AFRL-RQ-WP-TR-2022-0011

DEVELOPMENT OF A NOVEL FAST-ACTUATING VALVE FOR IMPROVED LUDWIEG TUBE ACTIVATION EFFICIENCY

Shawn Willette
Mainstream Engineering Corp.

JULY 2021
Final Report

THIS IS A SMALL BUSINESS INNOVATION RESEARCH (SBIR) PHASE II REPORT.

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April 1, 2022

Dr. Matt Borg
AFRL/RQHF
2145 5th St.
WPAFB, OH 45433

Subject: Contract Number FA8650-17-C-2437, Phase II SBIR

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Sincerely,

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1. REPORT DATE 09-07-2021	**2. REPORT TYPE** Final	**3. DATES COVERED** **START DATE** 30-08-2017	**END DATE** 09-06-2021

4. TITLE AND SUBTITLE
DEVELOPMENT OF A NOVEL FAST-ACTUATING VALVE FOR IMPROVED LUDWIEG TUBE ACTIVATION EFFICIENCY

5a. CONTRACT NUMBER FA8650-17-C-2437	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER** 65502F
5d. PROJECT NUMBER 3005	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER** Q1W2

6. AUTHOR(S)
Willette, Shawn

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Mainstream Engineering Corp. 200 Yellow Place Rockledge, FL 32955	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Aerospace Systems Directorate Wright-Patterson Air Force Base, OH 45433-7542 Air Force Materiel Command	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/RQHF	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-RQ-WP-TR-2022-0011

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Cleared for public release; distribution unlimited.
PA-AFRL-2022-1673 11 APR 2022.

13. SUPPLEMENTARY NOTES
This is a Small Business Innovation Research (SBIR) Phase II report. Contractor has waived its SBIR Data Rights.

14. ABSTRACT
This report was developed under a SBIR contract for topic AF161-077.
Mainstream has successfully developed a new valve technology for the rapid initiation of flow in hypersonic wind tunnels. The multi-use valve, designed to replace single-use rupture disks, opens to full bore on the timescale of milliseconds. Mainstream has improved the Phase I prototype of the 10-inch fast valve for AFRL's 600 psi, 450°F, Mach 6 Ludwieg Tube. We have also developed new sealing technology, which we implemented into the Phase II prototype of a 24-inch fast valve for UTSI's 150 psig, room-temperature, Mach 4 Ludwieg Tube. This report summarizes the development and results of Mainstream's fast-valve technology during Phase II.

15. SUBJECT TERMS
SBIR Report, Gate Valve, Ludwieg Tube, Hypersonic Wind Tunnel

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**C. THIS PAGE** Unclassified	SAR	34

19a. NAME OF RESPONSIBLE PERSON N/A	**19b. PHONE NUMBER** *(Include area code)* N/A

PREVIOUS EDITION IS OBSOLETE.

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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1. EXECUTIVE SUMMARY

The overarching goal of this Small Business Innovation Research (SBIR) program has been to develop a fast-acting valve to replace Ludwieg Tube burst diaphragms. Mainstream has researched pre-existing valve technologies and developed a new valve technology capable of sealing against the temperatures and pressures commonly found in Ludwieg Tube wind tunnel applications, while still able to completely open the valve bore on the order of milliseconds. Given this “fast-valve” opening timescale, replacement of burst diaphragms with a valve will not significantly affect wind tunnel starting performance, as this opening time is less than half of most driver tube’s first expansion wave reflection time. We have demonstrated this technology through fabrication, testing, and delivery of two differently sized valves.

In Phase I, Mainstream designed and built a 10-inch diameter (full-bore) fast-valve prototype. In Phase II, we refined the sealing and triggering mechanism, and then scaled the design to a 24-inch diameter fast- valve prototype. The initial Phase I fast-valve (1GFV) prototype was purpose-built to AFRL’s Mach 6 Ludwieg Tube, requiring a temperature and pressure rating of 450 °F and 600 psi, respectively. This prototype has been tested and modified several times during Phase II, thereby providing AFRL with an improved valve system and serving as a test platform for several design changes that were to be implemented in the next design iteration. During Phase II 1GFV testing, the valve was able to reliably seal at driver tube pressures up to 600 psi at 90 °F, and registered consistent opening times between 47 and 69 ms (Mainstream’s pressurized test conditions using its 5 ft driver tube are not identically representative of valve performance within an actual Ludwieg Tube due to the difference in valve thru-bore pressure over the entire actuation event). However, systemic seal disengagement problems with the pneumatic gate seal mechanism led Mainstream to develop a new mechanically-driven seal design. This mechanical design was implemented into the 1GFV as well as the larger 2nd-generation fast-valve (2GFV).

The primary focus of Phase II has been the design and fabrication of a larger 2GFV for Ludwieg tubes. For example, University of Tennessee Space Institute’s (UTSI) Mach 4 Ludwieg Tube has a 24-inch thru- bore, possesses a pressure rating of 150 psi, and operates at room temperature. The 2GFV is significantly more sophisticated and refined than the 1GFV, integrating more automated valve control and state awareness. This includes the sensors and data recording hardware to autonomously record the valve opening time. Mainstream recommends 2GFV validation testing be performed in-situ once the valve is installed at UTSI.

While a great deal of research and development was devoted to the design, analysis, and manufacturing of both valves, additional time was spent producing a user-friendly system. Therefore, the content of this final report is based on the 2GFV Operator Manual (found in the Appendix) that will be delivered with the valve and aid personnel in installing, operating, and maintaining this system. With proper operation and care, the 2GFV should improve Ludwieg Tube wind tunnel testing turnaround time by a factor of five or more, thereby eliminating the need and cumulative costs of burst diaphragm replacement.

With the conclusion of this SBIR contract, Mainstream will ship the 1GFV to AFRL and the 2GFV to UTSI for installation, validation testing, and general use within their respective Ludwieg Tube facilities.

Furthermore, as pioneers of this technology and desiring for the continued advancement of these valves, Mainstream can provide technical and installation support to ensure AFRL and UTSI researchers realize the greatest utility possible from such devices.

2. FAST-VALVE DESIGN PROGRESSION & RESEARCH

Mainstream has completed a successful Phase II SBIR program to refine the Phase I 10-inch valve and develop a 24-inch valve. The research and development that Mainstream performed is well documented in the monthly reports. This final report summarizes the highlights during Phase II.

- Refinement of Phase I 10-inch Fast Valve (1GFV)
  - O-ring Shroud Sleeve – Mainstream redesigned the original two-piece, press-fit, assembly, consisting of the o-ring shroud sleeve and tunnel shroud sleeve, with a single component. This alteration removes the tunnel shroud cavity and eliminates a potential leak path.
  - Tigger Mechanism Down-lock Piston – Mainstream enlarged the pneumatic piston (1.002 inches to 1.367 inches) that maintains gate down-lock prior to trigger actuation to provide additional piston force (increased factor of safety from 1.3 to 2.3) and ensure that the down-lock remains engaged in the event of a primary gate seal failure. The larger trigger mechanism maintains gate down-lock at the maximum rated pressure during a bleed-off event.
  - Fast-Valve Control Scheme – Mainstream redesigned the external pneumatic plumbing to automate valve operation, allowing the valve to be set, fired, and reset remotely. This modification eliminates the need for manual human operator interaction with the valve,thereby increasing operational safety for both wind tunnel personnel and the valve.
  - Transfer Carriage: To improve reliability, Mainstream retrofit the 10-inch valve with the transfer carriage technology developed for the 24-inch valve (scaled for the smaller size).This replaces pneumatic actuation of the o-ring shroud and with mechanical actuation.
  - Additional Testing – Mainstream added high-speed fiber-optic sensors behind the gate to measure the time required for the gate to traverse from full down-lock position to clearing the bottom of the bore. Unpressurized valve opening times were in agreement with Phase I test results, clocking valve actuation at 65 ms.
- Development of Phase II 24-inch Fast Valve (2GFV)
  - Mainstream worked with UTSI to define the requirements for a 24-inch valve for integration into UTSI's TALon Mach 4 Ludwieg Tube.The salient requirements are:
    - Valve must open in approximately 100 ms
    - Valve must seal against dry air at maximum rated conditions of 180 psig at 85 °F.
    - Valve must have an unobstructed bore of 24 inches
    - Valve must have integrated, single-action, reset mechanism
    - Valve flange interfaces shall consist of the following
      - INLET: 24-in. Victaulic® AGS Style W07 Vic-Ring® System
      - OUTLET: 24-in. ASME/ANSI B16.5 Class 150 socket-weld flange
    - Valve actuation direction shall be downward, or gravity-assisted, in relation to driver tube position
    - Valve must have a design lifetime of at least 50,000 cycles
  - Mechanical O-ring Shroud – Mainstream developed a new mechanical actuation system for the 24-inch valve that does not rely on pneumatic actuation as in the 10-

inch valve. This development stemmed from two derived requirements evident from the 10-inch valve testing. First, the need to quickly pull and maintain vacuum on the o-ring shroud cavity to reliably retract the annular ring within the necessary time scale. Second, the aspect ratio of the rod-gland o-rings would exceed a value specified by the aerospace standard for dynamic seals, making them vulnerable to in-groove twisting.

- Transfer Carriage: Mainstream developed a gear-driven ring assembly, referred to as a transfer carriage, that unidirectionally revolves around the inlet pipe while rolling on the upstream plate face. It is driven by a master gear and an externally-mounted motor. Within the transfer carriage, four yoke bearings roll along a periodic face gear track machined into the upstream-side of the o-ring shroud. Therefore, as the transfer carriage rotates, the embedded yoke bearings push against the o-ring shroud and mechanically extend the primary o-ring seal embedded within the downstream-face of the o-ring shroud. This extension also compresses a wave spring that encompasses the o-ring shroud and ultimately applies the necessary retraction force during 2GFV actuation. After the transfer carriage progresses far enough, the yoke bearings uniformly "falloff" a plateau on the face gear track and allow the wave spring to rapidly force o-ring shroud retraction.
- Reset Ram Retraction Sensors – Mainstream developed an inductive proximity sensor to integrate into the spring shroud flange cap. The sensors can withstand 600 psi, which is the pressure required to charge the actuation springs. These sensors ensure that the rams have fully retracted after the gate is locked into place.
- Testing: Mainstream cycled the mechanical seal extension and retraction functions 30 times to ensure proper operation.

