hertz
NDA	Non-Disclosure Agreement
psi	Pounds per square inch
psi/min	Pounds per square inch per minute
psi/sec	Pounds per square inch per second
psig	Pounds per square inch, gauge
PWM	Pulse Width Modulation
sec	Seconds
SwRI	Southwest Research Institute

1.0 BACKGROUND

This task developed a laboratory apparatus to test the compatibility of brake fluid with a commercial heavy-duty anti-lock brake system. Heavy-duty hydraulic anti-lock brake systems utilize pumps, accumulators, and high-speed solenoid valves to regulate hydraulic braking pressure to individual wheel braking circuits. The test rig was designed to mimic the components and environment of what is found in field testing.

2.0 INTRODUCTION AND OBJECTIVES

The objective of this task was to develop a laboratory-based apparatus (hereafter “test rig”) which can differentiate between brake fluids that are compatible with an anti-lock braking system and those which are not. The test rig was designed for a wide range of testing capabilities to evaluate the life and performance of brake fluids. The test rig was also set up to provide a testing environment that is a close approximation of field testing. The test rig components included pumping elements and solenoid valves representative of what is found in heavy-duty commercial anti-lock braking systems. These components were designed to be easily removed and disassembled from the test rig for post-test wear analysis.

A control software was developed to simulate an anti-lock braking event by controlling the pump and solenoid valves. The control strategy aimed to produce system pressures similar to what is seen in real life anti-lock brake events. A test plan was developed and executed to demonstrate the capabilities of the test rig. In addition to the anti-lock braking event, these capabilities included the ability to heat and cool the brake fluid to 200 °C and -55 °C, respectively. The test rig was also tested for the ability to increase the system pressure from ambient to the working pressure in less than 0.2 seconds.

3.0 TEST RIG

3.1 TEST RIG DESIGN AND BUILD

The test rig was modeled after the Hydraulic Power Brake (HPB) unit used in previous testing [1]. The design was simplified by using only one brake circuit and removing the master cylinder. The resulting hydraulic circuit is shown in Figure 1. The circuit consists of two solenoid valves for flow control, a hydraulic accumulator, a pump (motor and pumping element), fluid reservoir, piston assembly, and a relief valve for pressure control.

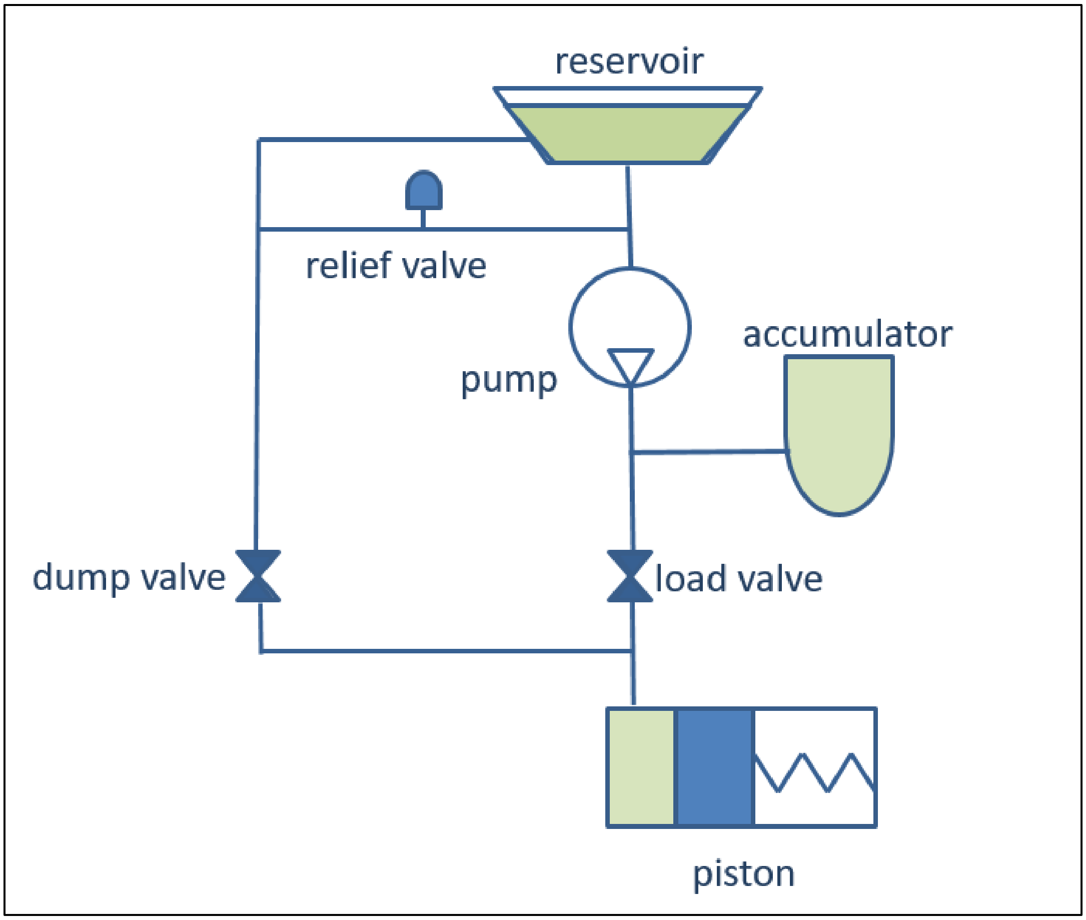

Figure 1. Anti-lock Brake Evaluator Rig Hydraulic Circuit

The pump and motor selected were from the WABCO HPB system, as was the accumulator. The valves chosen were screw in, cartridge style solenoid valves. These valves allow for easy removal and non-destructive post-test wear analysis. For the piston assembly, a Duralast brake caliper was purchased and modified. A list of parts and their respective manufacturers and part numbers is shown in Table 1.

Table 1. Anti-lock Brake Evaluator Rig Parts List

Description	Mfg.	P/N
Load valve	Parker	GS028000N
Dump valve	Parker	GS028000N
Pressure relief valve	Parker	RDH042S30V
Motor	WABCO	S478 407 947 2
Pumping element	WABCO	S478 408 926 2
Reservoir	Dorman	54002
Accumulator	WABCO	S458 501 924 2
Caliper	Duralast	C846
Cartridge heaters	Tempco	HDC0003

The rig assembly consisted of a valve block and piston assembly, both mounted on 1 inch aluminum plate using 80/20 T slot aluminum framing. The reservoir was mounted above the valve block to gravity feed the pump. All components were connected using stainless steel overbraid Teflon lines. Photos of the test rig are shown in Figure 2, Figure 3, and Figure 4.

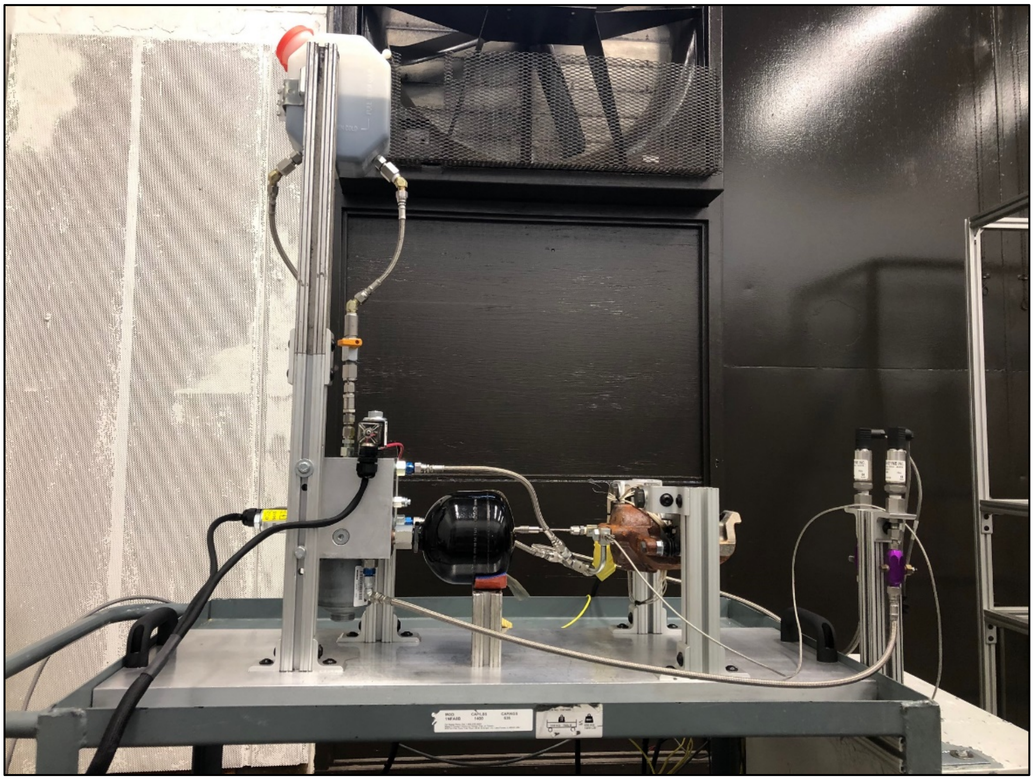

Figure 2. Anti-lock Brake Evaluator Rig Photo 1

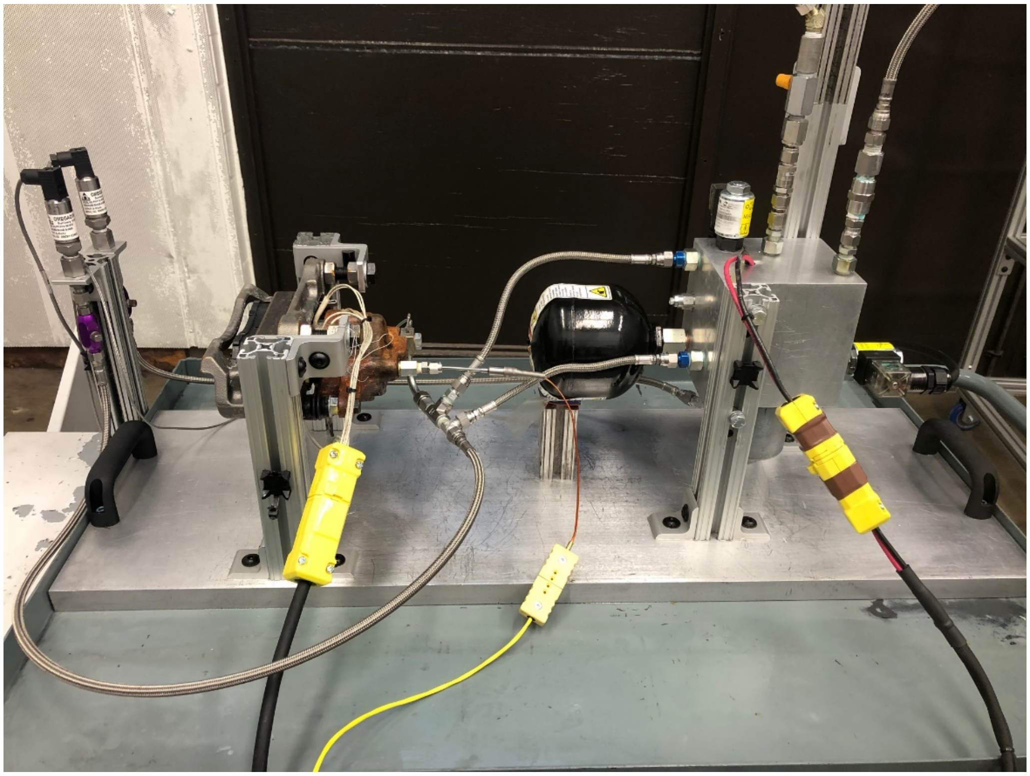

Figure 3. Anti-lock Brake Evaluator Rig Photo 2

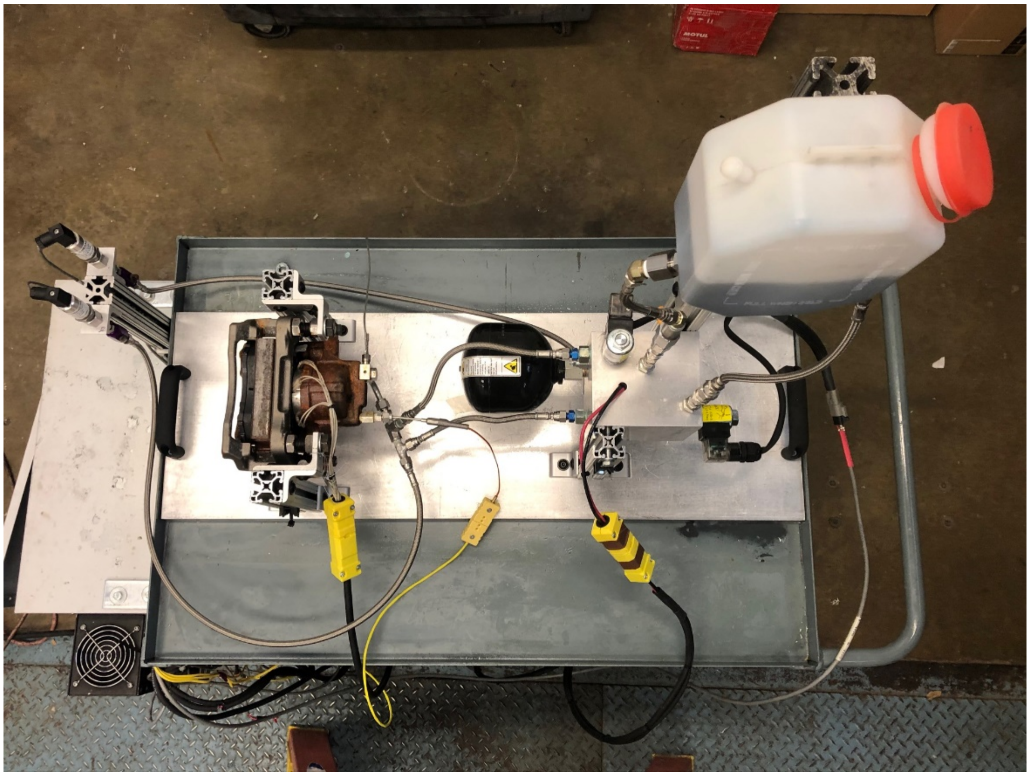

Figure 4. Anti-lock Brake Evaluator Rig Photo 3

The valve block was made using a 5 inch cube of 6061 aluminum which was machined to house the valves, pump, motor, and accumulator. Technical drawings of the valve block are shown in APPENDIX A. The valve block was connected to the piston assembly using stainless steel overbraid Teflon lines.

The caliper was modified by removing the factory piston and replacing it with a machined aluminum piston. Five bores were added to the piston to house half inch cartridge style heaters. This allowed the rig to heat the brake fluid in a manner closest to the real world application, simulating heat from friction during a braking event. Technical drawings of the piston are shown in APPENDIX A. A photo of the caliper and modified piston prior to heater installation is shown in Figure 5.

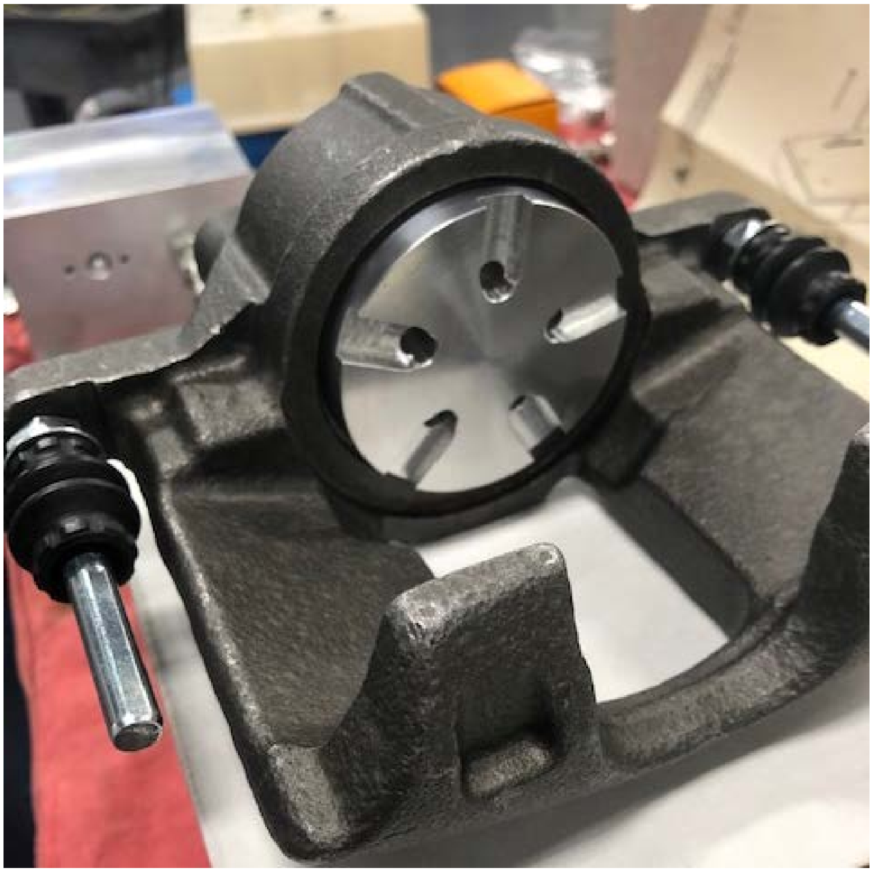

Figure 5. Caliper and Machined Piston

A 0.02 inch flow orifice was installed between the dump valve and the reservoir to slow fluid return to the reservoir.

After approximately 250 hours of run time, the rig developed a leak at the piston. The caliper was disassembled and inspected. The piston was found to have significant wear present. Fretting wear was evident around the circumference of the piston over the travel length of the stroke. Additionally, two spots of galling wear were located on opposite sides of the piston. Photos of the piston are shown in Figure 6 and Figure 7.

Figure 6. Aluminum Piston Side 1

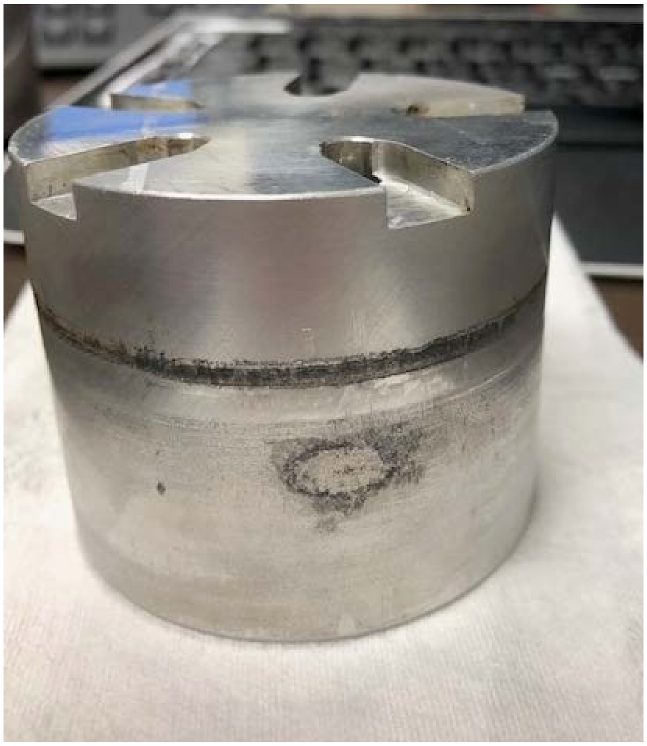

Figure 7. Aluminum Piston Side 2

To attempt to reduce wear, a replacement piston was machined from 304 stainless steel and installed for use with any further testing.

3.2 Operation and Control

The test rig consisted of one braking circuit. The circuit had an electric motor that drove a pumping element to build braking pressure, a gas charged accumulator to store circuit pressure, and two solenoid valves. One of the solenoid valves (the "load" valve) controlled pressure to the brake caliper. The second solenoid valve (the "dump" valve) released brake pressure back to the reservoir. Both valves were normally closed. The circuit also included a pressure relief valve which allowed brake pressure to bypass the caliper and relieve to the reservoir in the case of an over-pressure event. Two pressure transducers were used to monitor both the circuit pressure and the pressure at the caliper, referred to as Pressure 1 (P1) and Pressure 2 (P2), respectively. A thermocouple was inserted into the caliper to measure the temperature of the brake fluid, referred to as Temperature 2 (T2). The instrumentation locations are shown in Figure 8.

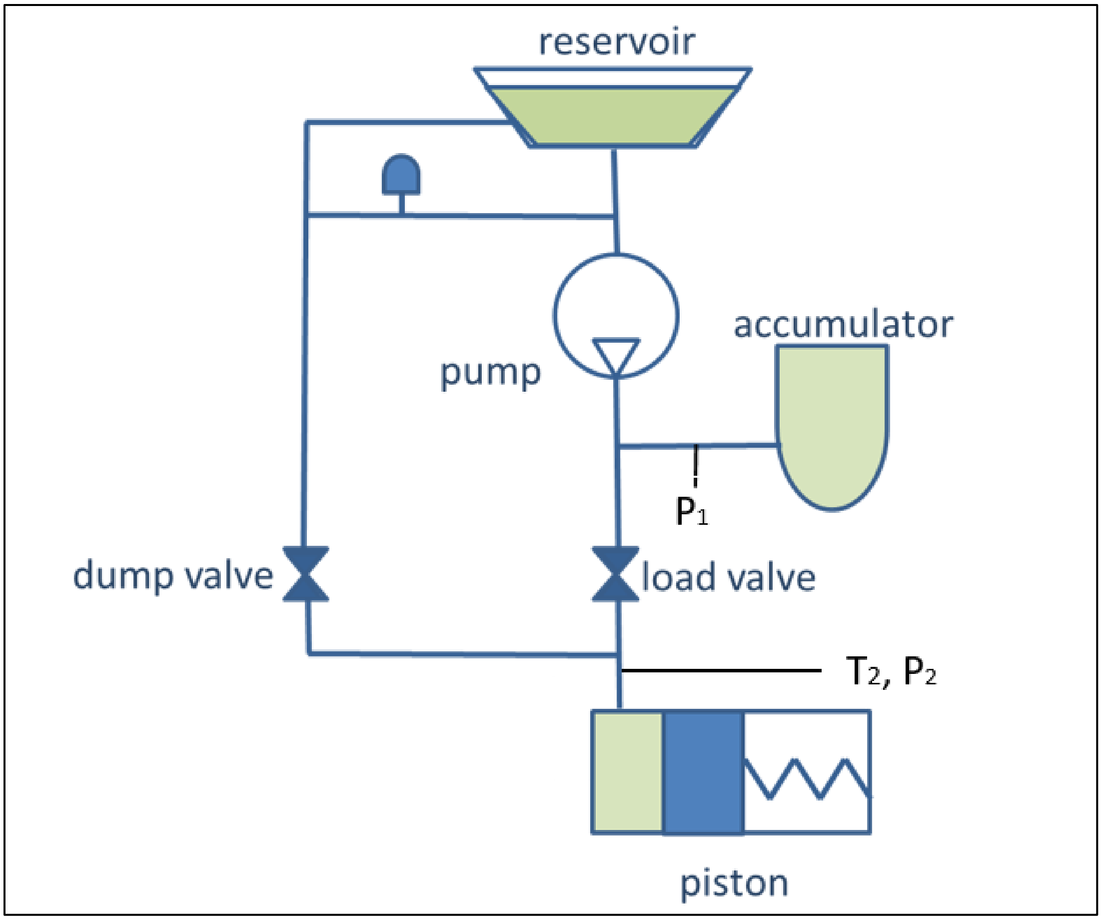

Figure 8. Anti-lock Brake Evaluator Instrumentation Locations

The ABS braking event was defined as one second of steady pressure followed by five seconds of modulating the load and dump valves to simulate anti-lock brake release action, after which all pressure was released from the brake caliper for five seconds. The target pressure at the brake cylinder at the start of the event was 2030 psig. The ABS braking event is shown in Table 2.

Table 2. Anti-lock Brake Event Modes

Mode	Duration	Description
1	1 sec	Apply 2030 psig and hold
2	5 sec	Modulate valves to simulate ABS
3	5 sec	Relieve pressure and hold for pump to recover

To maintain circuit pressure, the pump was turned on with both valves closed to allow the system to reach the target pressure. The control software monitored the pressure, and once the target pressure was reached, the pump was switched off. Throughout the brake event, a lower limit for circuit pressure was established at 1950 psig. When the lower limit was reached, the control software turned the pump on until the circuit pressure was once again 2030 psig.

To begin Mode 1, the load valve was opened to fully pressurize the caliper, and one second elapsed.

Mode 2 was then started, which consisted of the ABS simulation. Based on available data, to simulate real world anti-lock brake action the valves were modulated at a rate of 5 Hz. To accomplish this, a pulse width modulation (PWM) signal was employed for each valve. Each pulse was 200 ms in length, and the actuation timing and duration of each signal was adjustable. A range of timing and durations for each valve were tested, and the best case PWM was chosen. The PWM found to provide best control is shown in Figure 9. The pulse length is 200 ms, with a signal of 1 indicating an energized valve state, and a signal of 0 indicating a de-energized state.

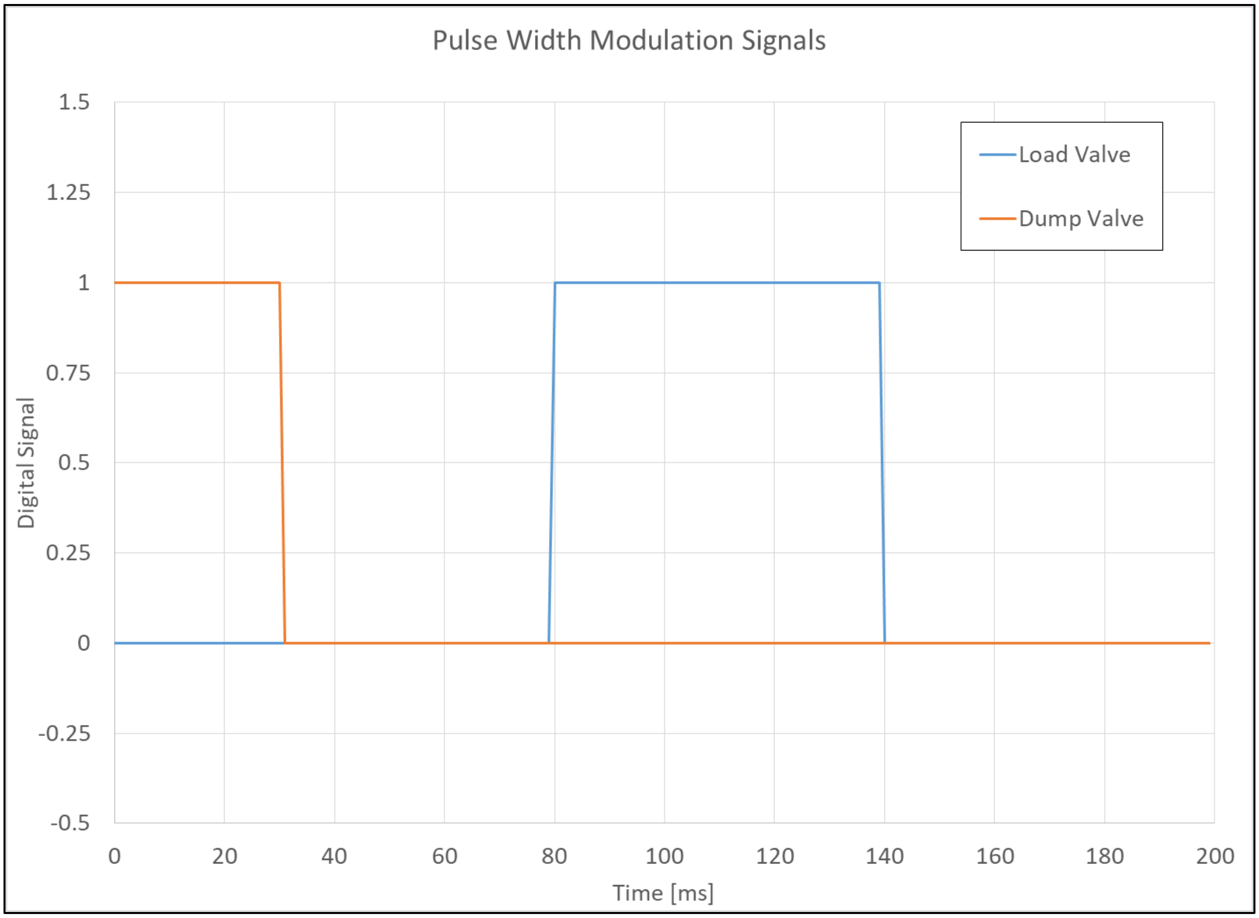

Figure 9. Solenoid Valve Pulse Width Modulation Signals

Finally, during Mode 3 the load valve was closed and the dump valve was opened to allow the caliper pressure to fall to ambient. It was held in this state for 5 seconds. The entire brake event is 11 seconds in length. Data from one brake cycle is shown in Figure 10.

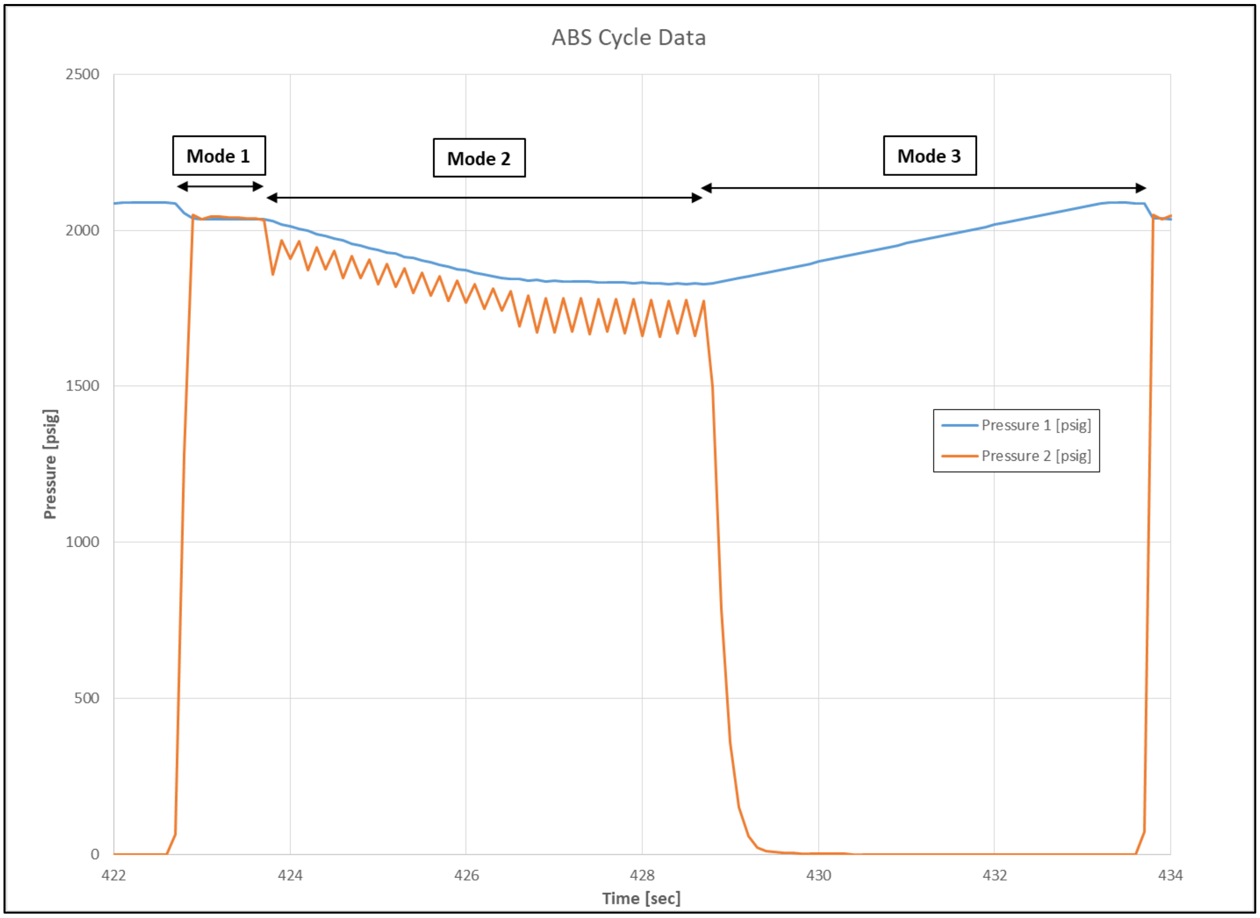

Figure 10. Anti-lock Brake Cycle Data – 1 Cycle

The brake event and subsequent testing were to be run at three temperatures: -55 °C, 25 °C, and 200 °C. Two separate methods were employed for cooling and heating. For heating, the five cartridge heaters installed in the cylinder of the caliper were energized. The control software turned on the heaters until the fluid temperature reached an upper limit, at which time they turned off. Once the fluid temperature fell to a lower temperature limit, the heaters were once again turned on.

For cooling, the entire rig was placed in an environmental chamber and cooled until the fluid temperature reached -55 °C.

4.0 CAPABILITY DEMONSTRATION

4.1 LEAK CHECK

The test rig was charged with brake fluid and pressurized to an intermediate pressure of 1000 psig to check for leaks. No visible leaks were seen. After returning to ambient pressure, the control software was used to pressurize the system while monitoring pressure for decay. Circuit pressure (Pressure 1) was brought to approximately 2100 psig and the pump was turned off. The load valve was then opened to pressurize the system through the caliper and up to the dump valve (Pressure 2). With the pump off, the pressures were recorded for five minutes. The leak check data is shown in Figure 11.

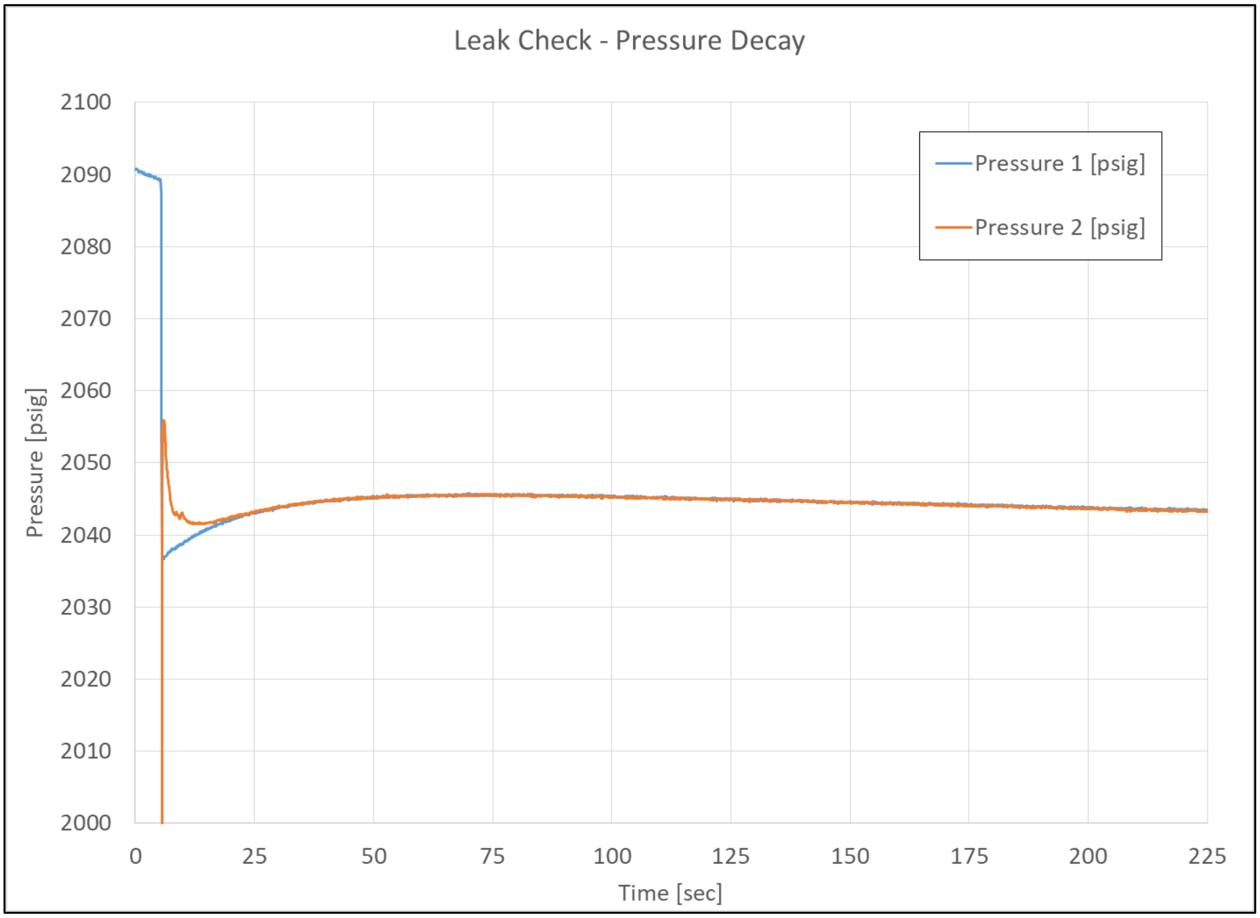

Figure 11. System Leak Check

Over a two minute period, Pressure 1 decayed 1.65 psi, resulting in a pressure decay rate of 0.83 psi/min. Pressure 2 had a decay of 1.96 psi over the same period, for a decay rate of 0.98 psi/min. Table 3 shows the pressure decay data from the system leak check.

Table 3. System Leak Check – Pressure Decay Data

	Time, initial	Time, final	Pressure, initial	Pressure, final	Pressure Change	Decay Rate	Decay Rate
	[sec]	[sec]	[psig]	[psig]	[psi]	[psi/sec]	[psi/min]
Pressure 1	80	200	2045.5	2043.9	-1.65	0.01	0.83
Pressure 2	80	200	2045.6	2043.6	-1.96	0.02	0.98

4.2 ABS BRAKING EVENT

The ABS braking event was previously defined as one second of steady pressure, five seconds of modulating the load and dump valves to simulate anti-lock brake release action, followed by the release of all pressure from the brake caliper for five seconds. This cycle was run using the control software for 60 minutes and recorded at 10 Hz. At 1648 seconds into the test, the cycle counter was inadvertently reset to 0 which caused the cycles to pause for approximately 100 seconds. During this time, both Pressure 1 and Pressure 2 were held at the working pressure of 2030 psig. The cycles were resumed and the test carried out to completion. Each individual cycle was reviewed and found to be satisfactory. The resultant pressure traces of the 60 minute test are shown in Figure 12. Figure 13 shows a three minute snapshot of the 60 minute test for better resolution.

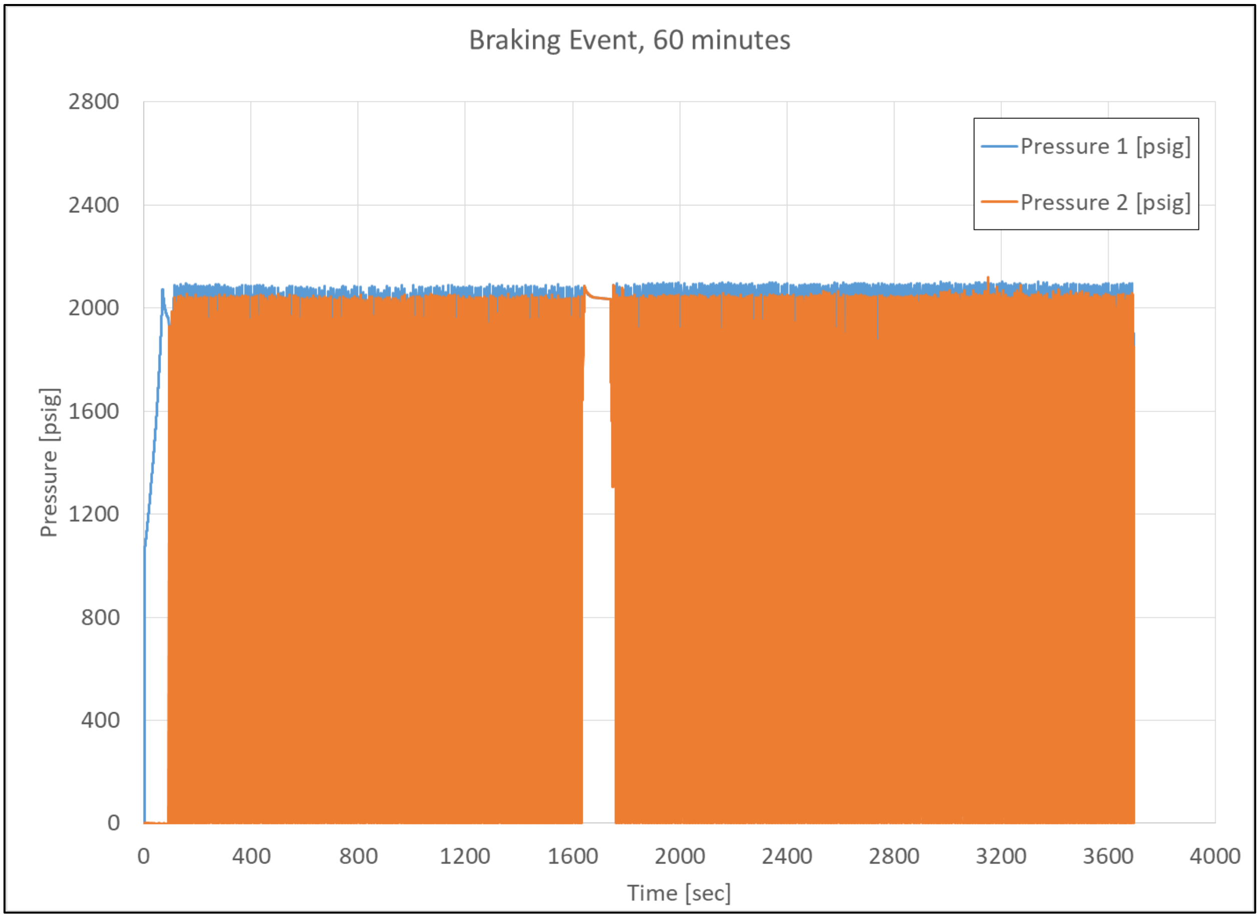

Figure 12. Anti-lock Brake Event, 60 minutes

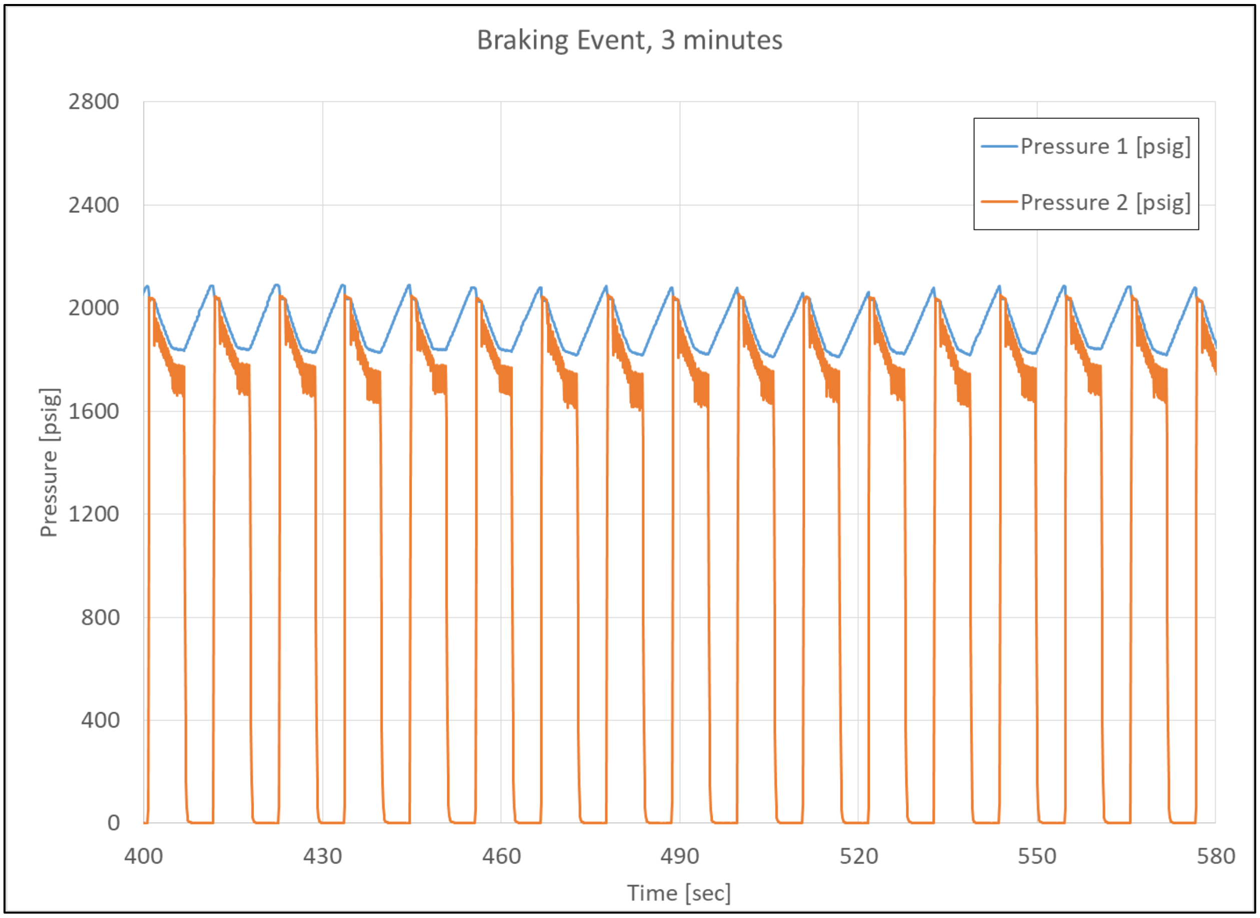

Figure 13. Anti-lock Brake Event, 3 minutes

To better evaluate the cycle data for validation, the data was sampled at 2000 Hz for a portion of the test. This greatly reduced the aliasing seen in the 10 Hz data. However, due to the large files produced by the high sampling frequency, the high speed data option was only used to validate data for short periods of time during testing. Three cycles recorded at the 2000 Hz data rate are shown in Figure 14.

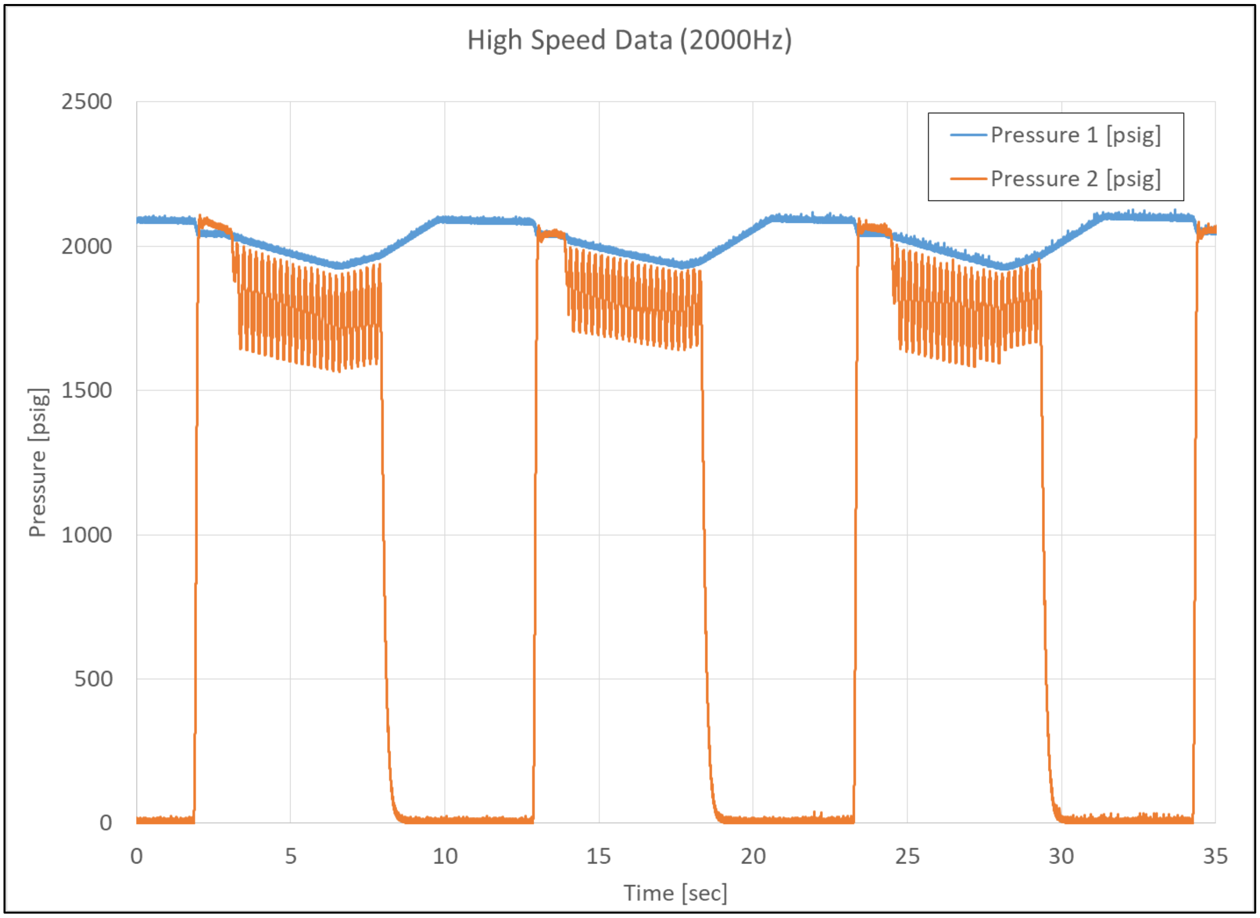

Figure 14. Anti-lock Brake Event, High Speed Data, 3 Cycles

4.3 PRESSURE RISE

At the beginning of Mode 1 of the ABS Braking Event, the load valve opened fully to pressurize the caliper with brake fluid to a desired 2030 psig. To determine the duration of the pressure rise from 0 psig (ambient) to working pressure (2030 psig), five cycles of high speed data were analyzed. These cycles are shown in Figure 15 and labeled A through E.

