



# Simulation of a Cold Gas Thruster System and Test Data Correlation

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Prepared for the  
47th Joint Propulsion Conference and Exhibit  
cosponsored by the AIAA, ASME, SAE, and ASEE  
San Diego, California, July 31–August 3, 2011

National Aeronautics and  
Space Administration

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## Acknowledgments

The authors would like to thank Brian Reed of the NASA Glenn Research Center's Propulsion Branch for providing access to the AA-1 system design and test data. The authors would also like to acknowledge Steve Grasl, Antony Skaff, Terry Hui and the rest of the staff at Sierra Lobo, Inc., of Milan, Ohio, who integrated and conducting the testing of the AA-1 developmental hardware.

This report contains preliminary findings,  
subject to revision as analysis proceeds.

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## Abstract

During developmental testing of the Ascent Abort 1 (AA-1) cold gas thruster system, unexpected behavior was detected. Upon further review the design as it existed may not have met the requirements. To determine the best approach for modifying the design, the system was modeled with a dynamic fluid analysis tool (EASY5). The system model consisted of the nitrogen storage tank, pressure regulator, thruster valve, nozzle, and the associated interconnecting line lengths. The regulator and thruster valves were modeled using a combination of the fluid and mechanical modules available in EASY5. The simulation results were then compared against actual system test data. The simulation results exhibited behaviors similar to the test results, such as the pressure regulators response to thruster firings. Potential design solutions were investigated using the analytical model parameters, including increasing the volume downstream of the regulator and increasing the orifice area. Both were shown to improve the regulator response.

## 1.0 Introduction and Background

The Ascent Abort 1 (AA-1) test vehicle was part of the Orion flight test program conceived of to verify the launch abort system (LAS). The AA-1 flight was to demonstrate the LAS performance during abort at maximum dynamic pressure. The AA-1 Reaction Control System (RCS) was to be used to provide roll control to the boilerplate Crew Module (CM) during descent, to determine the response of the main parachutes to torque. The AA-1 RCS was also to demonstrate a roll control algorithm to position the CM for landing and provide rate damping as needed. The AA-1 RCS was designed to use non-flight components with no heritage to the production vehicle. A developmental test was performed on the RCS system in February 2010. During the testing, the regulator experienced significant pressure undershoot and overshoot when the thruster valve was cycled open and closed. