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HYDROSTATIC TEST APPARATUS

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ABSTRACT

Cooper Crouse-Hinds currently uses a hydrostatic test to certify some of their products. Specifically, electrical enclosures are tested to meet standards UL1203, UL2225, and CSA22.2 no.30 for internal burst pressure. By combining a stepper motor, ball screw, needle valve, three pressure transducers, and a data acquisition unit (DAQ) that are all controlled by a custom Labview VI, Cooper Crouse-Hinds manual system was able to be automated. The new test apparatus is able to accommodate all the different enclosures currently manufactured by Cooper Crouse-Hinds and is able to be modified for any future product offerings. As of this date, final testing has not been completed, because we are waiting on the installation of the system on site in Syracuse. Depending on the timing, we anticipate being able to complete testing before the end of the senior design time frame but, that remains to be seen. Overall, the system meets all the customer needs set forth at the initiation of this project and, after testing, will be able to complete the tests desired by Cooper Crouse-Hinds.

INTRODUCTION

The current apparatus is manually controlled. The goal of this project was to redesign the apparatus so that the test process can be automated and can be performed via a digital control interface. The interface allows for multiple tests to be queued by entering in the desired test pressure and hold time. A manual mode was included so that a test may be run by live editing the desired test pressure to be reached. Once an initial valid test has been added to the queue, the first test is able to take be performed. The building of test pressure is controlled by the test controller built into the system so that the technician can observe and record the results. The design for the new test apparatus needed to include minimal system maintenance recommendations, an easily programmable digital interface, the ability to interface with the existing pump and test enclosures, automation of tests being performed, and the ability to withstand a maximum internal pressure of 10,000 PSI. The apparatus is designed around performing tests on electrical enclosures to ensure they meet the operational specifications as outlined in the standards mentioned above.

PROCESS AND METHODOLOGY

The first task in this project was to generate a list of customer needs and requirements to be met in the final implementation of the design. All of the requirements came from either Cooper Crouse-Hinds themselves or from the initial information packet provided.

Revision #: 4

Customer Rqmt. #	Importance	Description	Comments/Status
CR1	2	Programable Digital Controller	
CR2	1	Test Automation complies with Standards	
CR3	2	Use of Pressure Transducer(s)	
CR4	3	Future Labview Logging Integration	
CR5	1	Ability to Interface with Current Cooper Product Line	
CR6	2	Safe Test Enviroment	
CR7	1	Ability to Aquire Data from Test	
CR8	1	Complete Apparatus for On-Site Testing	
CR9	1	Control of Pressure, Hold Time, and Ramp Rate	

From this list of customer requirements, a list of engineering requirements was generated to help to ensure that all the customer requirements were met.

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rqmt. #	Importance	Weight	Source	Function	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Comments/Status	Test (how are you going to verify satisfaction)
S1	9	340.9	CR2		Withstand Maximum Internal System Pressure	PSI	10000		ANSYS Analysis
S2	9	286.4	UL1203 & UL2225		Pressure Ramp Rate	PSI/Min	100-600		Run tests with gauge
S3	9	377.3	PRP		Deliver Maximum Required Pressure to Enclosure	PSI	10000		Run on customer pump
S4	9	295.5	UL1203		Deliver Minimum Required Pressure to Enclosure	PSI	>50		Run with a pump
S5	3	245.5	UL1203		Maximum Conduit Trade Size	in	1.5"		Connect 1.5" pipe
S6	3	245.5	UL1203		Minimum Conduit Trade Size	in	.75"		Connect .75" pipe
S7	9	259.1	UL1203		Hold Time for 4X Max Internal Explosion Pressure	Sec	10		Run Test
S8	9	259.1	US1203		Hold Time for 1.5X Max Internal Explosion Pressure	Sec	10<t<60		Run Test
S9	3	231.8	Customer Interview		Ability to Alter Test Parameters Midtest	Binary			Alter Parameters
S10	3	200	CR15		Number of Analog Outputs for Data Logging	Decimal	1		Look
S11	3	172.7	Customer Visit		Store Peak Pressure Value Before Failure	Binary			Run Test with Gauge to verify
S12	3	95.5	CR16		Emergency Shutdown Proceedure	Binary			Look
S13	6	245.5	PRP		Test Controllable Outside Explosive Proof Area	Binary			Look
S14	6	240.9	UL1203 & UL2225		Reaction time of Valve	Sec	<2		Time System
S15	3	122.7	Customer Visit		Maximum Dimensions	ft (L x W x H	5 x 2 x 3		Measure finished design

Once the overall scope of the project was defined, it was split into smaller subsystems to be analyzed. Our major subsystems were the controller, pressure transducers, needle valve and motor assembly, and the general structure/piping. For each component of each subsystem, a new set of engineering requirements were generated.