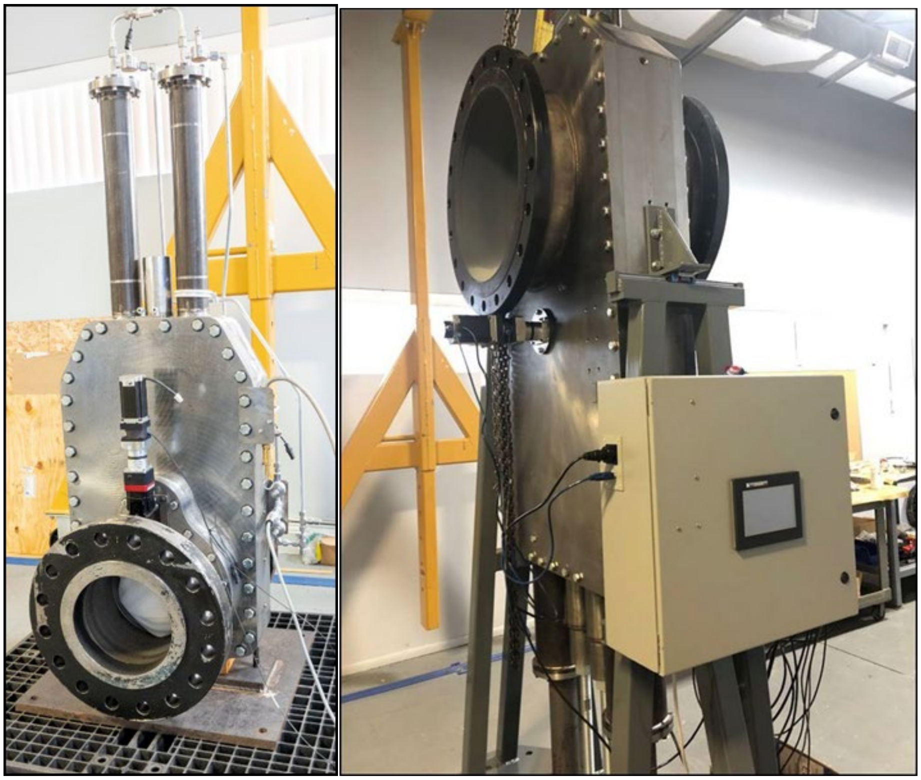


Figure 1. Left: 10-inch 1GFV Prototype, Right: 24-inch 2GFV Prototype

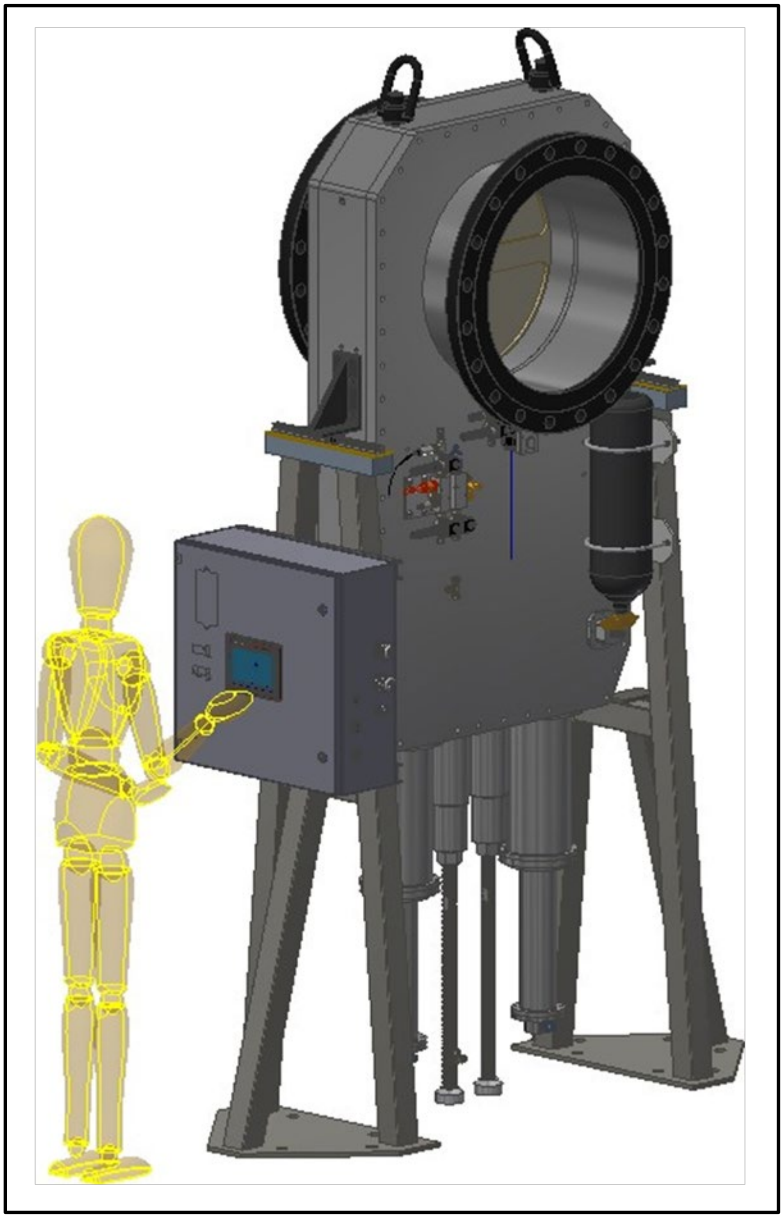
3. CONCLUSIONS

Mainstream has successfully developed a new valve technology for rapid initiation of flow in hypersonic wind tunnels. This valve, termed “fast valve,” is based on gate valve technology but has the ability to open to full-bore cross-sectional flow area within milliseconds, even for 24-inch diameter Ludwieg tubes. Mainstream has researched fast-acting linear bearing systems, actuators, and seals resulting in the design and fabrication of reliable and safe fast valves. The first prototype small valve, shown in Figure 1 (left), has a 10-inch thru bore and will be delivered to AFRL. The first prototype large valve, shown in Figure 1 (right), has a 24-inch thru bore and will be delivered to UTSI. Both valves are shown in their uncoated state. Both will be coated for environmental protection prior to shipping.

LIST OF ABBREVIATIONS AND ACRONYMS

1GFV	1st-Generation Fast-Valve (10-inch bore)
2GFV	2nd-Generation Fast-Valve (24-inch bore)
AFRL	Air Force Research Laboratory
ASME	American Society of Mechanical Engineers
FV	Fast-Valve
GUI	Graphic User-Interface
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
PRV	Pressure Relief Valve
SBIR	Small Business Innovation Research
USB	Universal Serial Bus
UTSI	University of Tennessee Space Institute

APPENDIX: 24-IN. FAST-VALVE OPERATOR MANUAL



24-inch Fast-Valve Operator's Manual

Mainstream Engineering Corporation Rockledge, FL 32955

321-631-3550

July 2020

Document Revision History				
Rev. Number	Date Reviewed	Date Approved	Description	Signature
0	7/9/20		Initial Release	

1. SCOPE

This manual covers the design and operation of Mainstream's 24-inch Fast-Valve (FV). This FV is intended to replace burst diaphragms within a Ludwieg Tube in order to initiate gas flow. The following sections cover the overall valve design theory, performance envelop, operator interfaces, installation interfaces, and maintenance schedules.

2. FAST-VALVE DESIGN AND OPERATION

The FV is a large gate valve with an actuation system designed to rapidly unseal and remove the flow blocking gate from the valve's thru-bore. Once the gate is removed, flow through the FV's bore will be completely unobstructed and the driver tube can discharge accordingly. With any flow initiation mechanism for a Ludwieg or shock tube, it is advantageous to release the charge pressure as quickly as possible, thereby establishing a "clean" starting shock wave and maximizing the amount of useful test time that can realized within the wind tunnel's test section during the limited blowdown duration. Therefore, this FV is designed to open on the order of milliseconds, yet close on the order of seconds.

There are several noteworthy features of this FV that generate its performance and make it novel. Mainstream's FV design incorporates an o-ring seal upstream of the gate face that maintains the valve's gastight performance. This seal is mechanically engaged and disengaged from the gate face (at user- selected intervals) in order to preserve o-ring life integrity and eliminate seal contact on the gate during gate actuation. Therefore, the FV gate actuation sequence consists of two decoupled retraction mechanisms acting in series; first, the gate seal is removed, followed immediately by the gate being retracted from the valve bore.

Gate retraction from the bore is facilitated mechanically by a pair of extension springs. These springs load the gate while it is locked in place within the valve bore. Then, upon gate actuation, the lock holding the gate in place is removed and the springs are free to pull the gate out of the bore. The trigger mechanism that maintains and releases this gate lock is reliant on a pneumatic piston. This piston is supplied pressure to hold engagement and is evacuated of pressure to disengage. Additionally, a trigger safety mechanism is built into the FV in order to mechanically support trigger piston extension in case of accidental pressure loss.

After the gate clears the valve's thru-bore, it impacts a pair of shock absorbers that rapidly decelerate the gate to a stop over their stroke length. The gate can then be reset within the valve bore and the actuation springs re-extended via twin pneumatic reset rams that are nested within the inner diameter of each spring. These rams are pressurized to reset the gate and depressurized prior to an actuation/firing event to ensure they are removed from the gate's path.

A high-level, cross-sectional schematic of the FV is provided in Figure 1, which depicts the location, orientation, and nomenclature of the aforementioned FV components. Additionally, Figure 2 shows the FV with the upstream plate assembly removed to show the relative gate stroke length within the valve body.