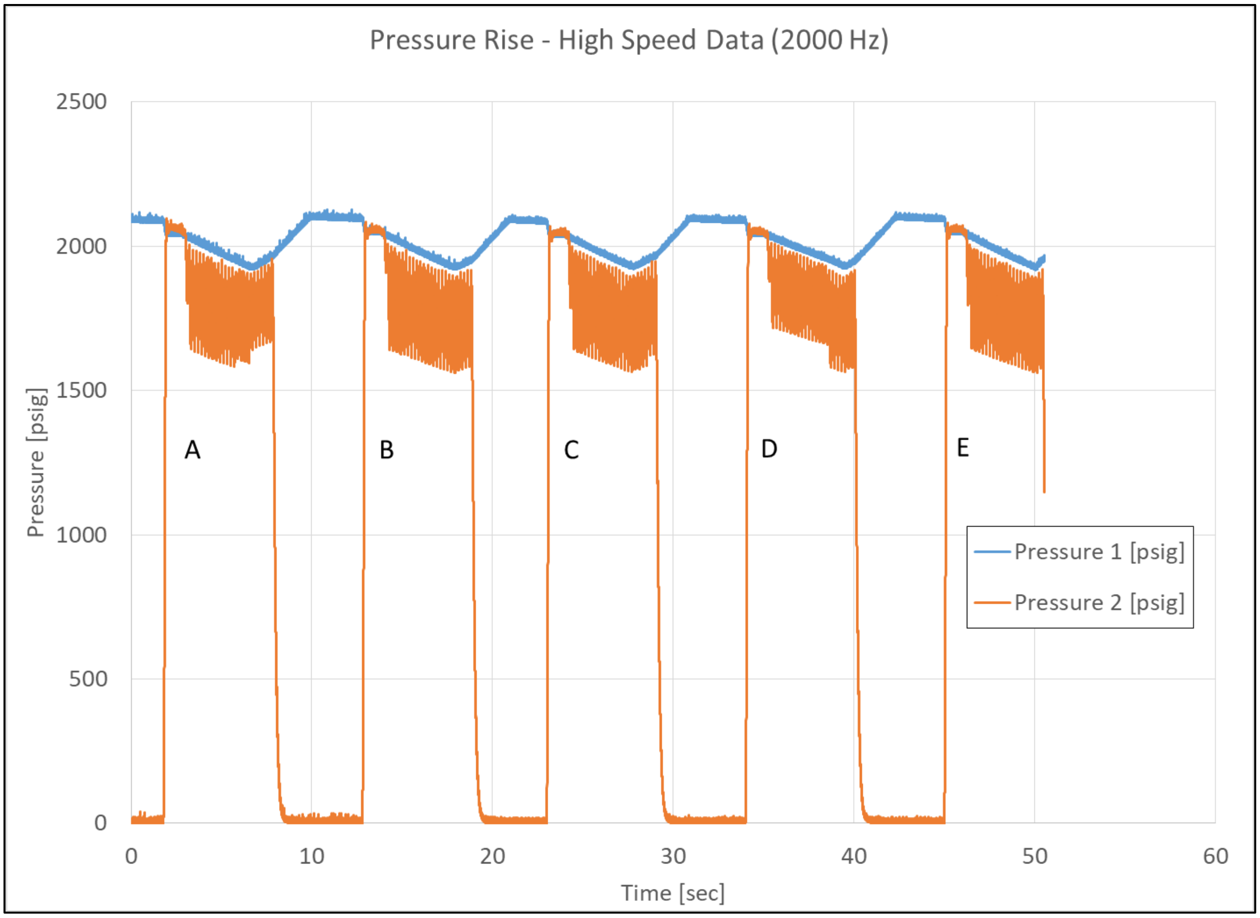

Figure 15. Anti-lock Brake Event, High Speed Data for Pressure Rise

Based on the data from Mode 1 of these five cycles, the rig took 0.170 seconds on average to raise the pressure at the caliper from 0 psig to 2030 psig. The individual cycle data can be found in Table 4.

Table 4. System Pressure Rise Data

Cycle	Pressure, initial	Pressure, final	Time, initial	Time, final	Duration
-	[psig]	[psig]	[sec]	[sec]	[sec]
A	0.00	2034.02	1.777	1.945	0.168
B	0.05	2034.62	12.783	12.952	0.169
C	0.15	2034.27	22.978	23.152	0.174
D	0.00	2033.88	33.981	34.155	0.174
E	0.10	2033.28	44.978	45.148	0.170
				Average	0.171
				St. Dev.	0.003

4.4 Cooling

The entire rig (not including electronics) was placed in an ESPEC Platinous EPX environmental chamber for cooling. The control temperature of the environmental chamber was set to -57 °C, and the temperature was recorded until the fluid temperature reached -55 °C. The temperature profile over time during cooling is shown in Figure 16.

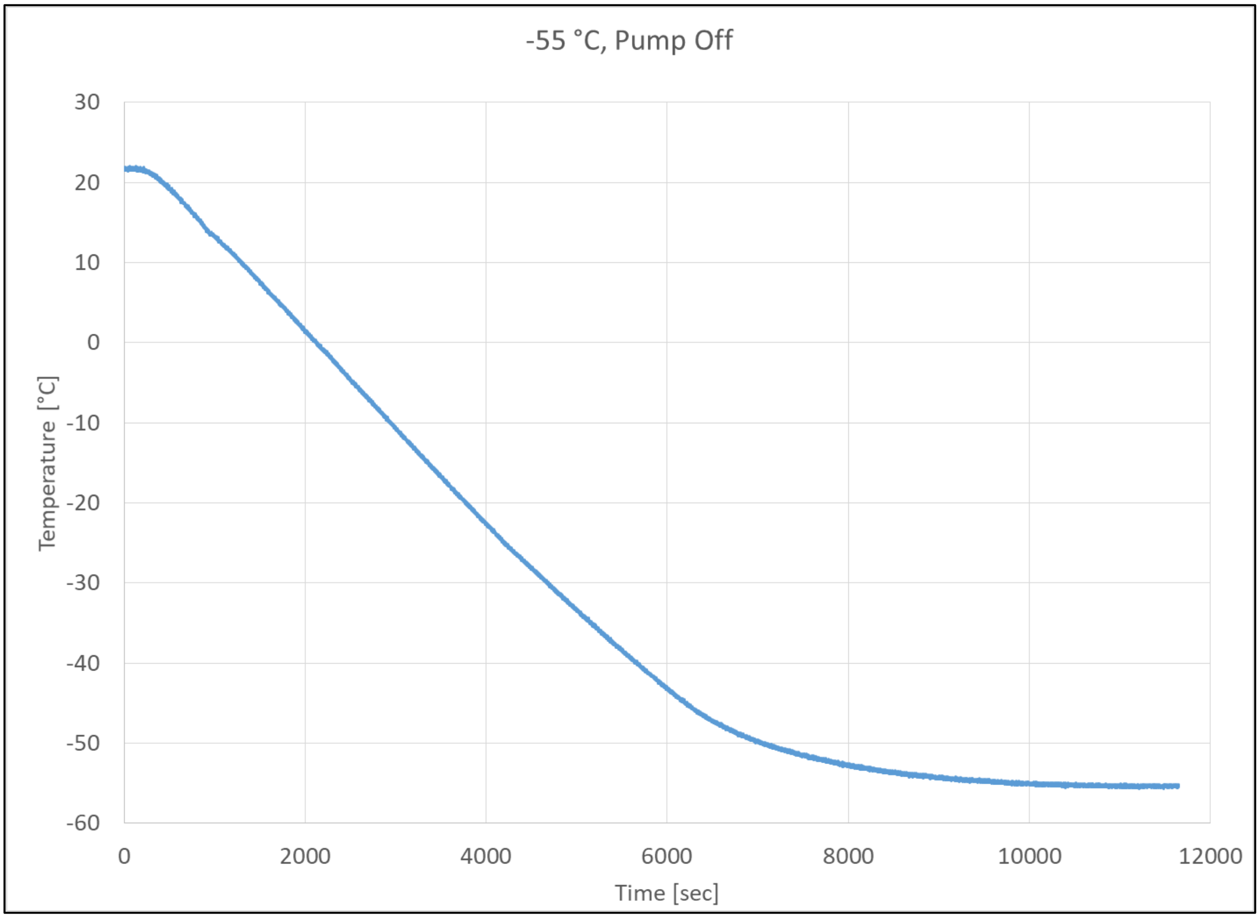

Figure 16. Cooling Validation, -55 °C, Pump Off

Once the brake fluid in the caliper reached -55 °C, the anti-lock brake event control was turned on. Although the pump motor turned on, very little pressure was able to build inside the system. The pump was run for 40 seconds and a pressure of approximately 13 psig was reached. An inspection of the reservoir showed the brake fluid had thickened considerably. The pump was unable to pump the viscous fluid into the accumulator and build pressure. The pressure profile of the system while the pump was on is shown in Figure 17.

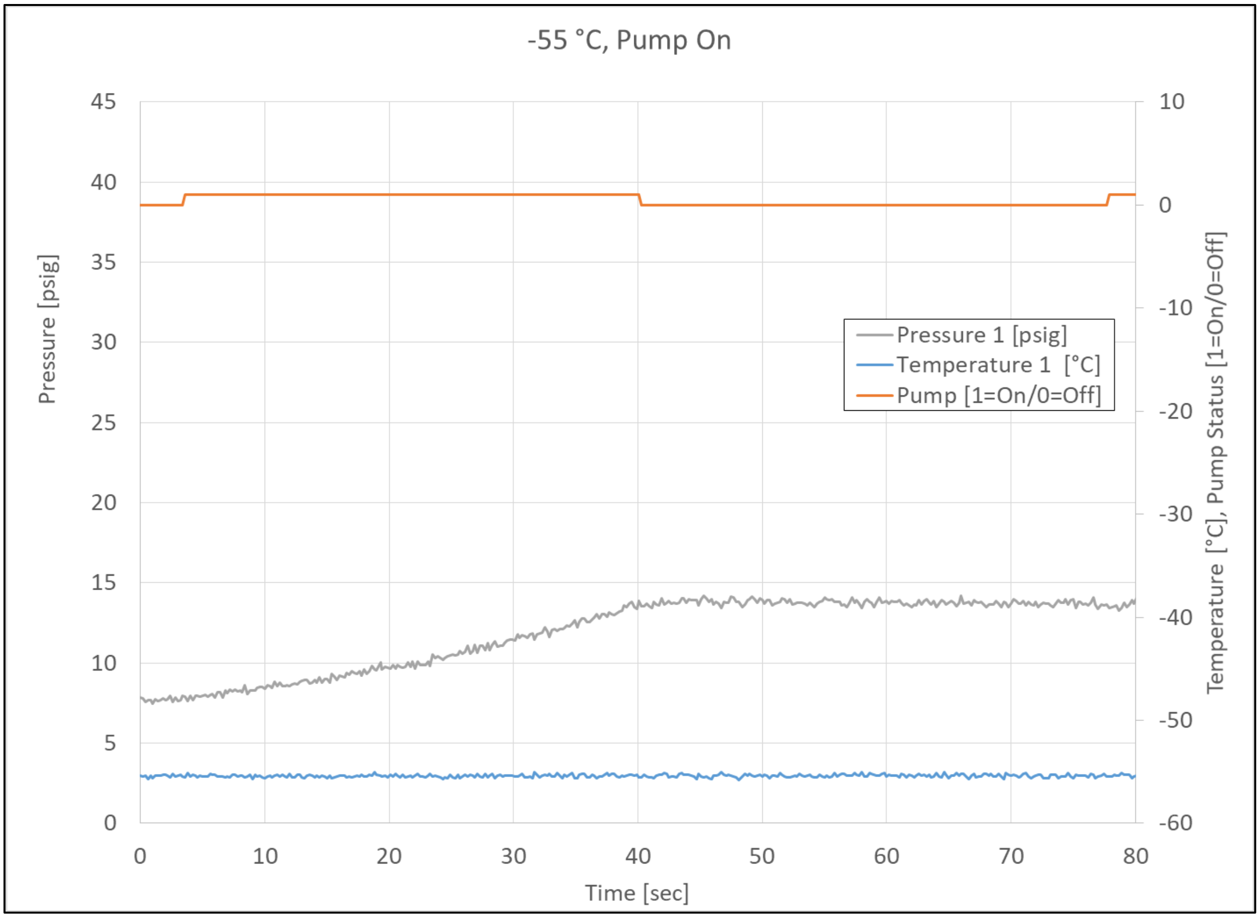

Figure 17. Cooling Validation, -55 °C, Pump On

The temperature in the environmental chamber was increased incrementally by 5 °C and the motor was turned on to check for fluid pressure. At -25 °C, the pump began to move the fluid and produced a pressure of approximately 1300 psig. The ABS braking event control was turned on. The results are shown in Figure 18. The test rig exhibited a different pressure profile than when run at ambient or 200 °C. The system pressure (Pressure 1) fell much quicker than previously during Mode 2 of the brake cycle. This is assumed to be due to less fluid stored in the accumulator at the lower pressure. The fluid seemed to have difficulty moving through the dump valves, with pressure at the caliper falling at a slower rate. The high viscosity of the brake fluid at -55 °C may be incompatible with the valves.

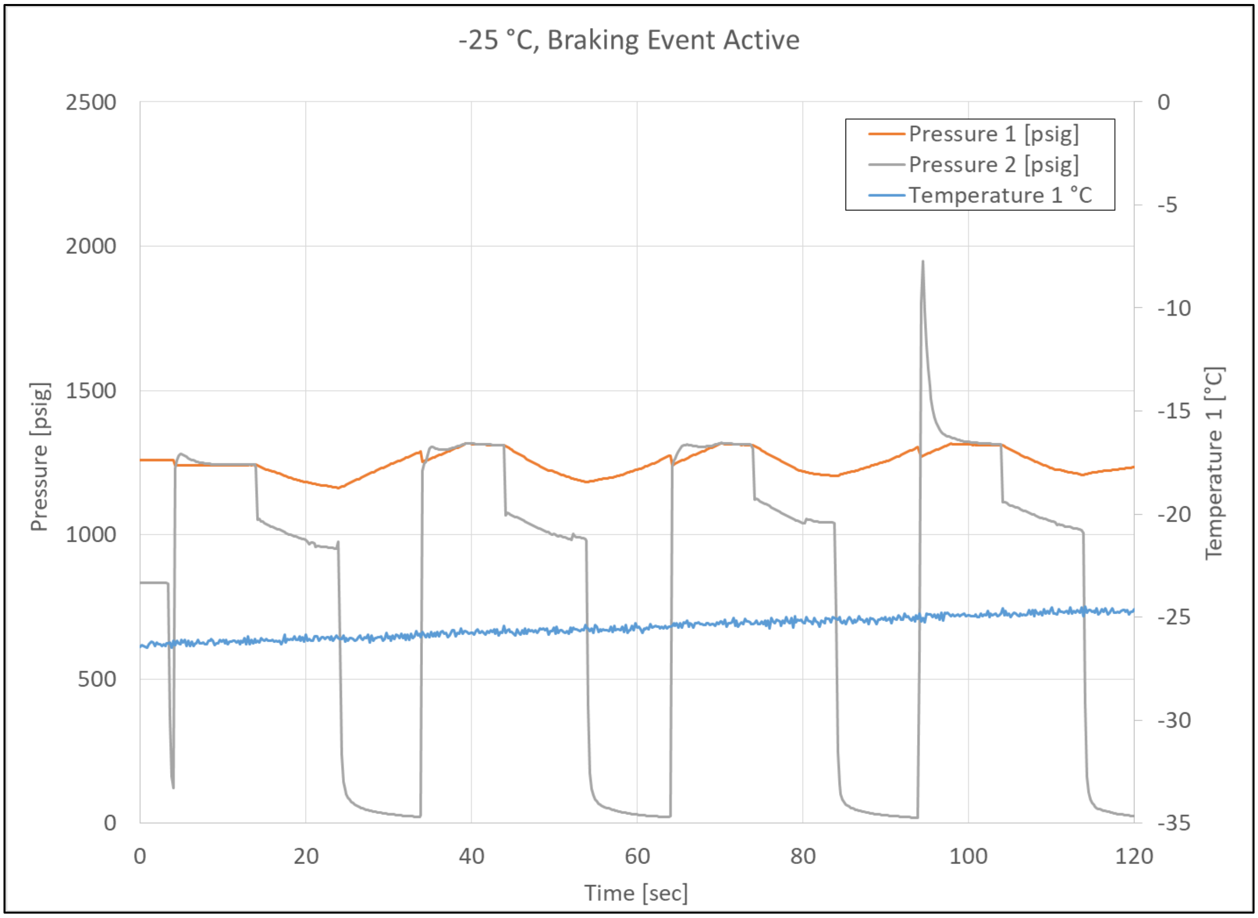

Figure 18. Cooling Validation, -25 °C, ABS Braking Event Running

Based on these results, a new low target temperature was specified at -40 °C. Additionally, the rig was cooled while the ABS Braking Event was active. This eliminated the need for the pump to overcome the initial suction of the more viscous fluid at the cold temperature. The rig was placed in the environmental chamber and the braking event control was turned on. The environmental chamber was set to -41 °C. The pump, motor, and valves were all operational at the target temperature. However, the algorithm for the brake cycle event proved incompatible with the lower temperature and higher viscosity of the fluid.