Controller

The controller is the electronic brain of the system which runs the desired hydrostatic test program as well as recording the enclosure pressure during the test.

rqmt. #	Importance	Engr. Requirement (metric)	Unit of Measure	Target Value/Range
1	3	Analog Input Range	Volts	±5 V
2	3	Analog to Digital Converter Resolution goes from 0 - 10,000	Bits	12
3	3	Controller Provides Enough Inputs	Number of Analog Input Ports	1 Differential Input Per Transducer
4	3	Controller Provides Enough Outputs	Number of Output Ports	6
5	3	Controller is Programmable via Labview	Binary	
6	3	Controller Provides Feedback to the Operator via Labview	Binary	
7	3	Controller Provides Clock Output to Drive Stepper Motor Driver Pack	Binary	
8	3	Minimum Analog Input Sensitivity	Volts	4 mV
9	6	Current Sourcing or Sinking Digital Outputs	Binary	
10	6	DAQ is Electrically Isolated to Protect Components and User	Binary	

Once the criteria for the controller were outlined, the potential risks and failure modes were analyzed.

ID	Potential Failure Modes	Potential Effects of Failure	Potential Causes of Failure	Severity	Probability	Rank	Recommended Action
1	ADC Doesn't Provide a High enough Resolution	Controller Will be Unable to Read Pressure Value	Controller was Incorrectly Chosen	2	1	2	Select a Controller with at least 12 bit Resolution
2	Controller Output Cannot Drive the Stepper Driver Pack	Controller will be Unable to Automate the building and holding of the Internal Enclosure Pressure	Controller Cannot Provide the Necessary Control Signals	2	2	4	Select a Controller with an Appropriate Number of Outputs to Act as Control Signals
3	Controller Cannot Interface with Pressure Transducer	Controller will be Unable to Read Pressure Value	Output of the Pressure Transducer is not in terms of Voltage	2	1	2	Select a Pressure Transducer with a Voltage output between 0-5V
4	Controller Cannot Sample the Transducer Output Fast Enough	Pressure Reading will not Accurately Reflect the Internal Enclosure Pressure	Controller will not be able to Actuate the Electronic Valve Properly	2	1	2	Select a Controller with a Sample Rate of at least 500 Samples per Second
5	Controller is not Interfaceable with Labview	Operator will be Unable to Program the Test or Receive Feedback	Controller was Incorrectly Chosen	2	1	2	Select a Controller that is Labview Compatible

After analyzing several different options, a NI-cRIO 9075 with Real-Time control and field programmable gate array was chosen. It provides four slots for NI

Real-Time modules, three of which are used. These modules are a NI 9215 analog input module, a NI 9401 digital input/output module utilized for pulse width modulation, and a NI 9472 digital output module.

Pressure Transducers

To accurately measure the internal system pressure, three inline pressure transducers were placed before the valve to provide consistent and precise measurements. Because the pressure transducers needed to account for several specific pressure ranges as well as maintaining compatibility with the rest of the system, a list of requirements was generated.

Rqmt. #	Importance	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Test (how are you going to verify satisfaction)
S1	6	Acceptable sensitivity for 10,000psi	mV/psi	12.5	Sensitivity Calculations
S2	6	Acceptable sensitivity for 5,000psi	mV/psi	4	Sensitivity Calculations
S3	6	Acceptable sensitivity for 1,000psi	mV/psi	4	Sensitivity Calculations
S4	6	Voltage output from pressure transduer	volts	0-5Vdc	Read specifications
S5	6	Reaction time of Pressure Transducer	Sec	<1	Time System
S6	9	Compatible pressure transducer port with manifold	in	1/4 MNPT	Design manifold to pressure transducer
S7	6	Compatible cable connection to DAQ	Binary		Look at connection ports of DAQ and pressure transducers

Because the measurement uncertainty increases with the overall transducer range, it was determined that three different pressure transducers were necessary to deliver the accuracy the customer required for test operating under the 5000 and 1000 psi levels. The following risks were identified and a recommended action was given to mitigate each risk.