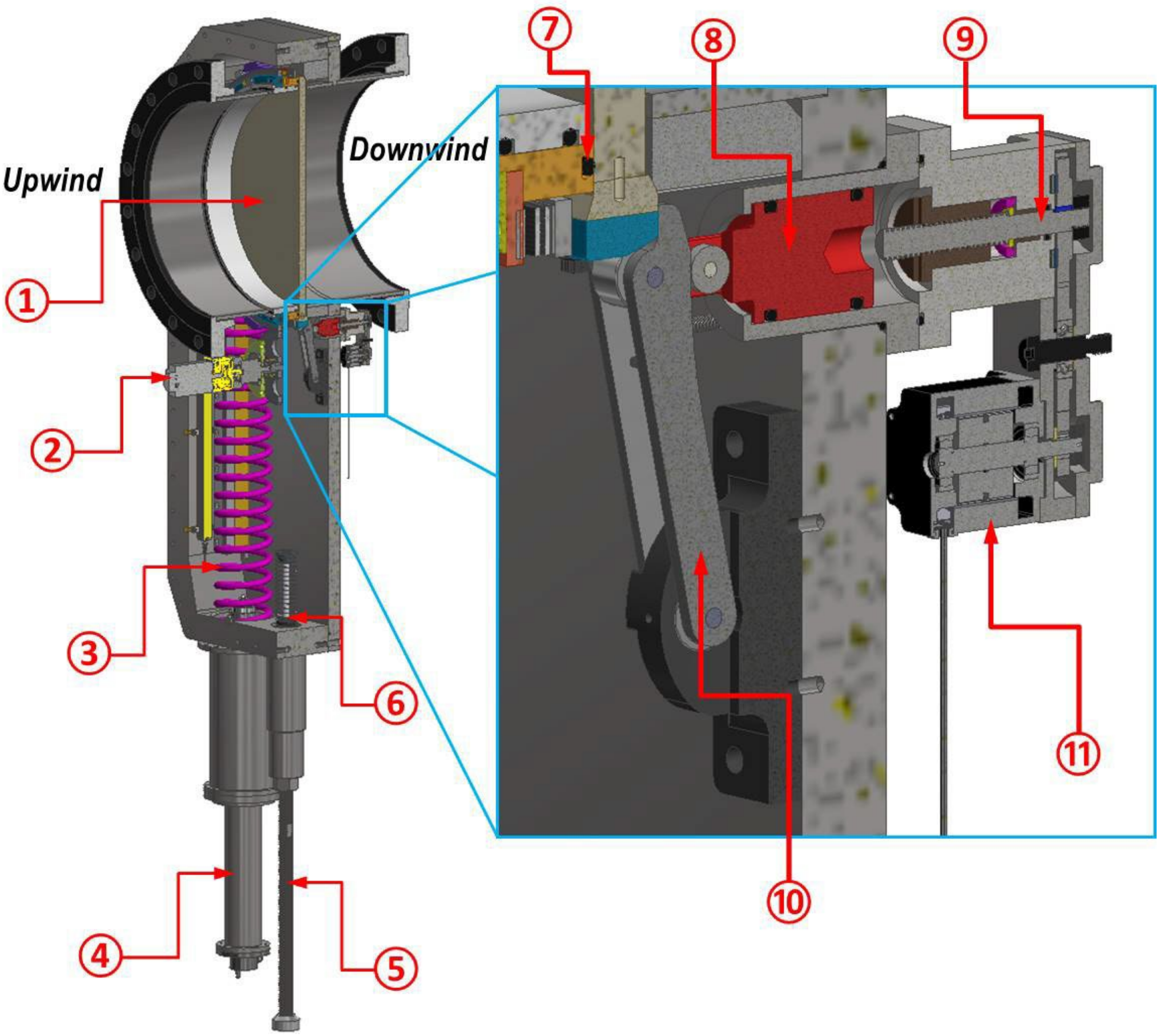


Figure 1: Cross-sectional depiction of FV with enumerated components defined below (Note, upstream plate and mounting structure removed for visibility)

① Gate
② Gate Seal Stepper Motor
③ Actuation Extension Spring [x2]
④ Reset Ram Housing [x2]
⑤ Shock Absorber Strut [x2]
⑥ Shock Absorber [x2]
⑦ Upstream Gate O-ring Seal
⑧ Trigger Piston Ram
⑨ Trigger Safety Mechanism
⑩ Trigger Lever Arm Assembly
⑪ Trigger Safety Stepper Motor

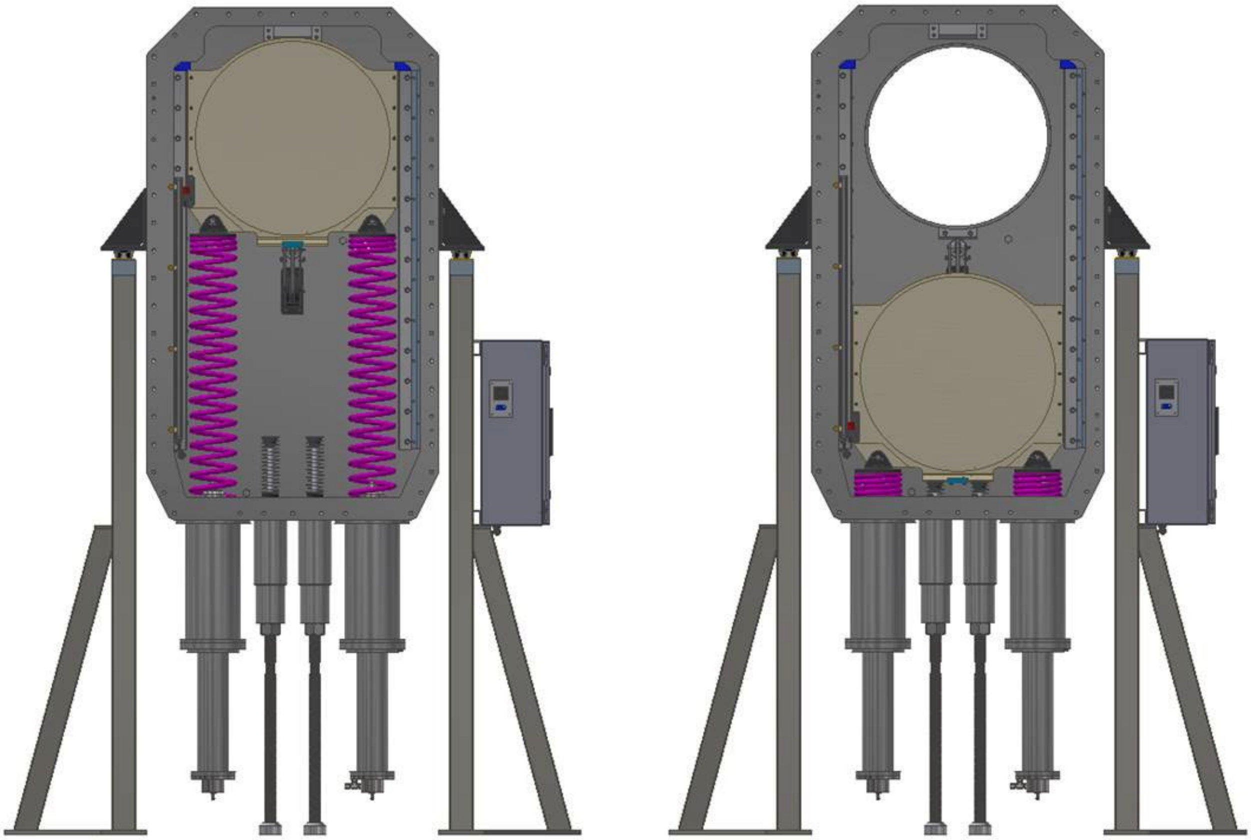


Figure 2: Upstream view of FV showing gate stroke with the upstream plate assembly removed

The FV is operated and controlled by a combination of electromechanical and pneumatic components. Pneumatics control the FV trigger and reset mechanisms, while stepper motors drive the mechanics controlling the gate seal and trigger safety mechanisms. In order to monitor these controls and provide system state feedback, an array of sensors is distributed throughout the system. A piping and instrumentation diagram (P&ID) of the FV's external control system is provided in Figure 3. The blue lines in Figure 3 represent pneumatic plumbing lines while the red lines represent electrical wiring harnesses running to their defined components. Each physical control component or sensor on the delivered FV is labeled in accordance with the nomenclature used in this P&ID. Furthermore, the pneumatic portion of the FV's P&ID, as installed on the physical FV, is shown in Figure 4, with the primary components identified for reference.