The previous method for running the brake cycle was time based, running a set number of pulses before continuing on to the next mode. Due to the increased viscosity of the fluid, the pump could not move the fluid and build pressure in the accumulator in the number of pulses required. This caused the system pressure to slowly decay to well below the set point of 2030 psig.

A new control strategy was introduced to allow for the pump to pressurize the system to the desired set point. The cycle was held in Mode 3 until both the number of pulses and a set pressure were reached. The new control strategy was implemented and the rig run for a second time at -40 °C. Five minutes of the run are shown in Figure 19. The average time of Mode 3 at -40 °C was found to be ~53 seconds. This is ten times longer than Mode 3 when running at ambient or 200 °C and significantly lengthens the cycle time.

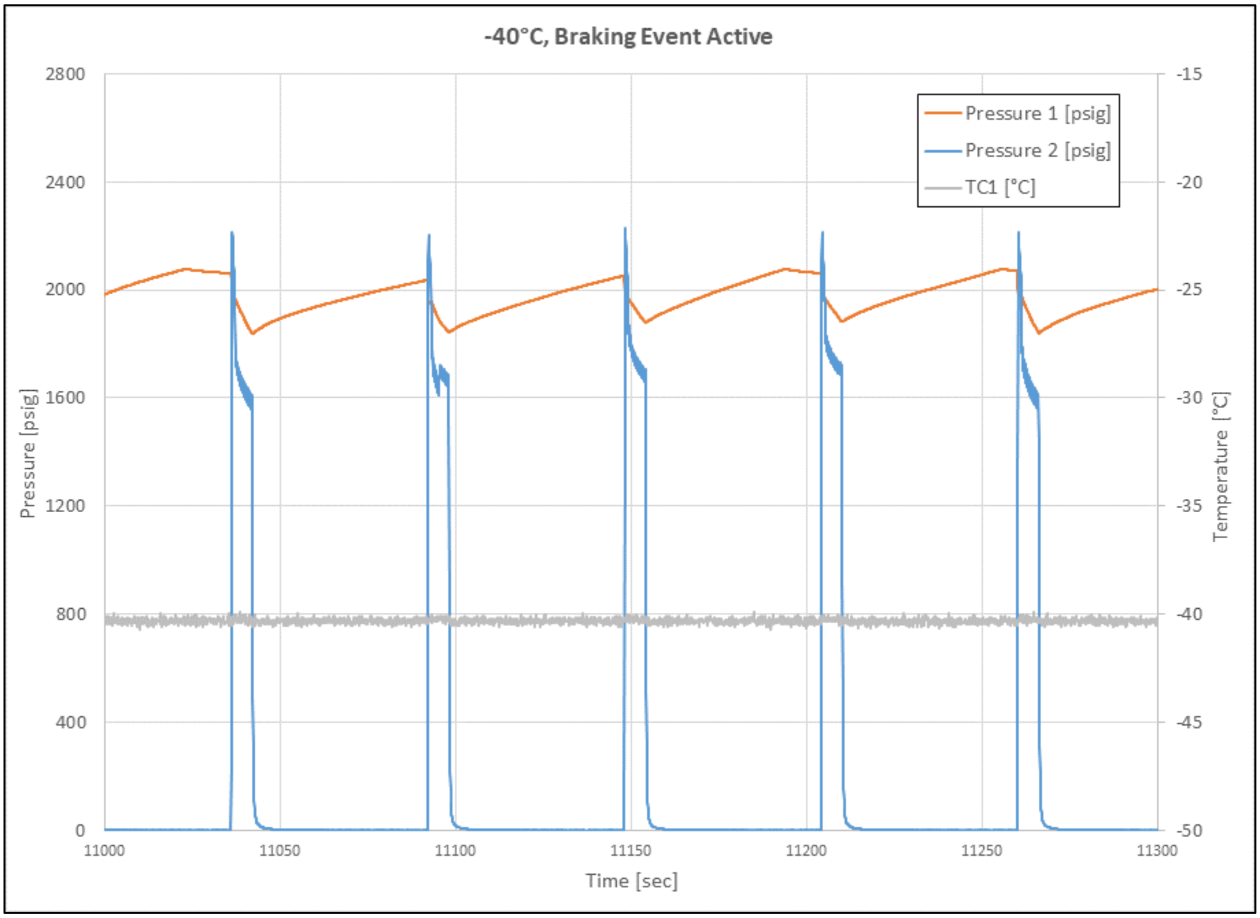

Figure 19. Cooling Validation, -40 °C, ABS Braking Event Running, 5 minutes

High speed data collection of one cycle of the ABS Brake Event at -40 °C is shown in Figure 20.

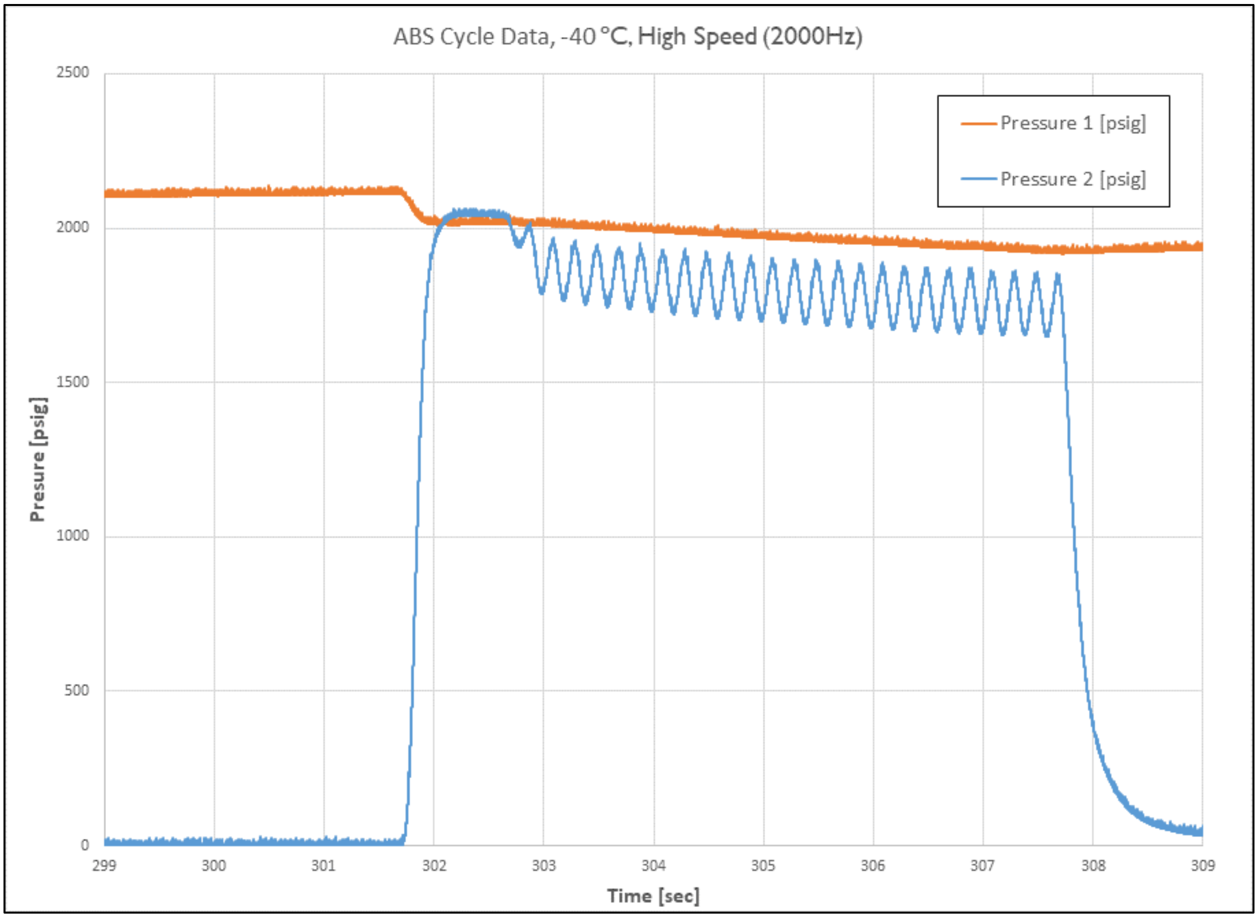

Figure 20. Cooling Validation, -40 °C, High Speed Data

4.5 HEATING

To initially test the heating capability of the rig, the heaters were turned on with the pump turned off and the fluid initially at ambient temperature. The heaters were held on until the fluid in the caliper reached 200 °C. This was repeated a total of three times, and the results are shown in Figure 21.

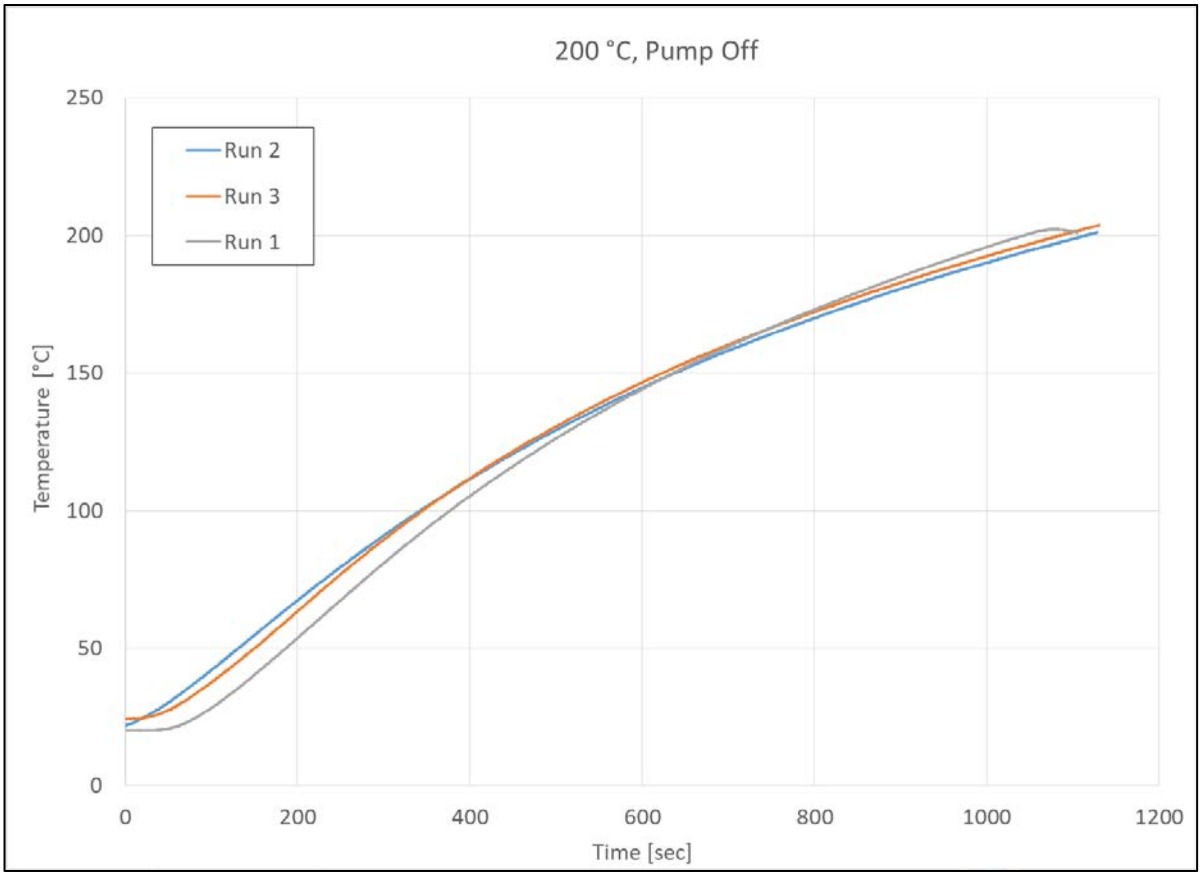

Figure 21. Heating Validation, 200 °C, Pump Off

Once heating capabilities were confirmed, the rig was run with both the heating and braking event control active. The ABS Braking Event as defined previously was run continuously for 60 minutes. The heating control strategy was to energize the heaters until the fluid temperature at the caliper reached an upper limit, at which point the heaters were turned off. When a lower limit was seen by the control software, the heaters were turned on. During the first 1500 seconds of the run, the temperature swings were ±5 °C. At 1500 seconds, the upper and lower temperature limits were tightened to 201 °C and 199.5 °C, respectively. Using the last 2100 seconds of data when these limits were in use, the average temperature was 200.2 °C, and the standard deviation was 2.2 °C. The 60 minute run is shown in Figure 22. The last five minutes of the run are shown in Figure 23.