Potential Failure Modes	Potential Effects of Failure	Potential Causes of Failure	Severity	Probability	Rank	Recommended Action
Pressure Transducer Connection Failures	Inaccurate Data	Mis matched manifold to PT connections	3	1	3	Choose correct connection type
	Damage to Pressure Transducer	Wear from excessive pressure	2	1	2	Buy more rugged designed pressure transducer
	Test cannot be completed	No proper readings achieved	3	1	3	Ensure proper connection type
Broken Cable from Pressure Transducer to DAQ	Test cannot completed	End connection not able to reach enclosure	2	1	2	Use flexible hose that is long enough to reach all enclosure connection points
	Electrical cables exposed to water	Overstretched cable fails	3	1	3	Ensure cables and connectors are water proof
Leak Excessively at pipe connection to Pressure Transducer	Inaccurate Data	Over or under tightening of pressure transduc	2	1	2	Use thread sealant to allow connection to be sealed properly
	Damage to Pressure Transducer	Wear from excessive pressure	2	1	2	Buy more rugged designed pressure transducer

The following three Omega pressure transducers were selected to meet the needs of our customer.

Company	Part	Part Number	Accuracy
Omega	10,000psi w/ 5' cable	PX309-10KG5V	±25 psi
Omega	5,000psi w/ 5' cable	PX409-5.0KG5V	±4 psi
Omega	1,000psi w/ 5' cable	PX409-1.0KG5V	±0.8 psi

Valve and Motor

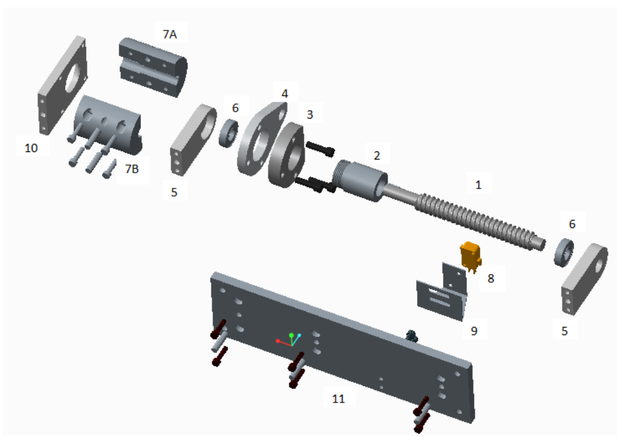
The valve and motor are arguably the most important mechanical features of the system as they are what control the building of pressure within the enclosure. The requirements of the valve and motor are shown in that order below. Because they are so closely related and reliant on one another, the failure modes were analyzed in one chart.

Rqmt. #	Importance	Source	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Test
1	3	CR2	Survive Max Pressure	psi	10000	Spec Sheet
2	1	S4	Produce Min Pressure Drop	psi	~50	Pressure Drop Calculation
3	3	CR2/S2/S13/S14	Actuator Controllable	Binary	-	Spec Sheet/Test using Controller
4	2	S13	DC Voltage Control	Binary	-	Spec Sheet
5	2	S13	Position feedback	Binary	-	Spec Sheet/ Look At Actual Output
6	1	CR12	Low Cost	$	0	
7	2	CR5	Common Connection	-	1"NPT	Spec Sheet
8	2	S14	Reaction time of valve	sec	<2	Spec Sheet

ID	Potential Failure Modes	Potential Effects of Failure	Potential Causes of Failure	Severity	Probability	Rank	Recommended
1	Valve structural failure due to overpressure	Test and system failure	Inappropriate valve selected	3	1	3	Select an appropriate valve
2	Motor speed too slow for adequate response	In-accurate test	Select fastest Motor available	2	2	4	Select adequate Motor
3	Motor position inaccurate	In-accurate test	Internal position feedback not adequate	2	1	2	Incorporate custom position feedback device
4	Valve torque exceeds motor capability	In-accurate test	Inappropriate motor selected	2	1	2	Select appropriate motor
5	Valve seal failure	Test and system failure	Inappropriate seal material selected for environment	2	1	2	Select appropriate seal material per manufacturer
6	Motor moisture failure	Test and system failure	Motor enclosure not water resistant	2	1	2	Select motor with moisture rated enclosure
7	Motor impact failure	Test and system failure	Motor enclosure not impact resistant	2	1	2	Protect hardware with shield
8	Couple shaft connection siezes	Test and system failure	Incorrect lineup of valve shaft and motor shaft	2	2	4	Ensure correct setup, use flex couplings