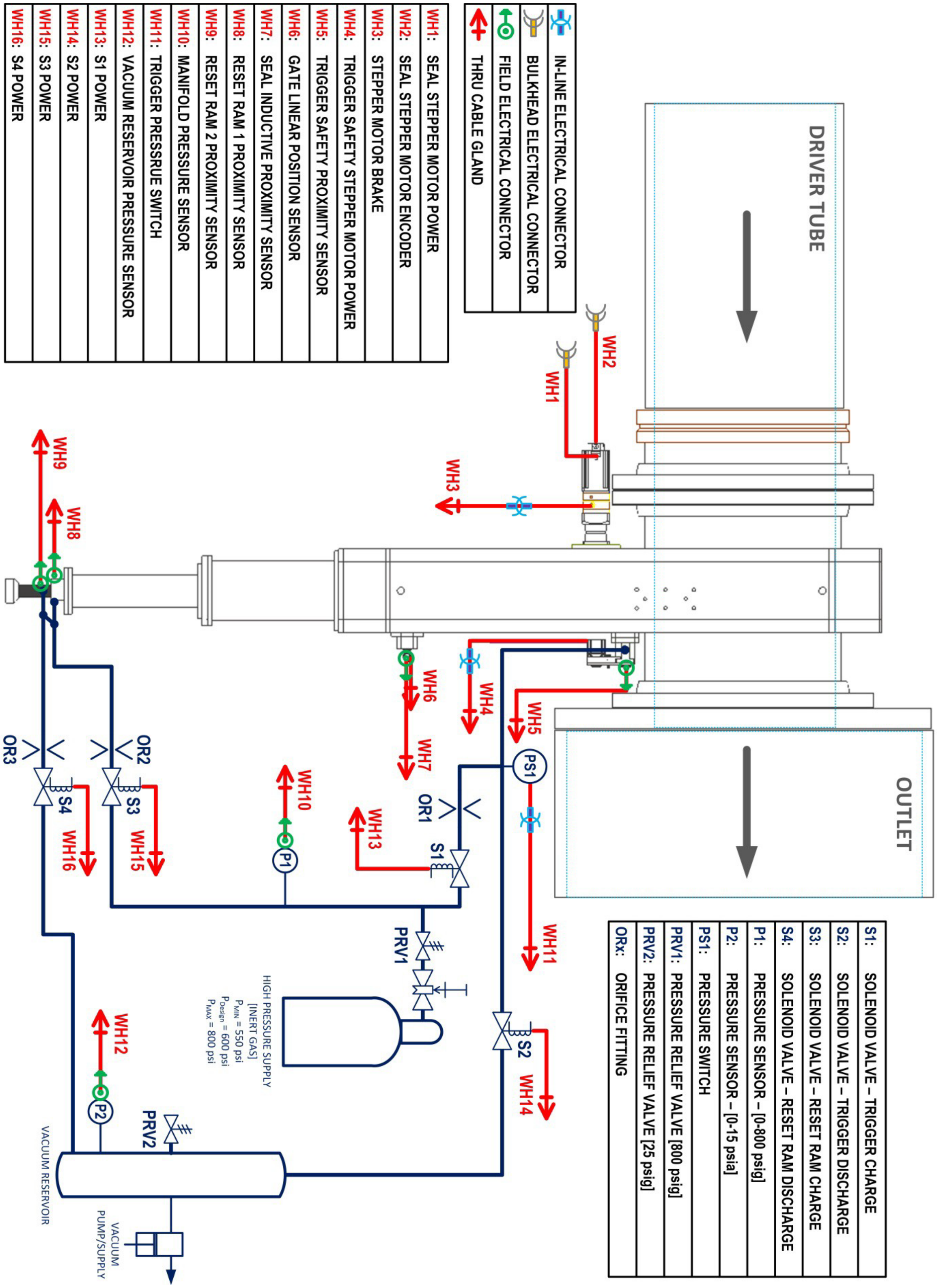


Figure 3: FV P&ID

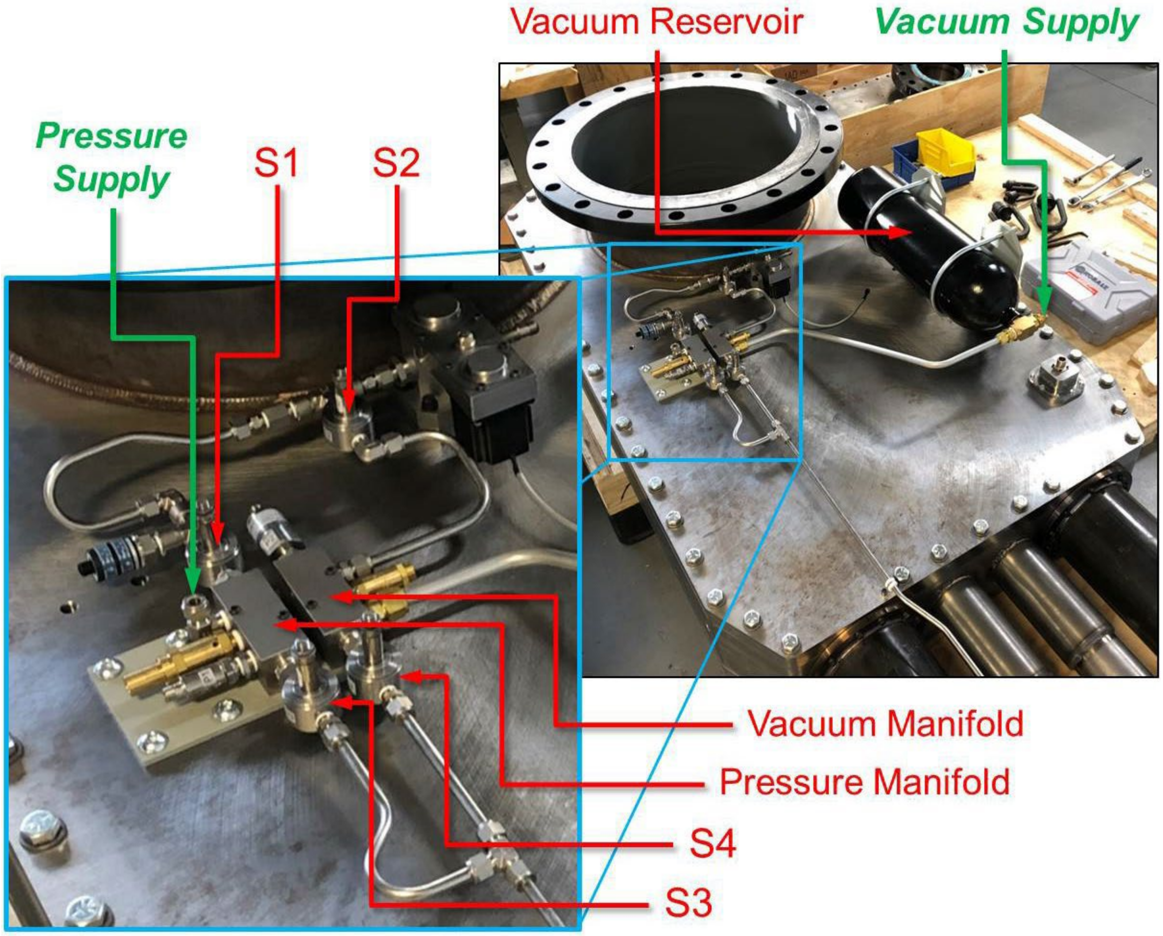


Figure 4: FV pneumatic control system architecture, as identified in Figure 3

Using the control architecture specified above, the FV is systematically progressed through a series of states to safely and reliably charge/discharge the valve. These states, diagramed in Figure 5, are navigated via operator commands, whether on the graphic user-interface (GUI) or remote Ethernet communication. In its lowest energy state point the FV is open with the gate fully retracted by the extension springs. Once the "RESET [VALVE]" command is given, the FV programmable logic controller (PLC) performs the sequence to raise the gate into position, establish the gate seal, lock the gate trigger, and retract the reset rams; thereby, progressing the FV to the "Gate Closed" state. Alternatively, this state progression can be reversed with the "SOFT UNLOAD" command, where gate seal is released and the reset rams extend and slowly lower/de-energize the gate back to the "Gate Open" state.

However, the nominal progression from the "Gate Closed" state is to the "Gate Armed" state via the "ARM" command. This command should only be sent to the FV when all other wind tunnel systems are ready for flow activation and the operator intends to fire the FV in the immediate future. The FV arming function disengages the trigger safety mechanism, awakens the gate seal stepper motor, prepares the FV's high-speed data acquisition hardware to record, and activates user-access to the "FIRE" command. The actions "ARM" command sequence is reversible though by selecting the "DISARM" command, thus reverting the valve state to "Gate Closed."

Once the FV PLC completes the arming sequence and arms the "FIRE" command, the system awaits the user's "FIRE" command to advance through the firing sequence. Since the firing sequence occurs over less than a second and is irreversible, there is no stopping the FV firing sequence once it is triggered. As concluded by the Figure 5 diagram, the result of the "FIRE" command is the release of the FV gate and its return to the initial, low-energy "Gate Open" state point.

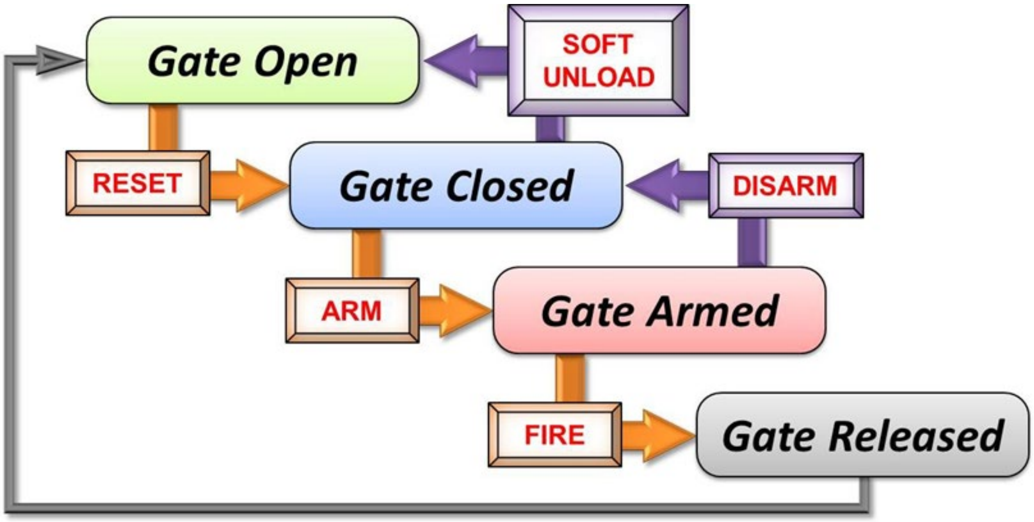


Figure 5: FV state diagram and command progression, showing state points in balloons with black text and commands in beveled rectangles with red text

3. OPERATIONAL LIMITS

The FV was designed for operation under room temperature ambient conditions (<90 °F) and artificially heated driver tube gas. The valve's wetted components allow for the use of any inert gas mixture to be used within the Ludwieg Tube. The FV possesses a sealed upstream driver tube pressure rating of 150 psig, while the entirety of the valve body is rated for a pressure range of total vacuum to 150 psig. Any deviation from these operating conditions is not advised. Please consult Mainstream if potential deviation from outlined performance envelop is desired.

4. OPERATOR INTERFACE(S)

There are two primary means of FV operation/interface. First, on the front cover of the FV's electrical enclosure, shown in Figure 6, there is a touch screen GUI that allows an operator to observe the current valve state and, if desired, control valve operation from this access point. Additional GUI screen information is provided at the end of this manual.