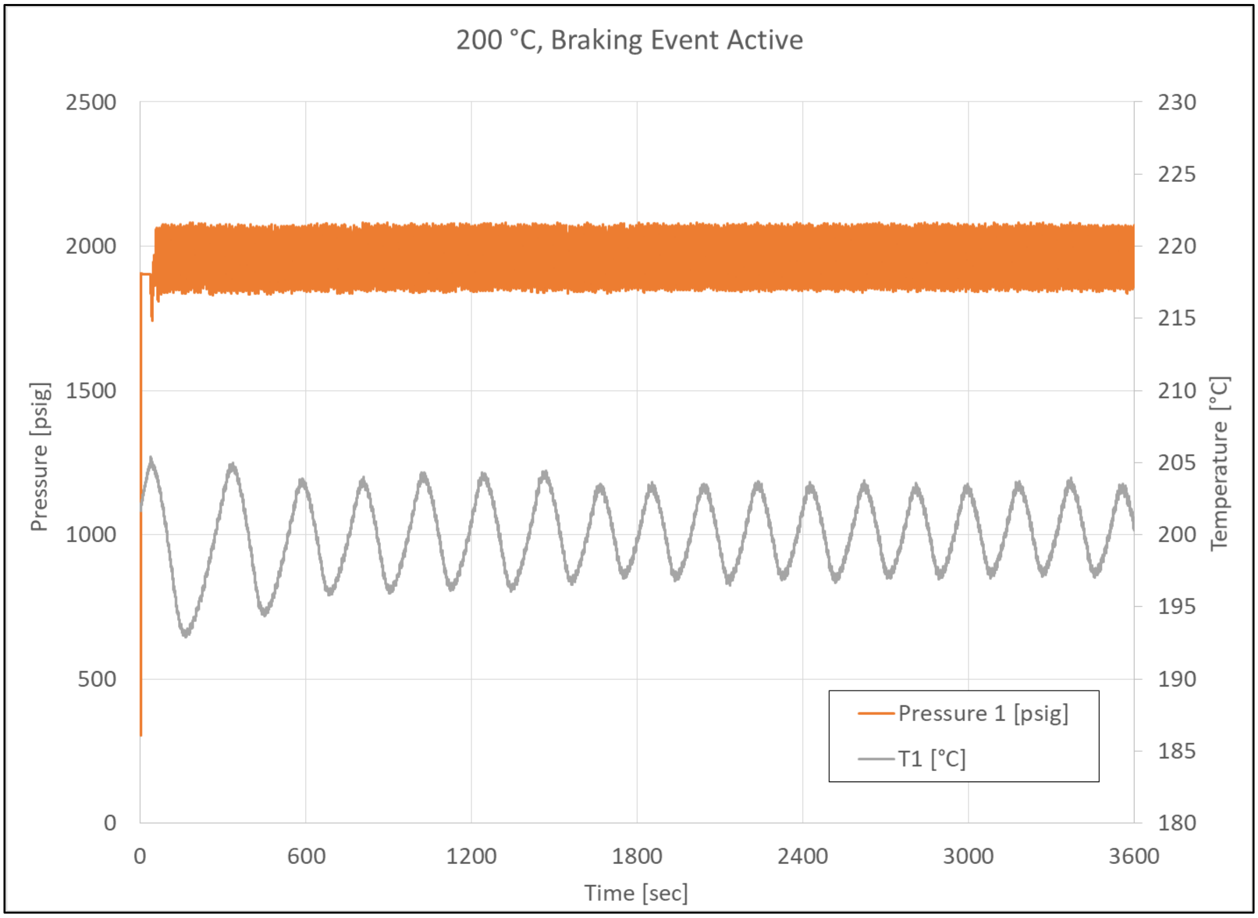

Figure 22. Heating Validation, 200 °C, ABS Braking Event Running

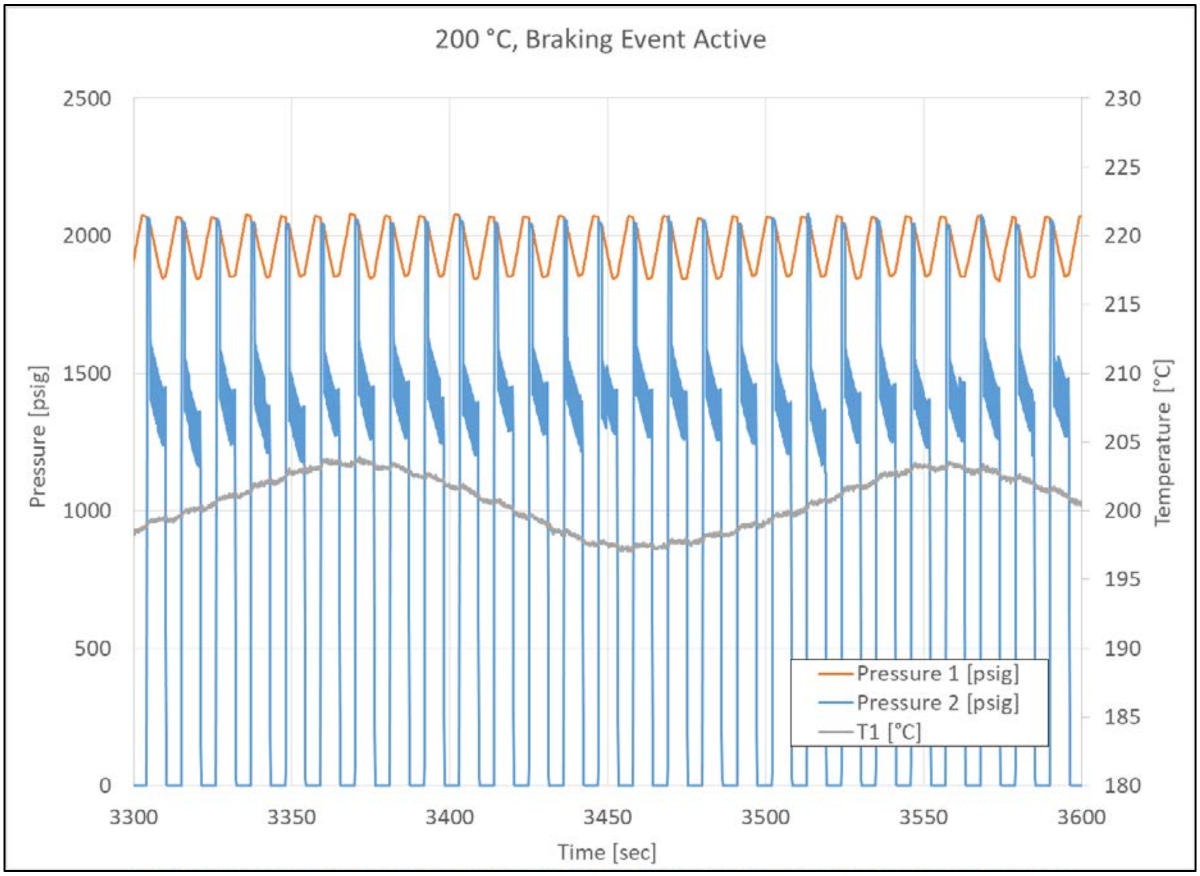

Figure 23. Heating Validation, 200 °C, ABS Braking Event Running, 5 minutes

4.6 Post Test Evaluation

The test rig was designed with test components that are easily removed and disassembled to allow for post-test wear analysis. The test components of interest were the pumping element, solenoid valves, and system elastomers. These parts were removed from the test rig prior to testing. They were disassembled and photographed. The photographs of these components are shown in APPENDIX B.

5.0 CONCLUSIONS, RECOMMENDATIONS AND REFERENCES

5.1 CONCLUSIONS

The anti-lock brake fluid evaluator test rig was designed and built based on commercially available in-use heavy-duty anti-lock brake systems. The rig was developed to differentiate between different brake fluids and their compatibility with the anti-lock brake components. After initial test runs were completed to validate the rig's capabilities, it was found that the rig is capable of producing a brake event that is satisfactory in mimicking an ABS event as found in field testing. The test rig is able to raise system pressure from ambient conditions to 2030 psig in less than 0.2 seconds. Additionally, the rig is capable of heating the brake fluid to a temperature of 200 °C while running the brake event cyclically. However, at fluid temperatures of -55 °C, the test rig was unable to run in a satisfactory manner due to increased viscosity of the brake fluid. A new target low temperature of -40 °C was chosen, and the test rig was capable of producing the brake event at this temperature. However, the brake event at -40 °C takes significantly longer to produce due to increased viscosity of the brake fluid at the low temperature.

5.2 REFERENCES

1. "Brake Fluid Compatibility With Hardware", Interim Report TFLRF No. 445, D.M Yost, U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, May 2014, ADA 1007438.