Rqmt. #	Importance	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Test (how are you going to verify satisfaction)
S1	6	Minimum of 200 steps per revolution	SPR	200	Product Specifications
S2	6	Voltage power supply to encoder	volts	5Vdc	Read specifications
S3	6	Bore Size of 5/8"	in	5/8"	Product Specifications
S4	6	Able to fit 3/8" shaft size	in	3/8"	Product Specifications

To meet our needs, we selected a Swagelok IPT series high pressure, linearly actuated needle valve to be paired with an Anaheim Automation NEMA 23Y65 motor. Because the valve stem moves in and out to open and close the valve, a ball screw is used to translate the rotational motion of the motor into linear motion to actuate the valve.



Force	200	lbf
Lead	0.2	in/rev
Efficiency	0.9	
Torque Required	7.07	in-lbs
	113.2	oz in
Gear box ratio	3	
Gear box effieciency	0.95	
Torque at Motor Input Shaft	39.7	oz-in
Stall Torque of Motor	175	oz-in
Safety Factor - Motor Torque	4.4	
Speed (motor)	40	rps
Speed (gearbox)	13.3	rps
Speed of ball screw carriage	2.7	in/s
Step Angle	1.8	deg
	0.6	deg/step
	0.0017	rev/step
	0.0003	in/step
	3.3	psi/step

The ball screw is ¾" in diameter with a 0.200" per revolution lead. The ballnut is rated to 900 lb. working load, but the valve will only need 150-200 lb of force to actuate it. To obtain the necessary torque while maintaining a high resolution on the stepper motor, a GBPH-060x-NP 3-1 ratio gearbox was used from Anaheim Automation. This effectively increased our resolution and torque produced by the stepper motor by a factor of three. After combining the stepper motor, ball screw assembly, and gear box, the valve will translate at a rate of approximately 2.7 in/s and offer a resolution of 3.3 psi per step of the motor. To accurately communicate its position back to the DAQ, the double shafted motor allows us to attach an ENC-A31, single ended, high resolution encoder with index channel. Because this encoder has an index channel, the DAQ can set a home position and a maximum translation position to help prevent damage to the system or inaccurate control of the pressure in the enclosure. As a secondary safety measure, a mechanical position switch is attached to the ball screw mounting fixture to prevent the motor from over travelling and damaging the valve. As the ballnut come into contact with the switch, power will be cut from the motor and not allow it to move any farther. This must be reset by the test operator before testing can continue.

General Structure/Piping

When determining what piping was needed for the system, the basic requirements were first examined. The most basic requirements were that it was able interface with their existing system, could withstand the maximum pressure, and that the internal pressure drop across the system was less than 50 psi.

rqmt. #	Importance	Source	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Test (how are you going to verify satisfaction)
1	3	CR2	Able to withstand 10000 psi	psi	10000	Material Properties/ Pipe Burst Calculations
2	1	-	Interfaces with all components	NPT	?	Component Spec Sheets
3	1	Visit	ID that does not restrict flow	inches	>0.483"	Pressure Drop Calculations

We then looked at the possible risks associated with the piping and methods to mitigate said risks.