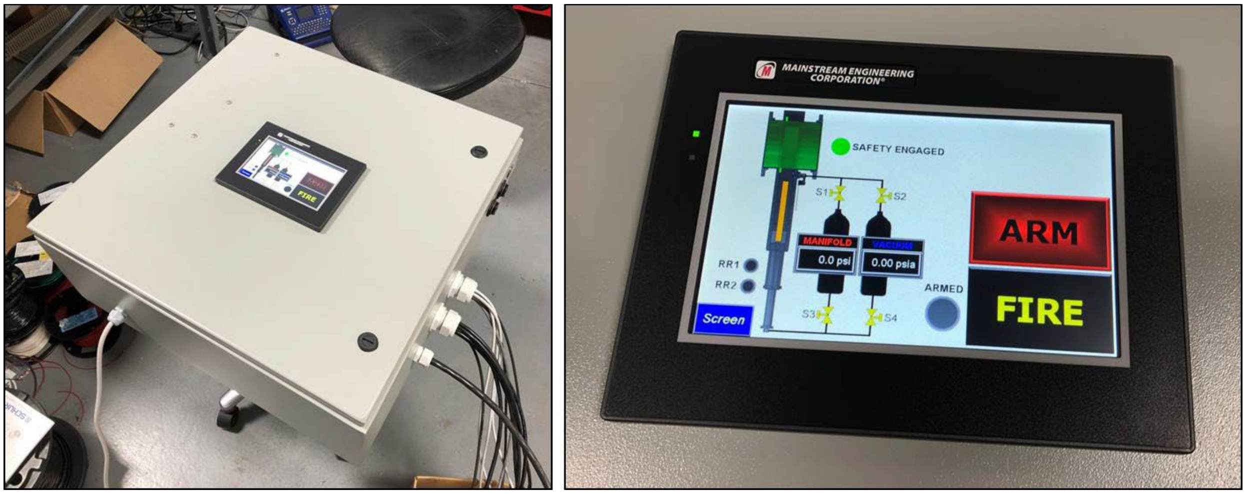


Figure 6: Front panel (left) of FV electrical enclosure with a close-up of the GUI touchscreen (right)

Second, two RJ45 receptacles, identified in Figure 7, are available for Ethernet communication with any compatible computer that wishes to interface with the FV. Both of these ports are networked together off of a single Ethernet switch that connects to the FV's Productivity 2000 PLC. Therefore, a remote wind tunnel administrator computer executing the correct Ethernet communication protocol will be able to monitor and control FV operation. For networking purposes, the relevant communication information is provided in Table 1.

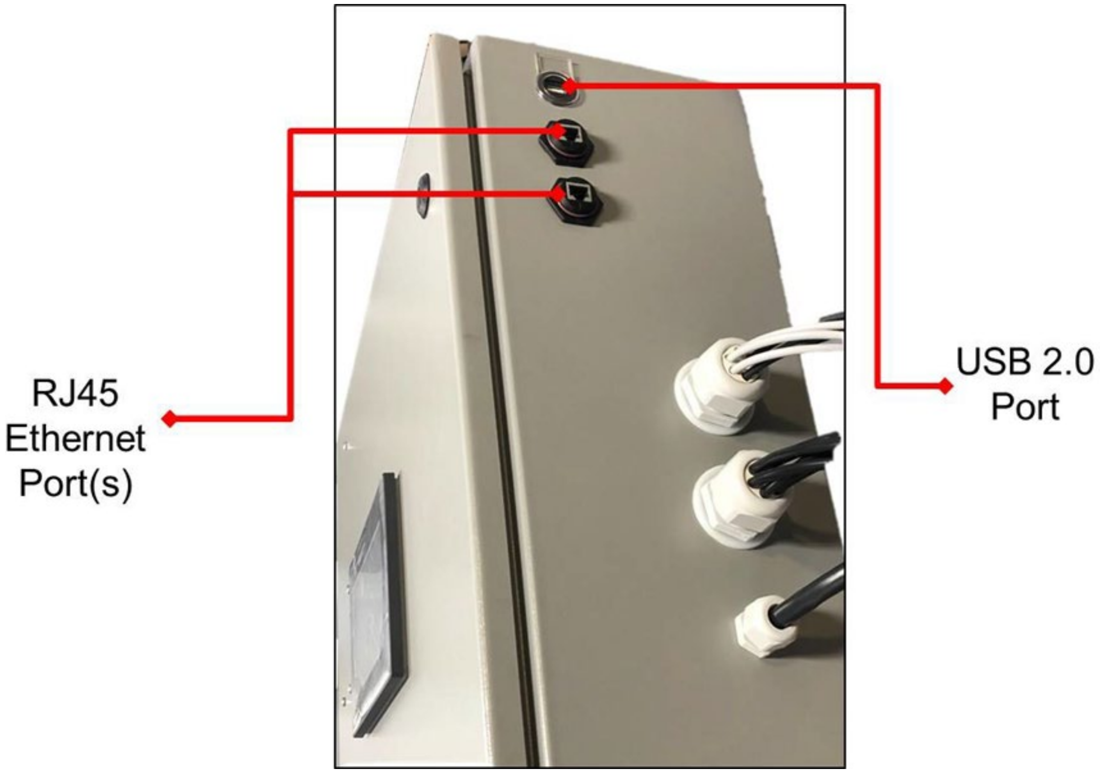


Figure 7: FV electrical enclosure with callouts for networking interfaces

Table 1: 24-inch FV Network Communication Parameters

Static IP Address	**192.168.6.12**

Subnet Mask	**255.255.0.0**
Subnet	**192.168.0.0**

Parameter	***PLC Address***	***Data Type***	***Unit***	***Purpose***	***Description***
RESET_VALVE	C-000013	Boolean	-	Command	FV Reset Command – SET ON
ARM	C-000038	Boolean	-	Command	FV Arm Command – SET ON
FIRE	C-000037	Boolean	-	Command	FV Fire Command – Momentary ON
UNLOAD_VALVE	C-000064	Boolean	-	Command	FV Soft Unload Command – SET ON
Armed	C-000041	Boolean	-	Feedback	FV Armed Status Bit
P1_psi	F32-000001	Float, 32-bit	psig	Feedback	FV Manifold Pressure
P2_psi	F32-000002	Float, 32-bit	psia	Feedback	FV Vacuum Reservoir Pressure
Gate_Pos_inch	F32-000004	Float, 32-bit	in.	Feedback	Gate Position (~0 in = closed)

Additionally, a single USB 2.0 receptacle is provided just above the electrical enclosure's Ethernet ports, also shown in Figure 7. This port is designated for dissemination of gate positional data during a discharge/firing event. The FV gate's opening time, maximum velocity, and acceleration can all be derived in post-processing. Until manually deleted, all data files from previous FV firing events are discoverable in time/date stamped files within any computer connected to the USB port. During the FV arming and firing sequences, this USB port is deactivated and will not reappear as a discoverable USB device until the firing sequence has concluded or the FV has been disarmed.

Due to the high-speed nature of the data acquisition hardware integrated into the FV's electrical enclosure, the raw gate opening data is stored in the native data format of the data acquisition system manufacturer, Dataq Instruments. This data is stored as a .wdc file formatted in the Common Ocean Data Access System (CODAS) syntax. Dataq offers a free, windows-based software package that provides for easy and user-friendly dissemination of data. Available for online download from their website (www.dataq.com), WinDaq Playback for the DI-2108 Data Acquisition Module provides users the ability to view the gate opening data and, optionally, export it to other programs (including Excel). Note that the raw data is recorded on a range of 1 to 5 Volts and must be converted using Equation Eq. (4.1) in order to analyze the gate opening profile in inches.

$$XX\,[iiii] = -7.6795 * VV\,[vvvvvvvvvvvv] + 38.3975 \qquad \text{Eq. (4.1)}$$

5. FAST-VALVE INSTALLATION

The primary FV interfaces with the Ludwieg Tube are two 24-inch ASME B16.5 Class 150 flanges, one upstream and one downstream of the main valve body. These flanges contain thru-holes for 20, 1¼-inch bolts that are evenly spaced on a 29½-inch bolt circle. Each bolted flange joint is to be torqued in accordance with the ASME Section VIII, Division 1, Appendix 2: Boiler & Pressure Vessel Design Rules and/or UTSI pressure rated assemblies' protocol. The general

FV installation dimensions are provided in Figure 8.

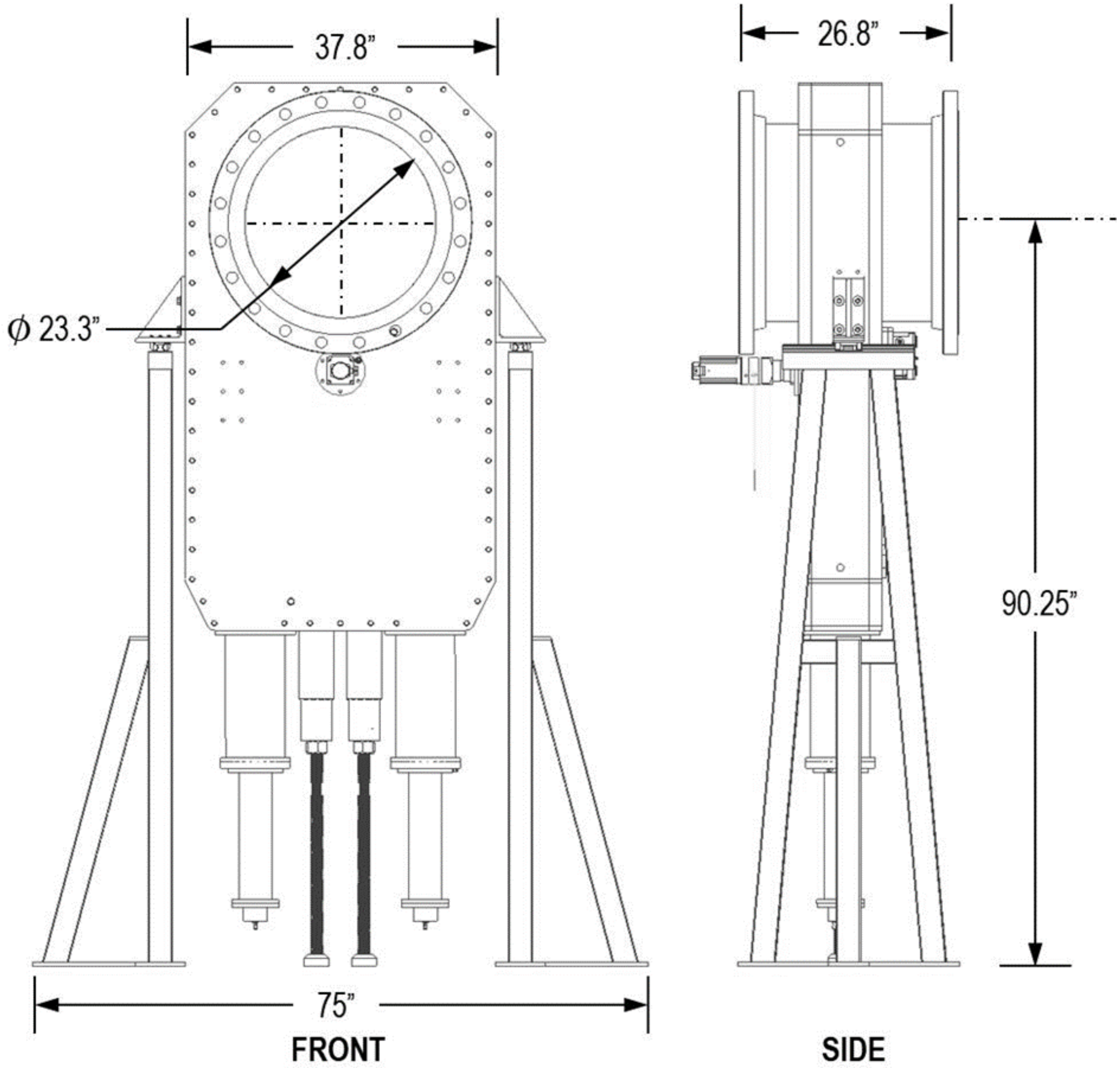


Figure 8: Overall FV dimensions

The FV is outfitted with a number of external threaded hardpoints by which the valve can be hoisted and moved. These hardpoints are identified in Figure 9, and will be used for both initial installation and mounting.