APPENDIX A
Valve Block Technical Drawings

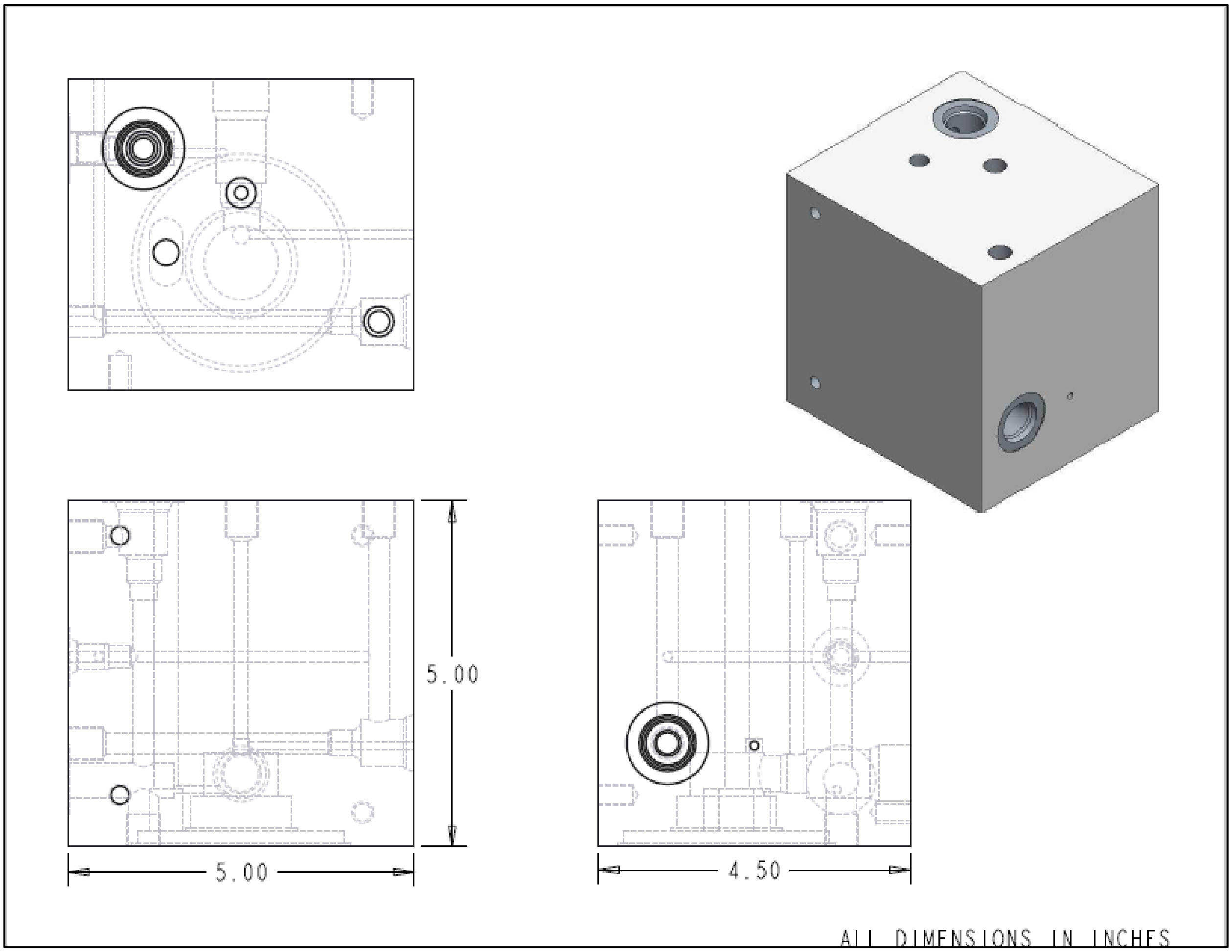

Figure A-1. Valve Block, Isometric View

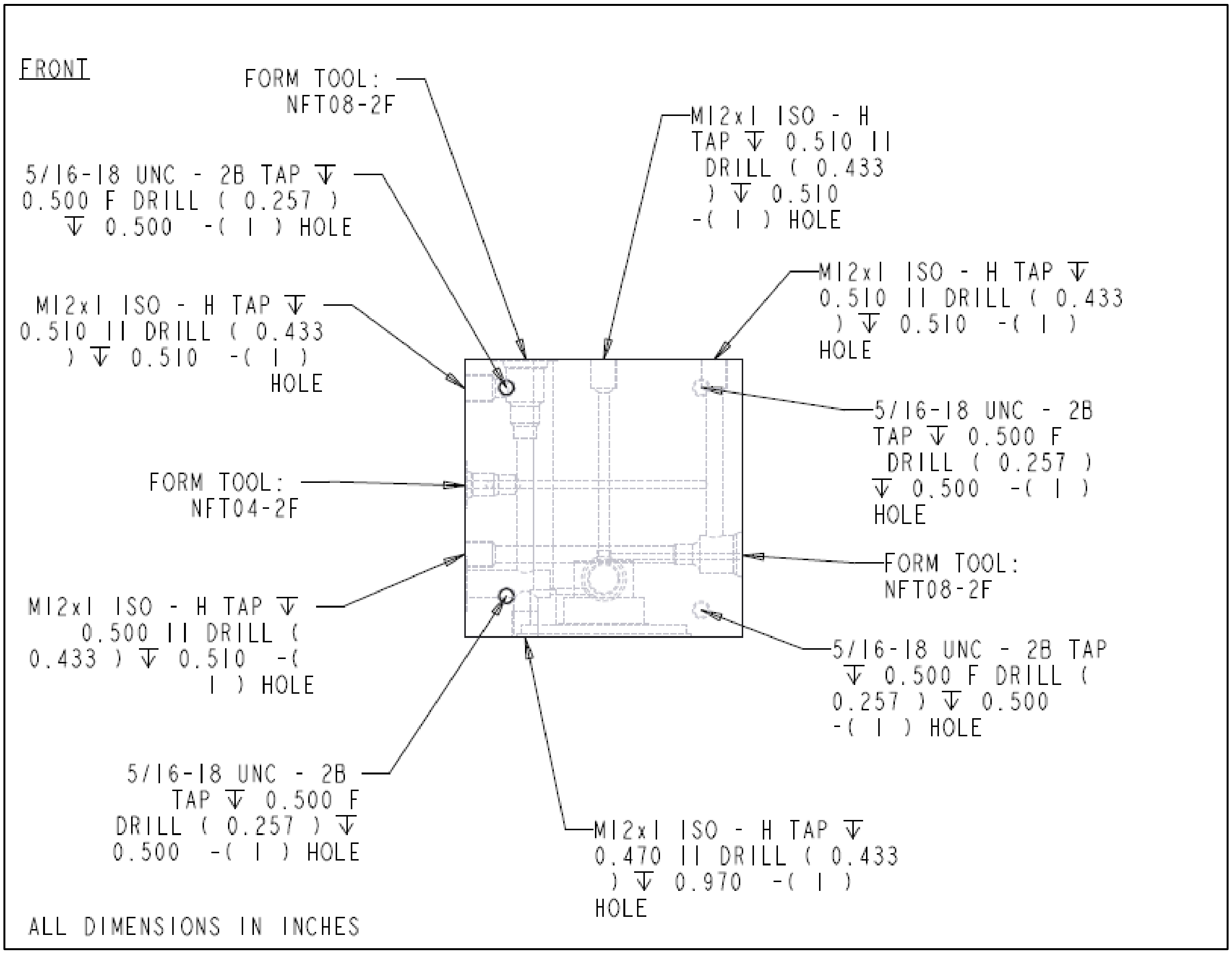

Figure A-2. Valve Block, Front View

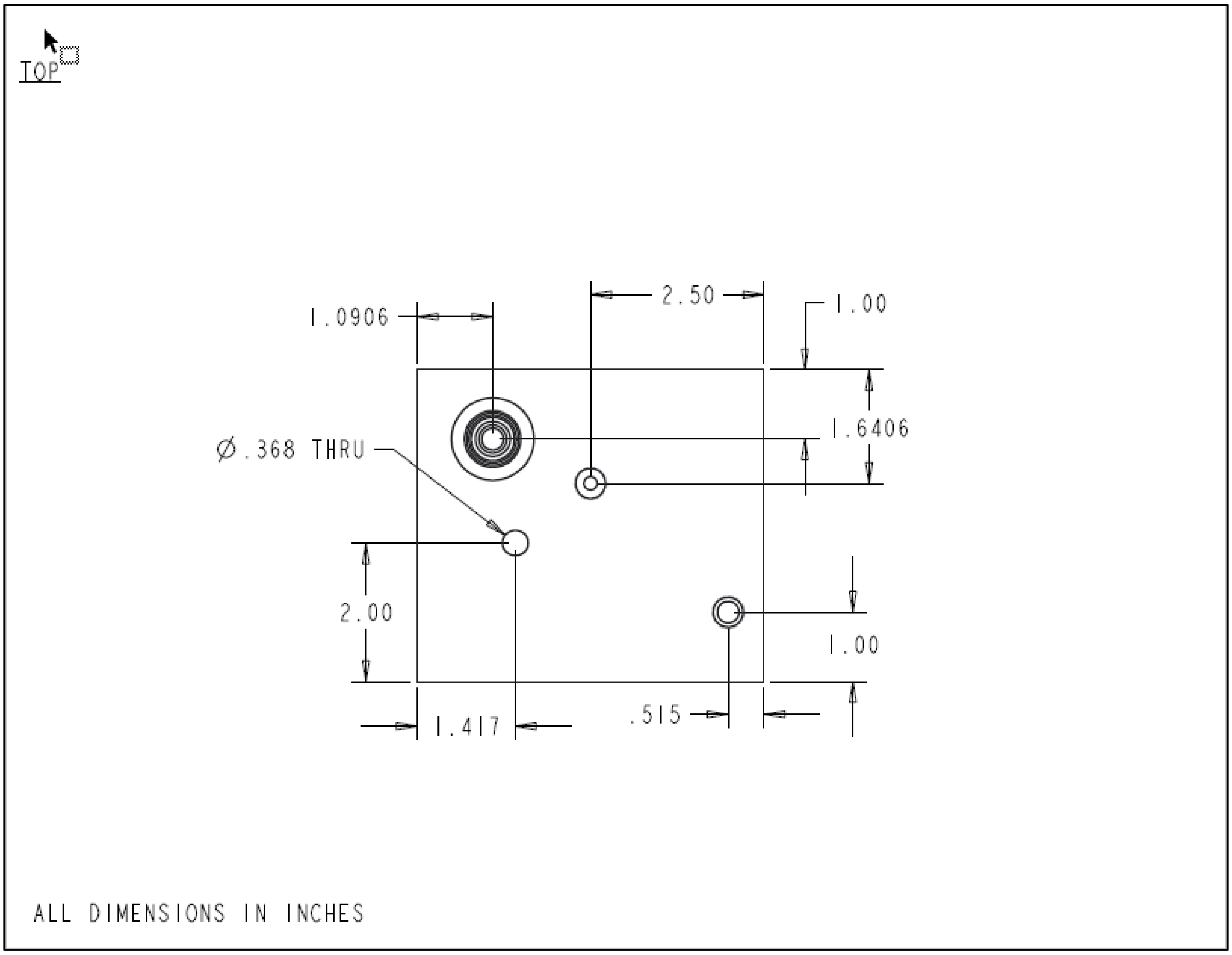

Figure A-3. Valve Block, Top View

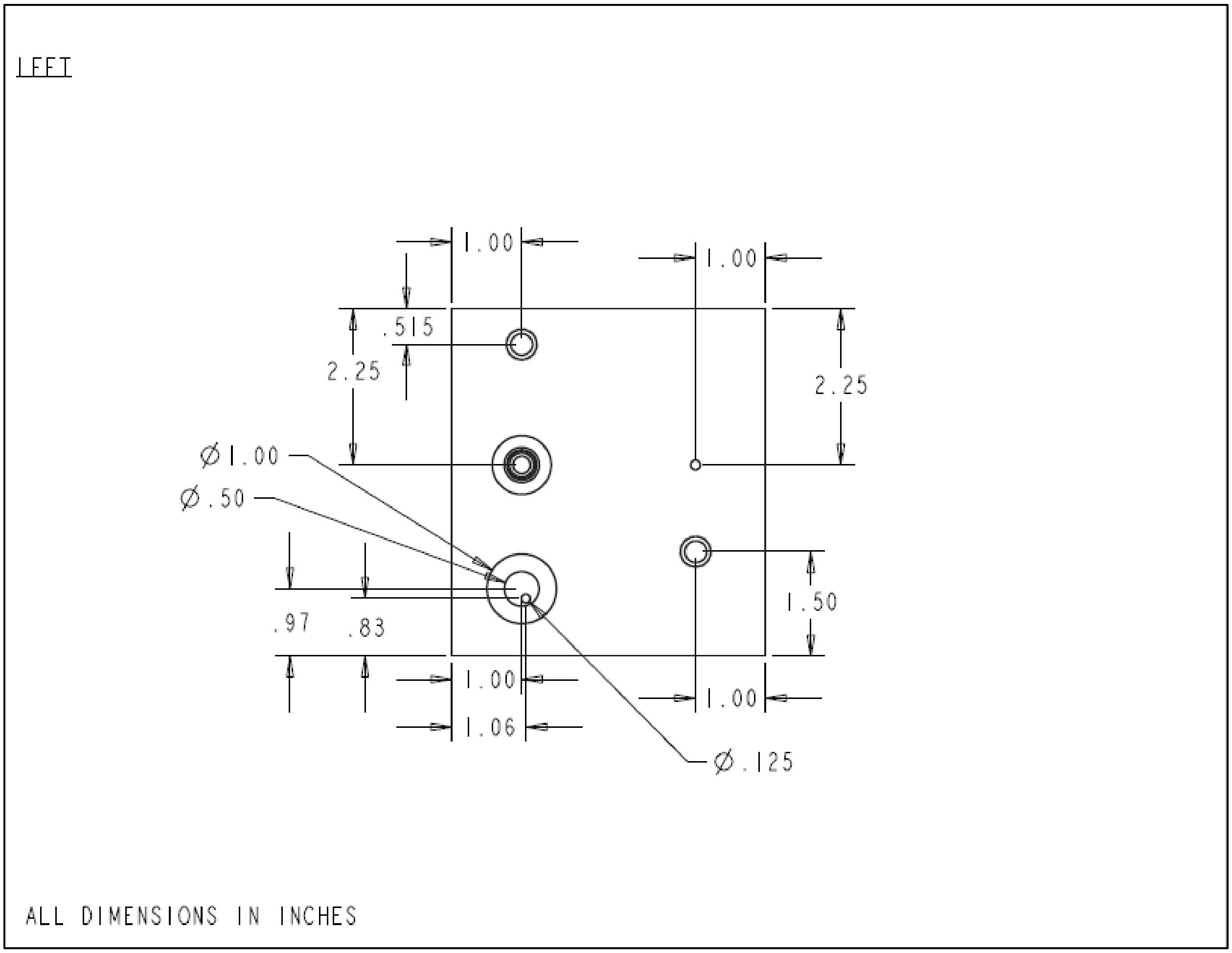

Figure A-4. Valve Block, Left View

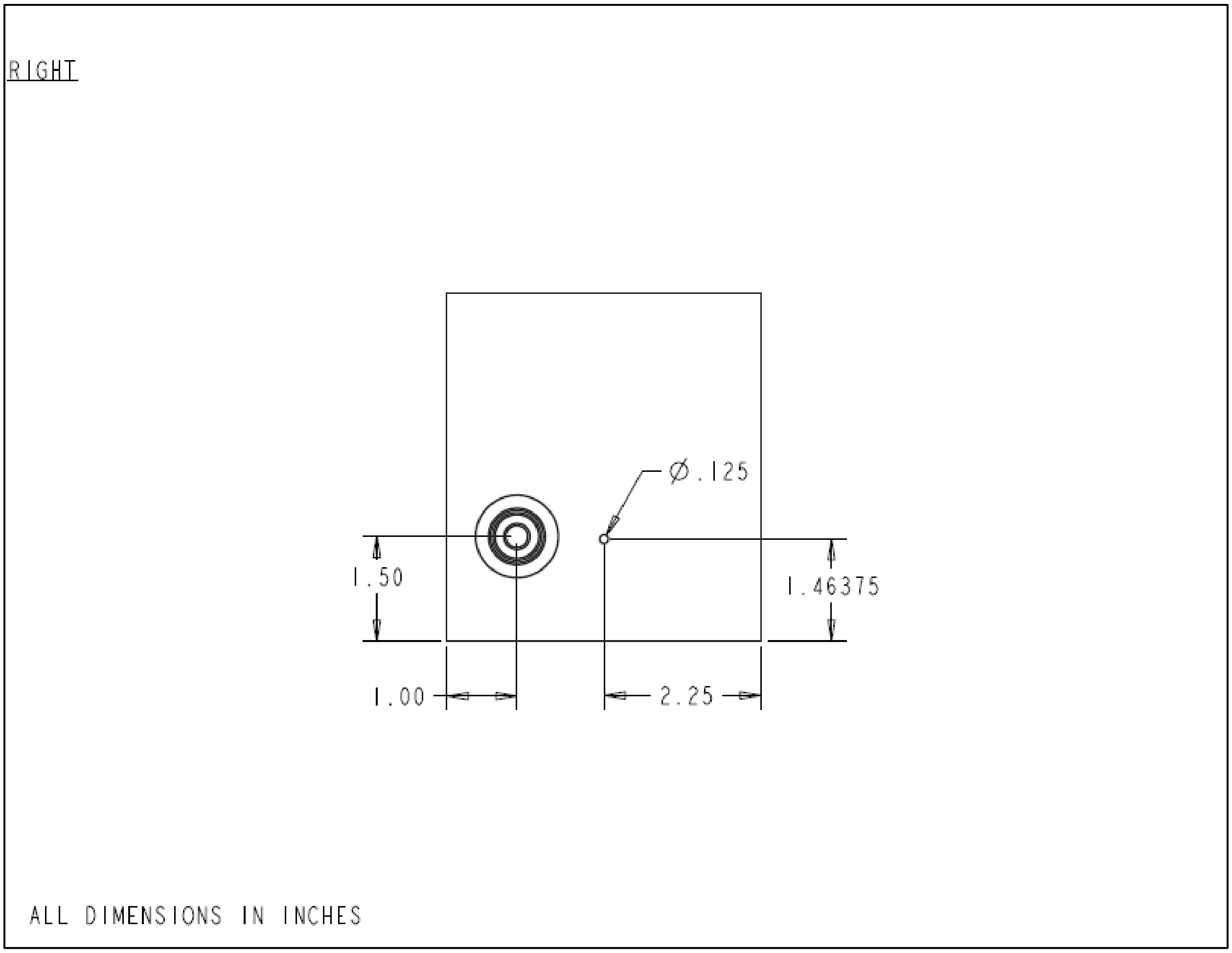

Figure A-5. Valve Block, Right View

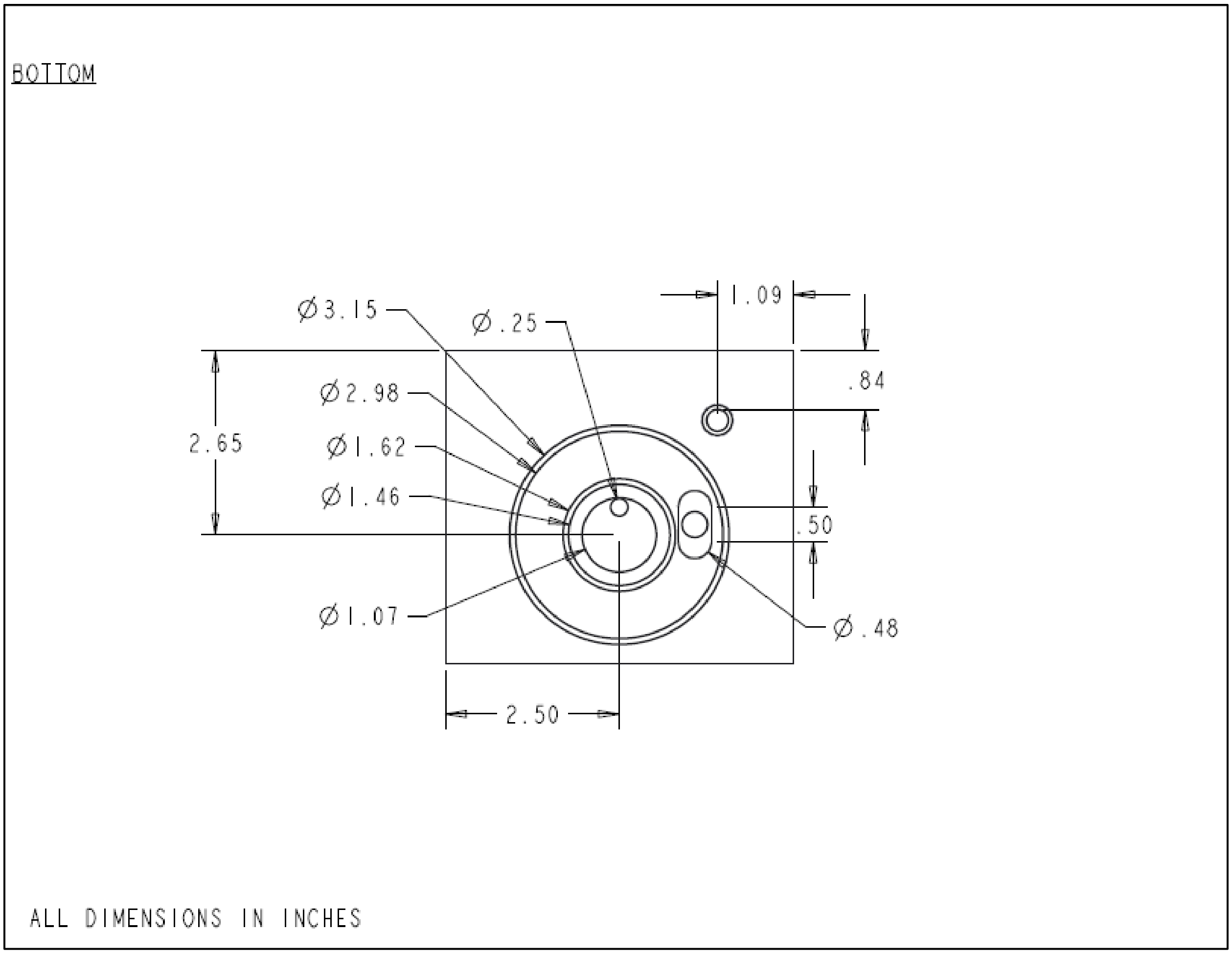

Figure A-6. Valve Block, Bottom View

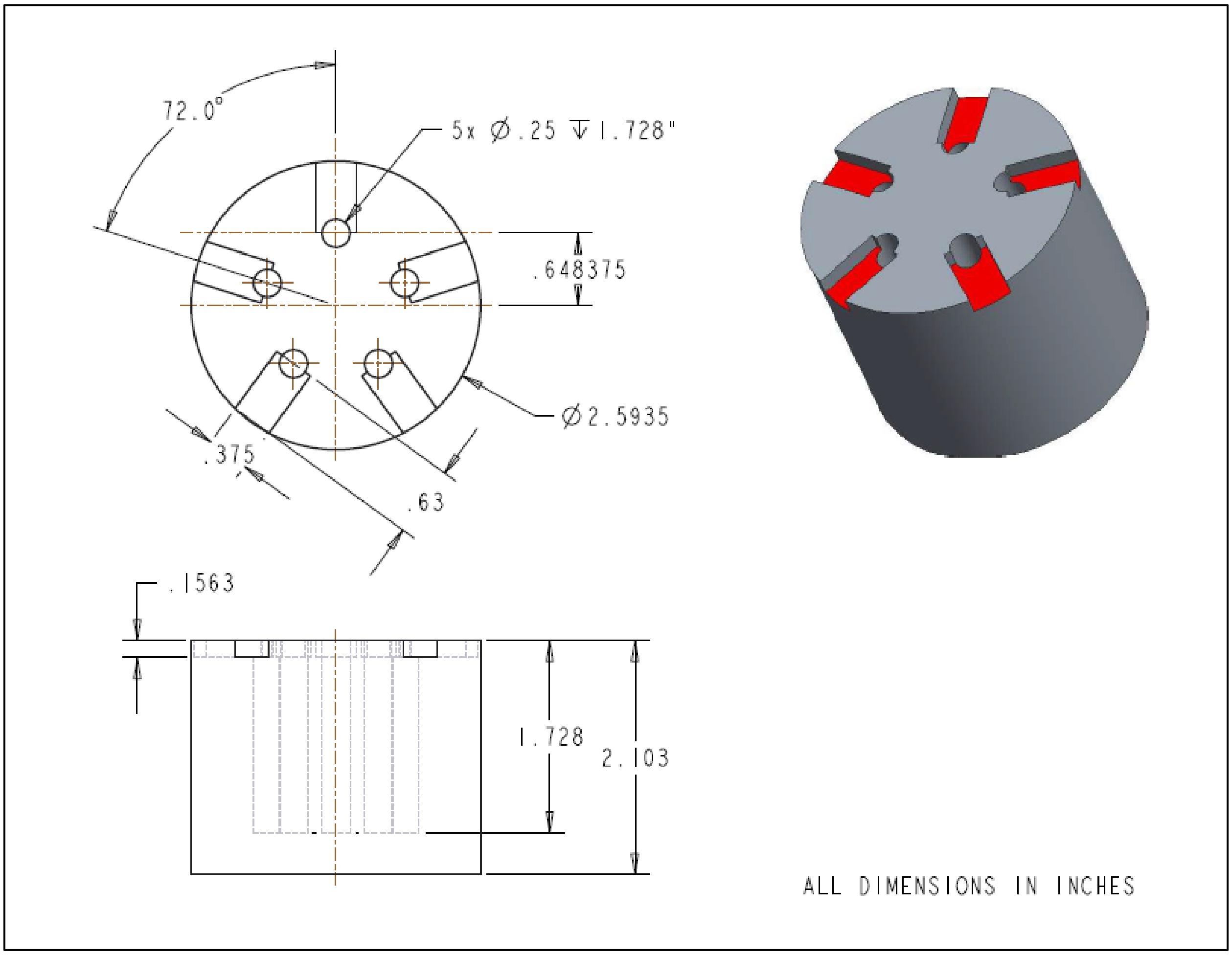

Figure A-7. Caliper Piston, Isometric View

APPENDIX B

Photographs of Test Components

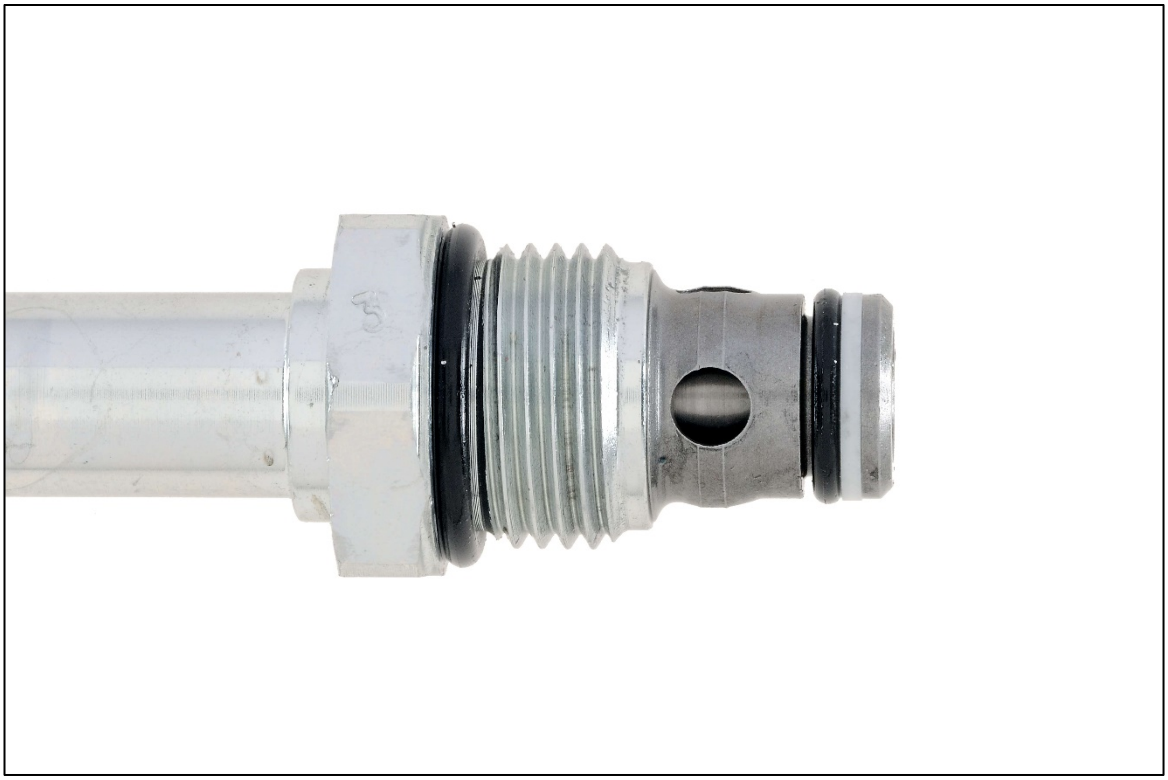