Potential Failure Modes	Potential Effects of Failure	Potential Causes of Failure	Severity	Probability	Rank	Recommended Action
Pipes/Connections Fail/Leak Excessively	Inaccurate Test	Materials not robust enough	3	1	3	Choose correct materials/ Do stress/fatigue calculations
	Loss of Test Control	Premature wear from vibrations	2	1	2	Add vibration dampeners if necessary
	Failure to Meet Operating Standards	Sudden, large increases in pressure	3	2	6	Pressure control system/ Robust enough to withstand max pressure
Not able to connect to all enclosures	Unable to complete test	End connection not able to reach enclosure	1	1	1	Use flexible hose that is long enough to reach all enclosure connection points
	Failure to Meet Operating Standards	Incompatable end connection	1	1	1	Use adapter that has compatable connector
Connections Do Not Line Up	Unable to complete build	Over or under tightening of pipes	3	1	3	Use thread sealant to allow pipes to be turned to correct angles
	Valve Stem Unable to connect to motor	Incorrect lengths of pipes	3	1	3	Use coupling that allows for misaligned shafts
Incompatable Pipe/Component Connections	Unable to complete build	Components do not have standard connections	3	1	3	Select Compatable Components
	Failure to Meet Operating Standards		3	1	3	Use adapter that has compatable connector

To best meet our needs, the piping needed to be 1" XXH Black Pipe with equivalent Class 6000 elbows and tees. The 1" XXH Black Piping gave us a working pressure of ~24,000 psi, which is well below our requirement of 10,000 psi.

$$P = \frac{2St}{(D_0 - 2t)SF}$$

$$P = \frac{2(60000)(0.358)}{(1.315 - 2 * 0.358)(2.5)}$$

$$P = \frac{42960}{1.8025}$$

$$P = 23833.56$$

Flow Rate	17	gpm
Flow Rate	65.45	in3/sec
Length of Pipe	20	ft
Length of Pipe	240	in
Pipe Diameter	0.599	in
Flow Area	0.281802	in2
Fluid Velocity	232.3	in/sec
Density of Water	1.94	slug/ft3
Dynamic viscosity	2.03E-05	lb/fts
Reynolds #	9.21E+04	
"e" value	0.00015	
f (from moody diag)	0.0145	
Pressure Drop - Pipe	**14.7**	PSI
# Bends	4	
Pressure Drop - Bends	**4.4**	PSI
Total Pressure Drop	**19.1**	PSI

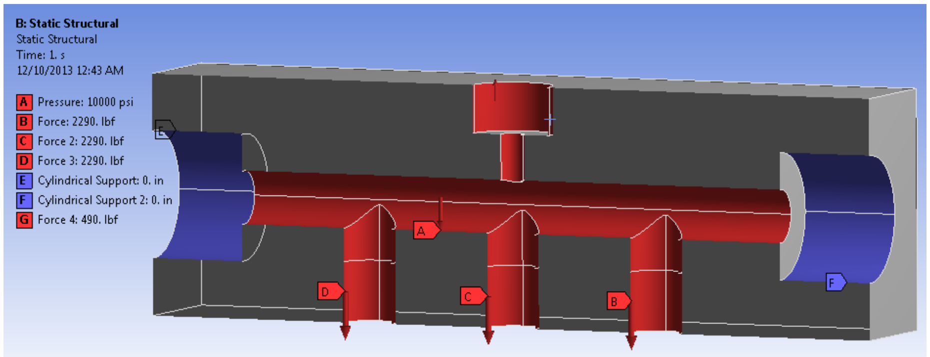
Because of the relatively large diameter and low number of bends, the pressure drop across the drain piping was limited to ~20 psi, which is less than the maximum allowable pressure drop of 50 psi.

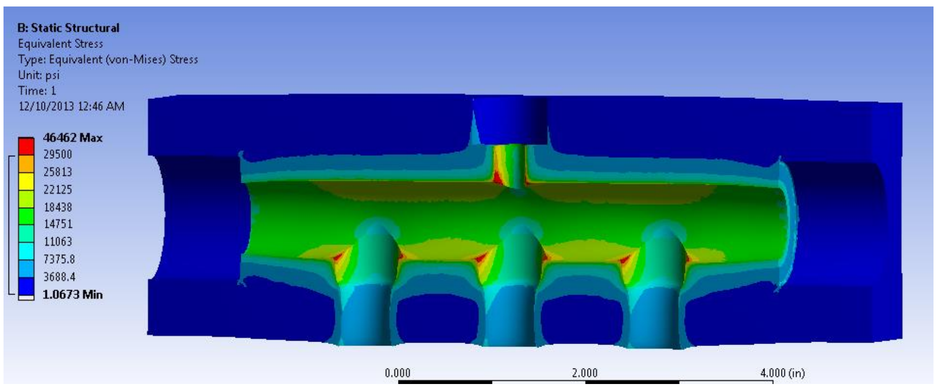
Manifold

Because we are retrofitting our design to be able to reuse components of the existing system, there was a limited amount of space in which we could install all the pressure transducers. It was determined that the use of a manifold would allow us to package the transducers into a smaller footprint with fewer components while still being able to produce accurate pressure readings.