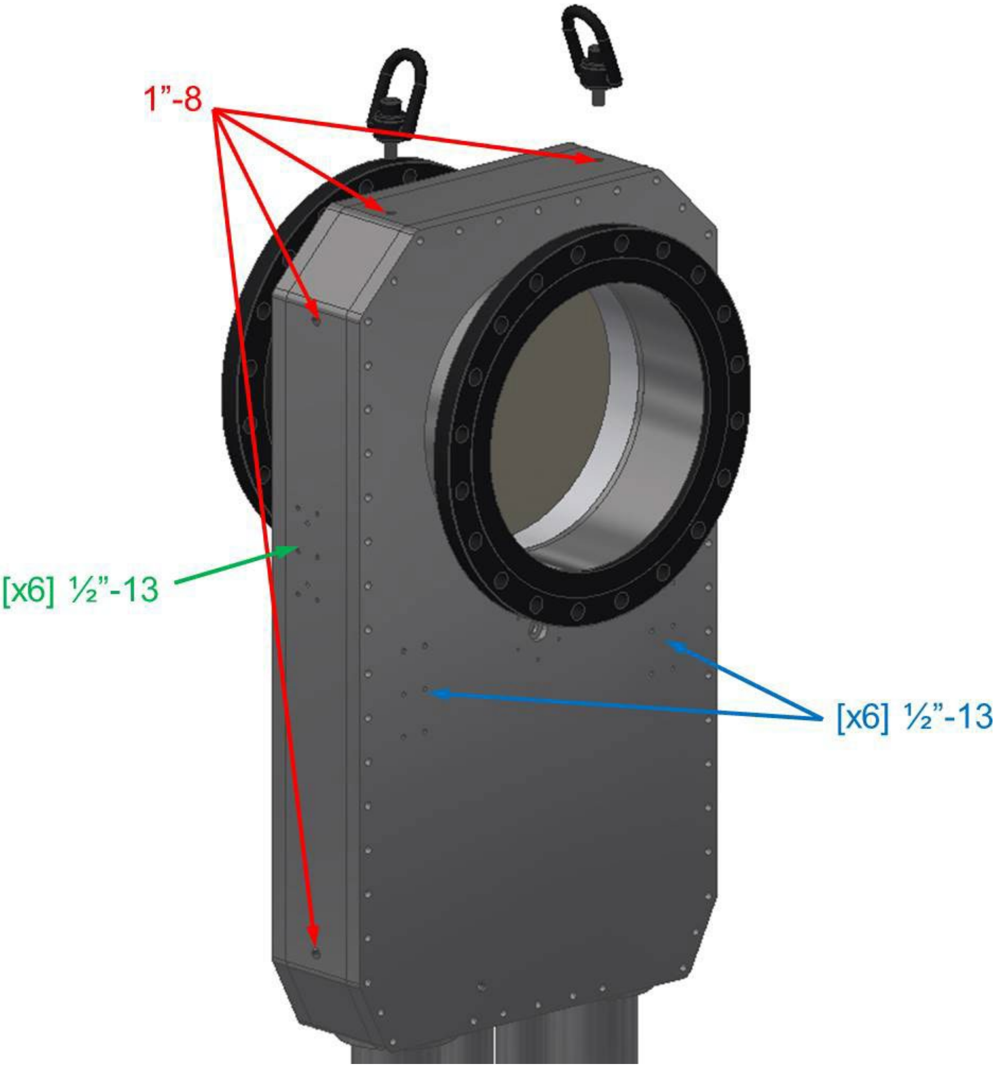


Figure 9: Thread specifications for FV lifting/mounting hardpoints. Note, all thread callouts have a mirror-image feature twin on FV surface not shown in this isometric view.

Once the FV is positioned within the Ludwieg Tube gap installation location, a number of position adjustment features have been built into the FV stand in order to account for misalignment. Slots machined into the FV mounting brackets allow for installation positioning perpendicular to the tunnel’s long axis (±1-inch; Y-axis), while linear bearings on the mounting stands allow for sliding of the FV along the long axis of the tunnel (±8-inch; X-axis). Finally, during installation, precision shims can be added beneath the FV mounting brackets to take up any vertical difference between the valve bore centerline and the Ludwieg Tube’s (Z-axis). A depiction of these components is provided in Figure 10.

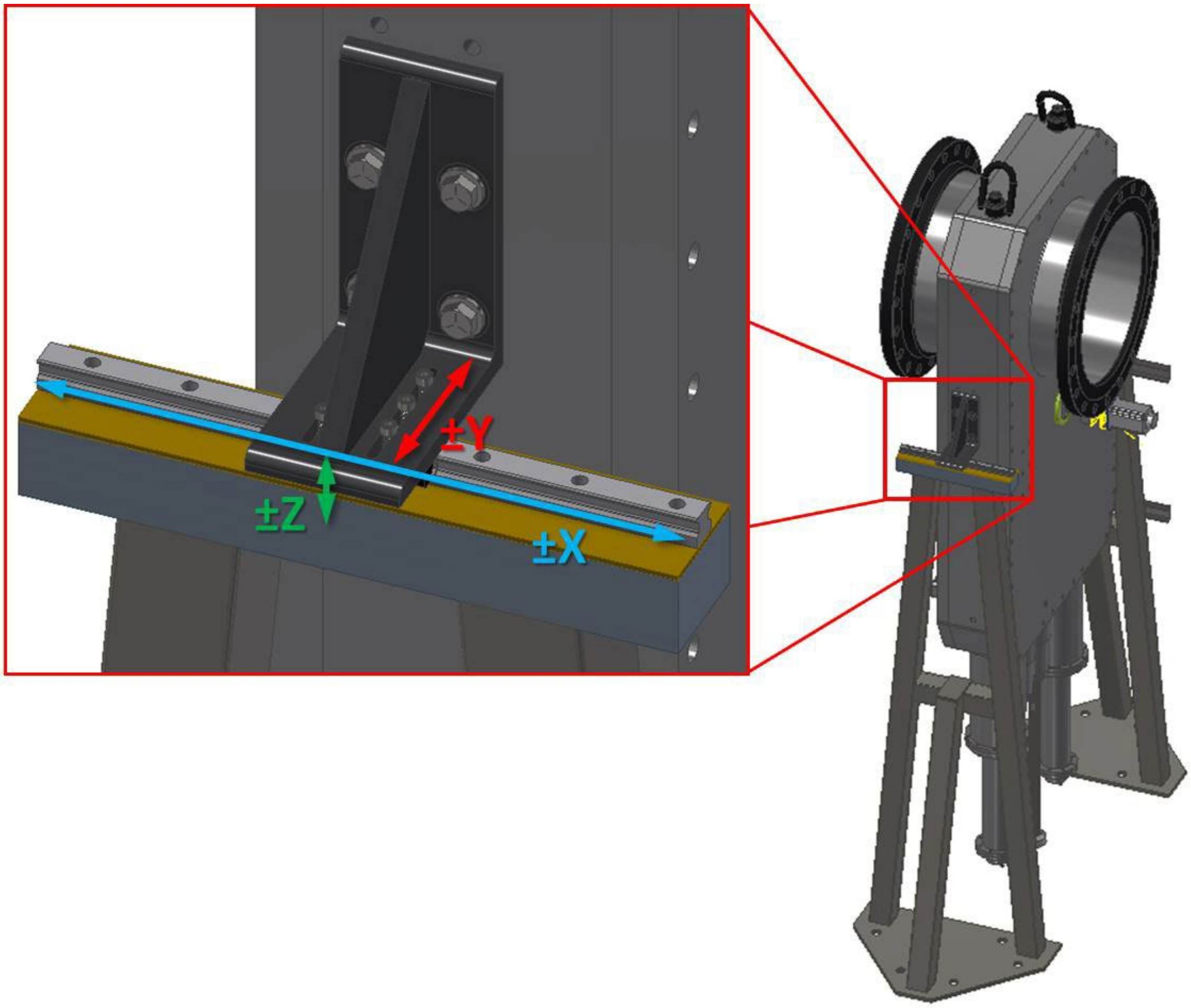


Figure 10: FV mounting position adjustment design

The foot of each mounting stand has six 1¼-inch diameter holes to anchor the valve to the laboratory floor. The method of anchoring is left to the user. Anchoring must be provided to properly support the FV weight and actuation reaction forces.

With the FV hard mounted in place, a pair of ACME threaded rods, located under the FV shock absorbers (see Figure 11), are to be extended to the floor and torqued until hand-tight. After which, these ACME threads are to be preloaded in compression to provide a minimal resistance in directing the shock absorber reaction force to ground. Therefore, each ACME thread is to be torqued to 38 ft-lbs, prior to a jam nut being tightened against the active thread.