Figure B-1. Load Valve with Seals

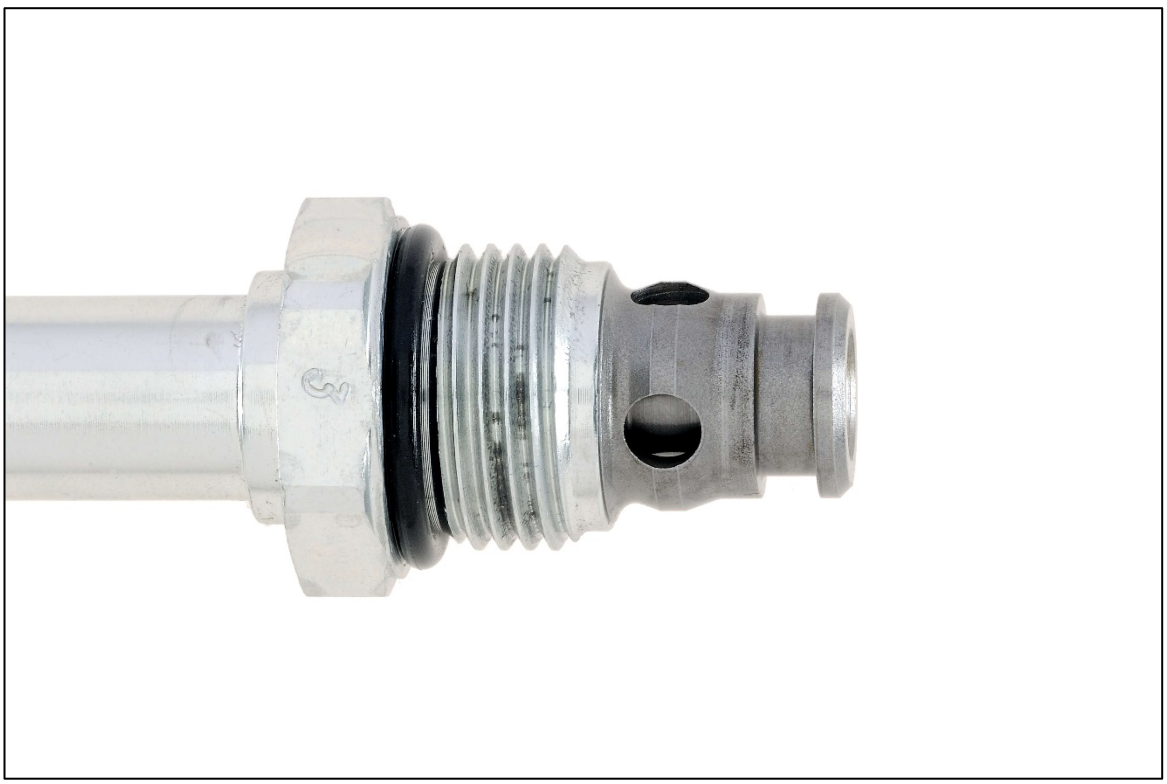

Figure B-2. Load Valve without Seals

Figure B-3. Load Valve Teflon Seal

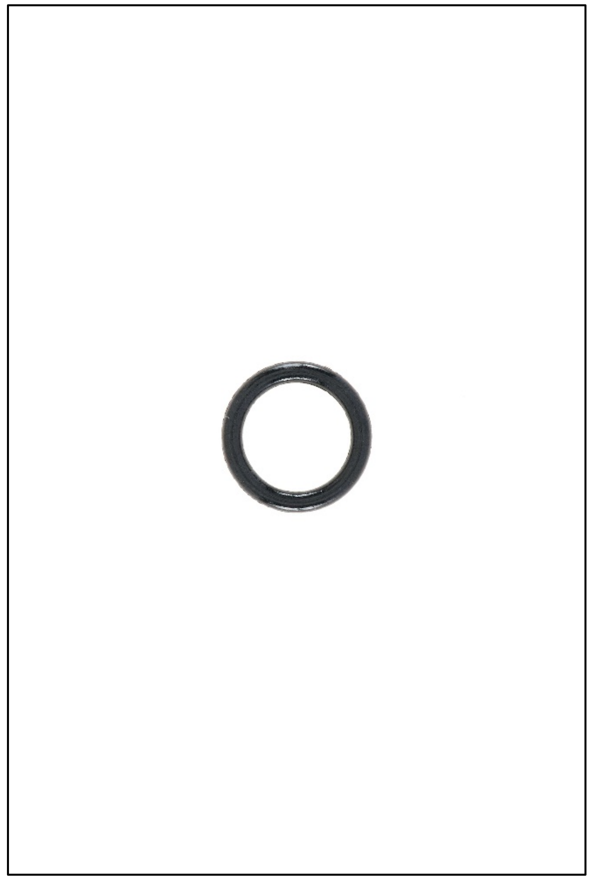

Figure B-4. Load Valve O-Ring

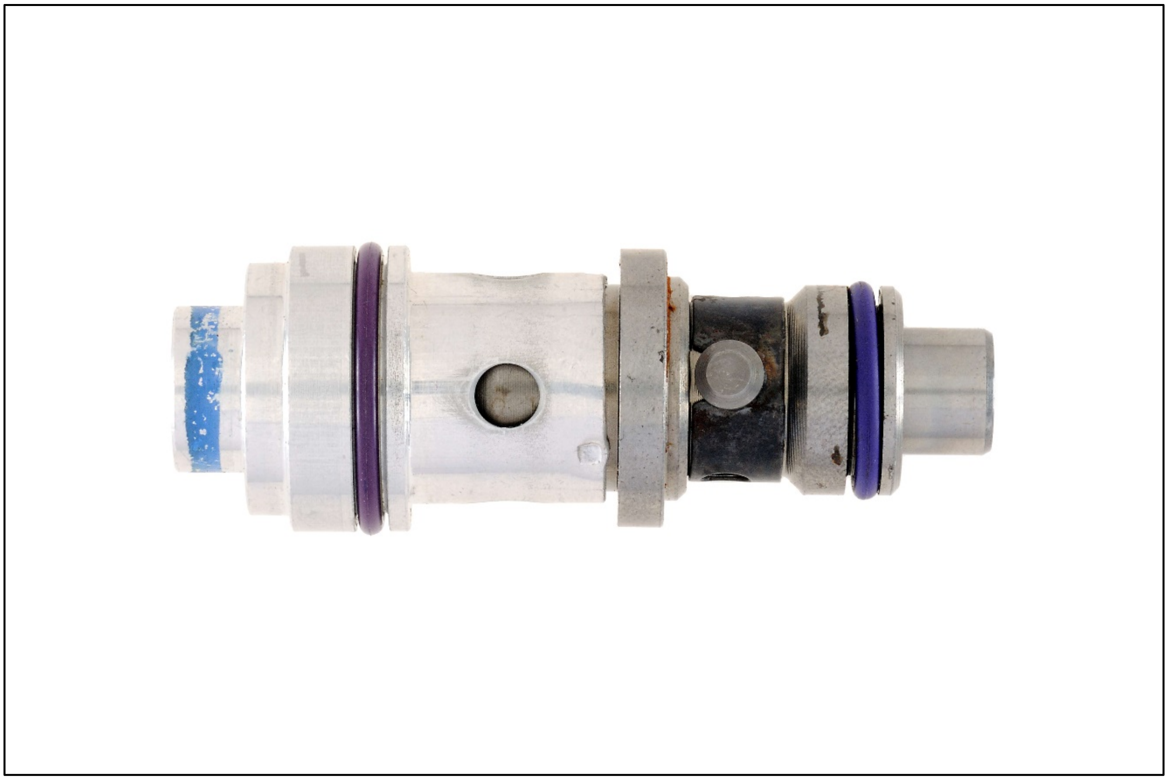

Figure B-5. Pumping Element, Assembled, With Seals

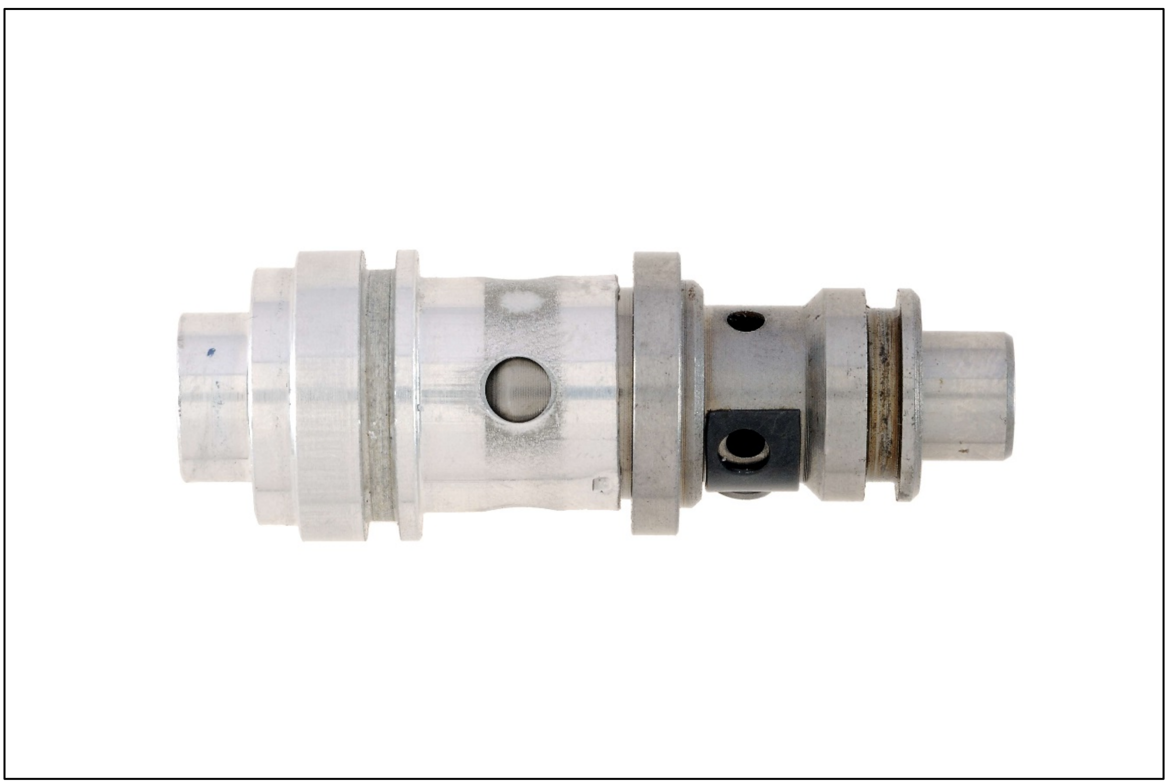

Figure B-6. Pumping Element, Assembled, Without Seals

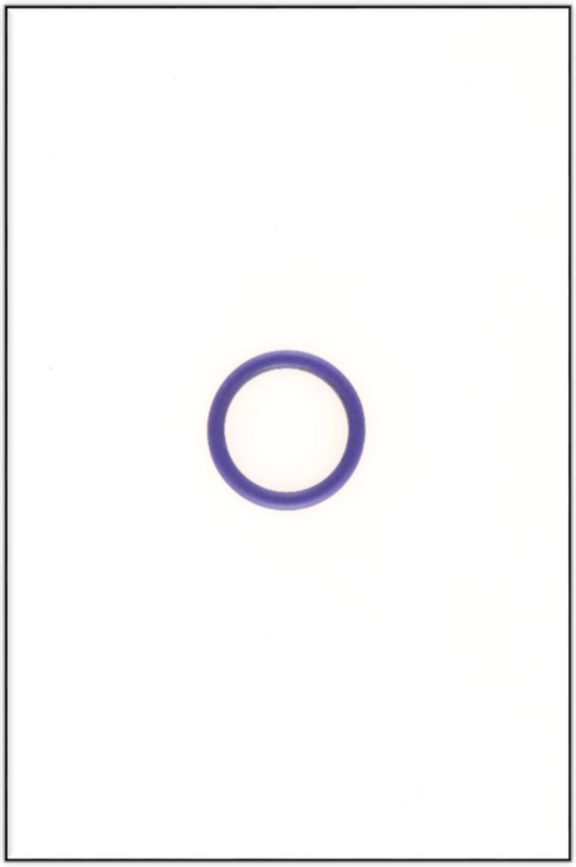

Figure B-7. Pump O-Ring, Small

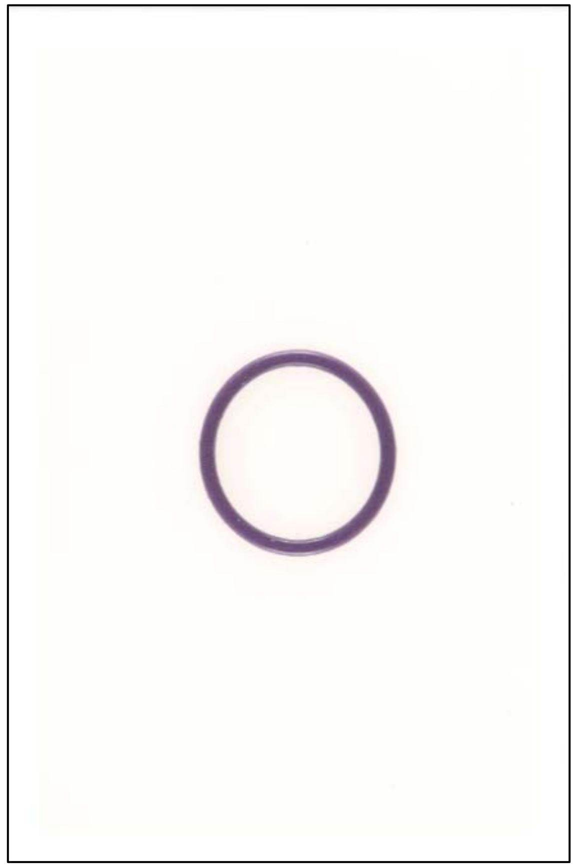

Figure B-8. Pump O-Ring, Large

Figure B-9. Pump Housing

Figure B-10. Pump Cap

Figure B-11. Pump Barrel

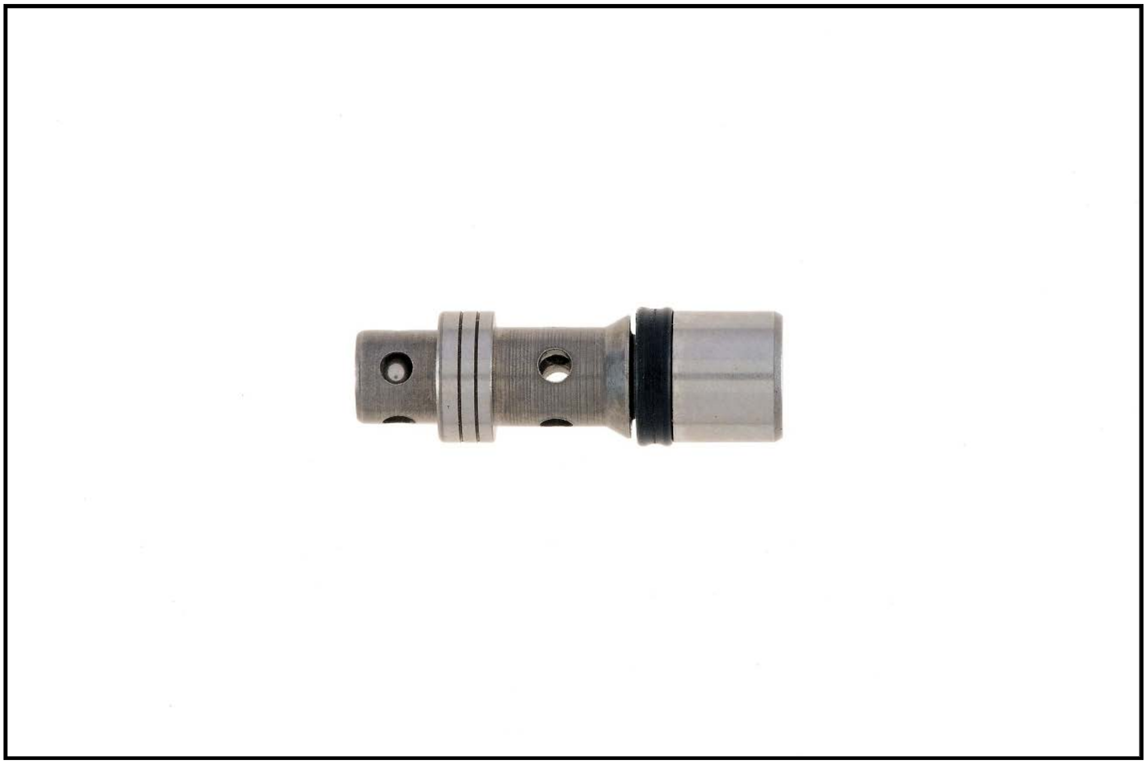

Figure B-12. Pump Plunger