rqmt. #	Importance	Source	Function	Engr. Requirement (metric)	Unit of Measure	Target Value/Range	Comments/Status	Test (how are you going to verify satisfaction)
S1	9	CR2		Withstand Maximum Internal System Pressure	PSI	10000		ANSYS Analysis
S2	9	PRP		Deliver Maximum Required Pressure to Enclosure	PSI	10000		Run on customer pump
S3	9	UL1203		Deliver Minimum Required Pressure to Enclosure	PSI	>50		Run with a pump
S4	9	-		Accept Pressure Transducer Interface	Inches	1/4 NPT		

To determine if the manifold would handle 10,000 psi, ANSYS was used to perform finite element analysis on our design. Most of the design fit well over our factor of safety of two. The lowest factor of safety was 1.27 in the red areas of the graph which allowed us to determine that 7075 Aluminum was an acceptable material to use to construct our manifold.





To help eliminate the risk of failure, we identified the major failure modes possible with our design and tried to identify a recommended action to reduce each.

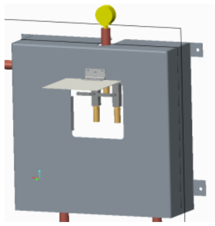
Potential Failure Modes	Potential Effects of Failure	Potential Causes of Failure	Severity	Probability	Rank	Recommended Action
Not able to interface with pressure transducers	Inaccurate Test	Incorrect connections in manifold	2	1	2	Use adapter where necessary
	Loss of Test Control	Non standard connections on components	2	1	2	Machine compatable connection type
	Failure to Meet Operating Standards					
Connections Do Not Line Up	Unable to complete build	Over or under tightening of pipes	3	1	3	Use thread sealant to allow pipes to be turned to correct angles
		Incorrect lengths of pipes	3	1	3	
Burst/Leaks before 10,000 psi	Inaccurate Test	Selected Wrong Material	3	1	3	Use factor of safety in determining material
	Loss of Test Control	Bad Machining/Weakened Material	3	1	3	Use proper machining practices
	Failure to Meet Operating Standards					

Because the 0-1,000 and the 0-5,000 psi transducers cannot handle the full 10,000 psi, they required a shutoff valve in cases where the test being performed went above their safe pressure ratings. The three pressure transducers go in each of the three bottom holes and the top hole will allow them to attach the digital pressure gauge they have on the existing system.

Enclosure

With all the electronic and sensitive components that make up our system, and the destructive nature of the test, we wanted to provide a layer of impact and water protection for the transducers, valve, and motor.

rqmt. #	Importance	Source	Engr. Requirement (metric)	Unit of Measure
S1	9	CR6	Protect system from impact and water damage	Binary
S2	9	-	Allow for easy access to shut off valves	Binary
S3	9	-	Not interfere with system in anyway	Binary



Because it is just a barrier made of sheet metal made to cover the components, the requirements and failure modes are not very specific. To allow for easy access to all components within the system and still be able to protect it during a test, the enclosure was designed out of 6061 aluminum sheet metal with a central access door. With an open bottom to allow for draining, the enclosure is attached to the wall by the tabs seen to the right. Cut outs allow for the pipes to pass in and out as needed. All the components are sealed and able to withstand splashes of water, so the enclosure did not need a 100% waterproof seal.

CONCLUSIONS AND RECOMMENDATIONS

Barring any major changes during testing, the final design of the system is one that will serve the customer well and meet the needs they outlined at the start of this project. In the future, to further refine the capabilities of the system and increase its accuracy, we would recommend moving the manifold downstream of the pressure control valve on the side going to the enclosure. It would see much less flow across the pressure transducers, which would increase the accuracy of the readings. To further insulate the low pressure transducers from seeing the full 10,000 psi, the shut off valves could be automated so that the system will require less human interaction to successfully run a test. With that being said, the system as it stands is more than adequate enough to be able to run all the tests the customer desires.

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