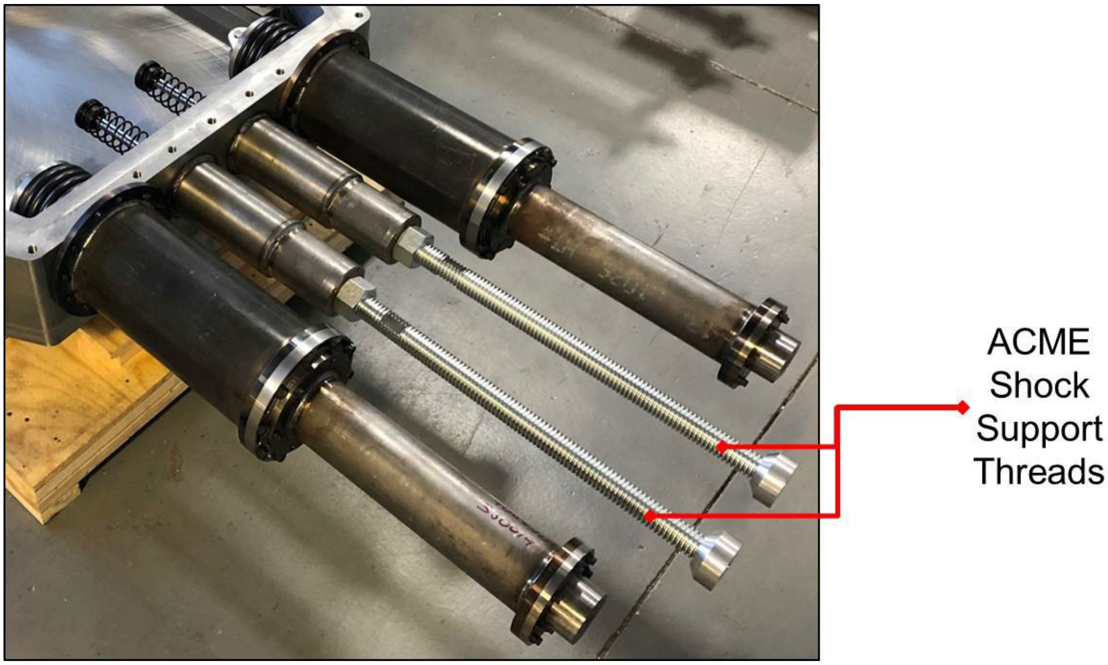


Figure 11: Photograph identifying the FV's ACME shock support threads

6. FAST-VALVE OPERATIONAL REQUIREMENTS

In order to operate properly, the FV must be supplied with both electrical and pneumatic power. The FV requires constant access to an electrical outlet supplying standard 120 VAC, 60 Hz, single-phase power for its electronics. A power cord runs from the bottom of the FV electrical enclosure that terminates in a standard NEMA 5-15 plug. Under highest load operating conditions, the FV is expected to intermittently consume no more than 13 A.

The FV must be supplied with a regulated source of an inert gas (e.g., nitrogen) to pressurize its control system. Supplied pressure must be 600 ± 50 psig in order for the FV to operate properly. The delivered pressure supply fitting is a 3/8-inch Swagelok® stainless steel tube fitting. As added precaution, the FV PLC will not allow valve operation under 500 psig and provides a user alarm on the GUI if such an attempt is made. Furthermore, a FV manifold pressure relief valve (PRV), set to 800 psig, is built into the valve's control architecture to discharge the system in the event of accidental overload.

The FV must be supplied with a source of vacuum, whether it is the primary tunnel's vacuum system or a designated vacuum pump. The FV has a built-in vacuum reservoir, but this reservoir will need to be evacuated between successive valve actuations. The vacuum interface fitting is a ¼-inch threaded male SAE tube fitting (45° flared). Required vacuum is set at a minimum of 2.0 psia. Additionally, a second PRV is built into the FV's vacuum manifold system to discharge any pressure in excess of 25 psig. However, the vacuum PRV is expected to discharge at least once per valve cycle when the valve's reset rams are retracted and their pressure is released to the vacuum reservoir.

The location of these inputs is identified in Figure 4.

7. RECOMMENDED FAST-VALVE MAINTENANCE SCHEUDLE

Mainstream recommends users establish a routine maintenance schedule to ensure proper and continued functionality of the FV. The FV was designed for long structural service life, with a handful of high-load components that are replaceable after failure or excessive wear. As this is a first prototype, the empirical service life of each component is unknown. Therefore, best engineering practices and analytical life calculations were employed to select/design components with the longest reasonable service life available. To this end, no one specific component has a calculated service life of less than 50,000 FV shot cycles.

As a first prototype, the service life of the FV must be diligently inspected on a periodic schedule to ensure smooth operation and no excessive wear patterns have originated/propagated. Mainstream recommends that the FV internals be visually inspected after every shot for the first 10 shots following initial installation and then every 50 FV shot cycles. These visual inspections do not require the removal or disconnection the FV from the Ludwieg Tube, as the FV has two borescope inspection holes built into the upstream valve body plate (see Figure 12). During normal operation, these inspection holes are plugged and sealed, however, upon removal of the plugs the valve internals are accessible for visual inspection. These ports are the selected size because they are large enough to permit tool access but are too small to permit human finger ingress. During a visual inspection, the components of interest and what to look for are indicated in Table 2.

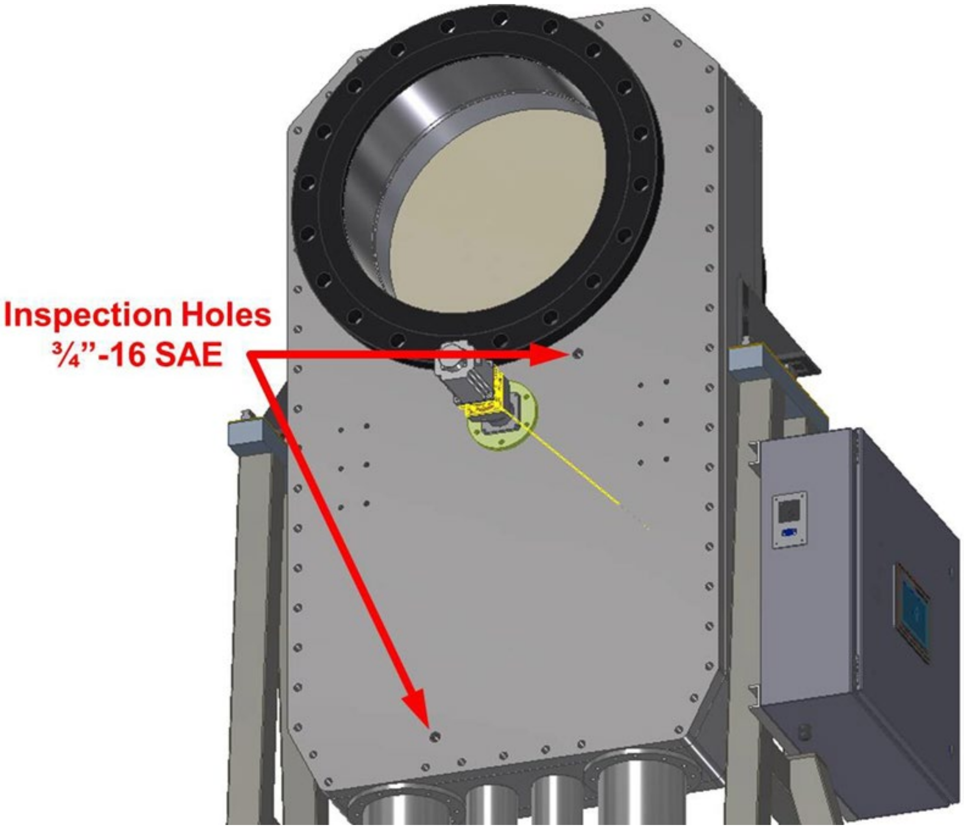


Figure 12: Relative location of the FV’s borescope inspection port

Table 2: FV Visual Inspection Checklist

Component to Inspect:	What to look for:
Linear Bearing Tracks [x2]	Signs of excessive wear or damage on the needle tracks, as well as

	signs of proper grease lubrication film thickness
Actuation Springs [x2]	While in the extended position, inspect for any wear or rub marks around the outer diameter of the coils, and ensure that the springs are still properly seated against their gate attachment plugs
Shock Absorbers [x2]	Using the FV reset rams, lift the gate off of the shock absorbers to inspect for signs of excessive wear or damage, and also that the shock pistons return to their fully extended position
Trigger Mechanism Piston Ram & Levers	Signs of excessive wear or deformation, including the contacting yoke bearings
Gate Seal Mechanism Spur Gears	Signs of excessive wear of or missing gear teeth

Furthermore, Mainstream recommends that after the first 1,000 FV shot cycles, and every 10,000 cycles thereafter, the FV be removed from the Ludwieg Tube and upstream body plate removed by qualified personnel. With the upstream body plate removed, personnel will have unobstructed access to the FV internal components (as depicted in Figure 13) and can perform a more thorough wear inspection. Additionally, these teardowns are required to inspect and, if necessary, reapply grease lubrication to certain FV components, specifically the linear bearings, trigger mechanism, and the primary gate seal o- ring. This o-ring is a standard AS568A-474 size, made from commercial-grade nitrile butadiene rubber (NBR). The preferred lubricant for all of these components is Chemours Krytox® GPL 206.

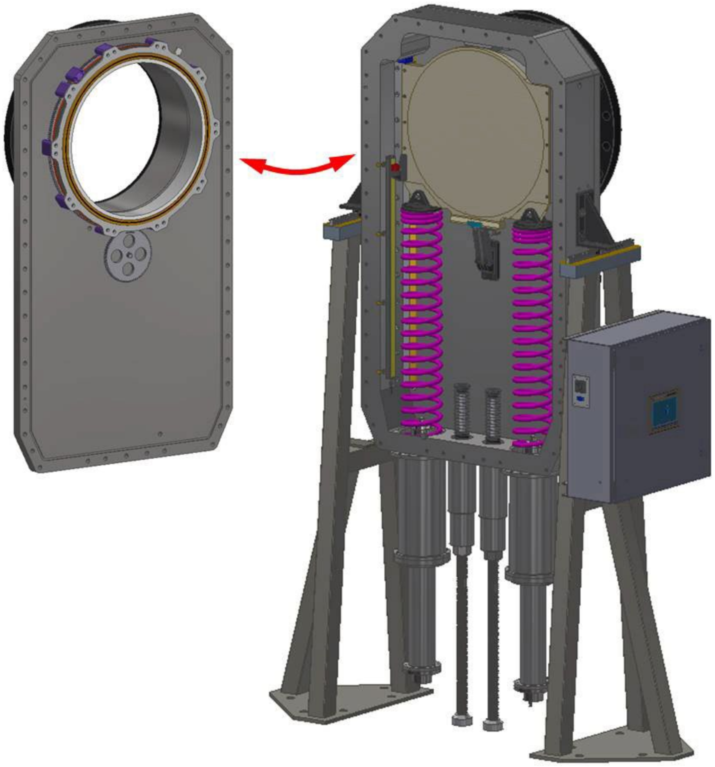


Figure 13: FV internals with upstream plate subassembly removed from the main body

8. GUI TOUCH SCREEN

Graphical user interface screens are shown in Figure 14 – Figure 19. Figure 14 is the default or home screen. This screen appears following powering on the controller and after autoinitialization. From this screen, the user can monitor gate position, manifold and vacuum pressures, safety engagement, and seal location and also determine if the valve is armed. The user can initiate armed mode and a firing event. Selecting the “Alarms” button takes the user to the alarm log screen where several other menus are also available.

Figure 14. Home (default) screen

Figure 15 shows the alarm log screen with two alarms present. In this instance, one alarm occurred for insufficient manifold pressure and the other for insufficient vacuum pressure. These alarms triggered because the controller was not connected to the pressure/vacuum sources nor the valve at the time of the screen capture. Pressing the following buttons navigates the user to the screens shown in the associated figures.

Button	Associated screen capture
Manual Valve Mode	Figure 16
Manual Motor Mode	Figure 17
Valve Setup	Figure 18
Unload	Figure 19

Alarm Summary — Total of 2 Alarms

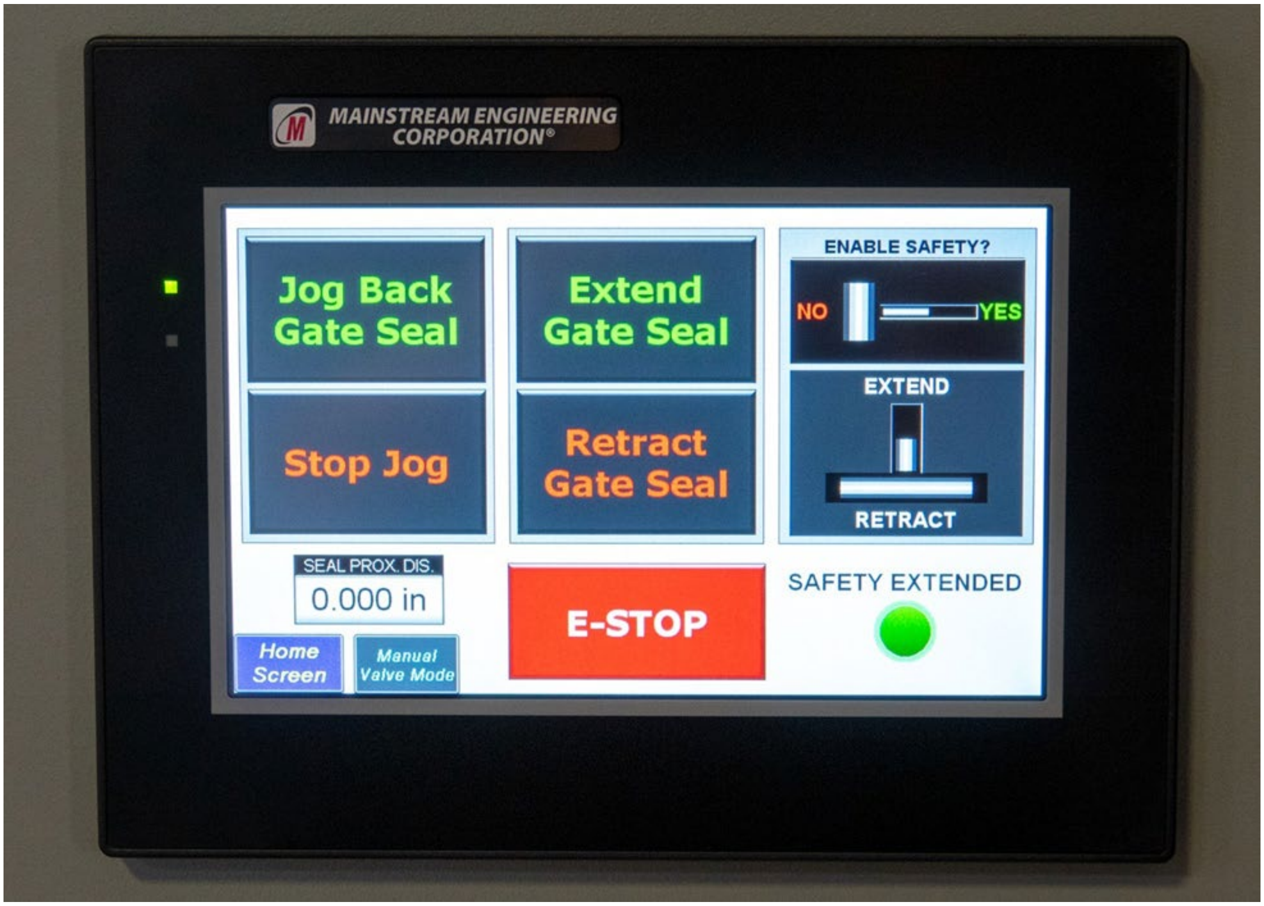
Message	Confirm	Activated	Confirmed	Deactivated
Insufficient Manifold Pressure for Valve "Arm"		06/02/19 11:33:47		06/02/19 11:33:55
Insufficient Vacuum for Valve "Arm"		06/02/19 11:33:47		06/02/19 11:33:55

Figure 15. Alarm log screen

Figure 16 shows the manual valve mode screen. From this screen, the user can select to manually override the valve controls. Selecting S1-S4 opens the associated solenoid valve releasing pressure or vacuum to raise or lower the reset rams and sealing mechanism.

Figure 16. Manual valve mode screen

Figure 17 shows the manual motor screen where the user can manually jog/stop or extend/retract the gate seal. The mechanical safety latch can also be set from this screen.



SEAL PROX. DIS. 0.000 in

Figure 17. Manual motor screen

Figure 18 shows the valve setup screen. From this screen, an authorized user can set the valve up and valve down positions.

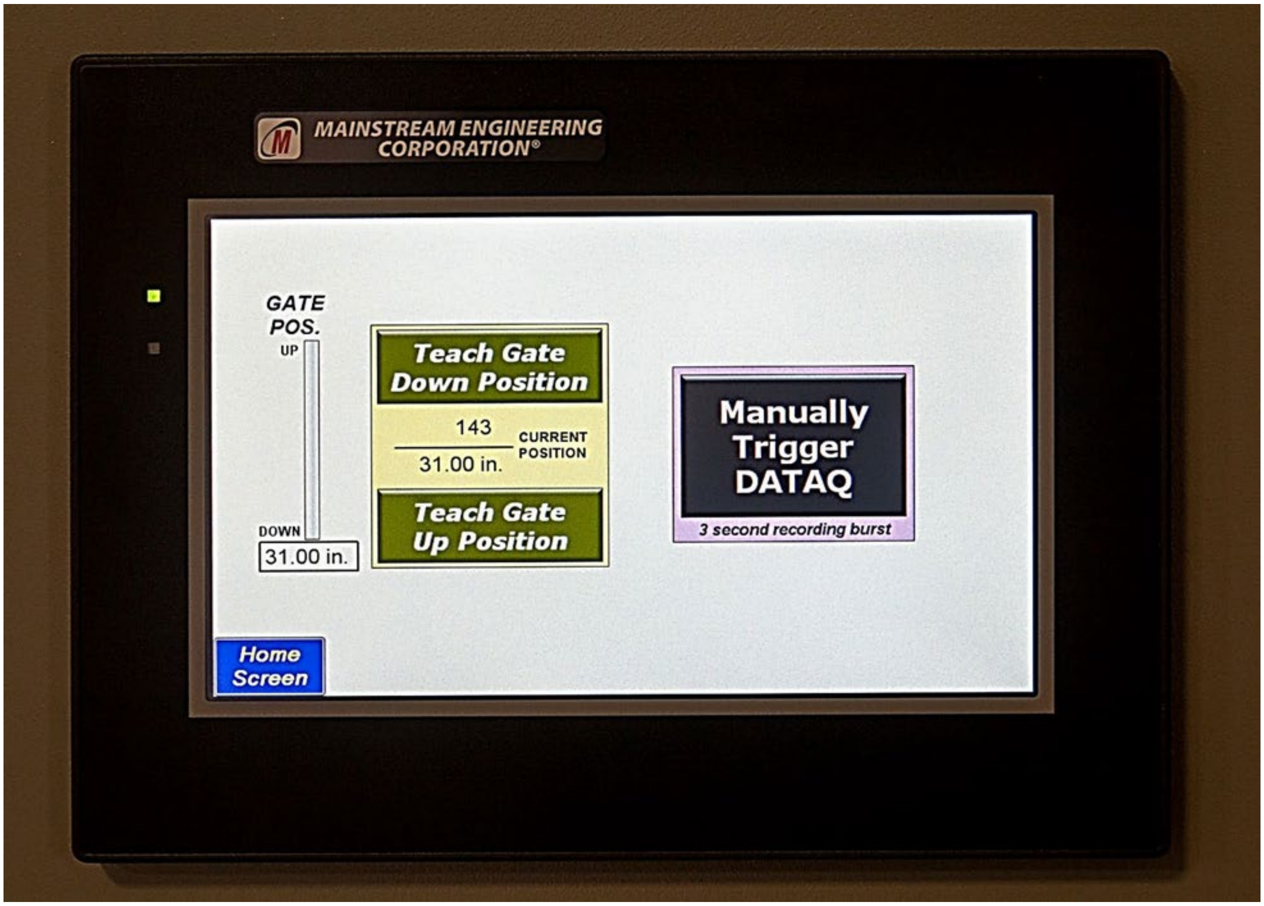


Figure 18. Valve setup screen

Figure 19 shows the valve unload screen. Pressing the Valve Soft Unload button safely allows the reset rams to unload the gate valve to a de-energized state.

Figure 19. Valve unload screen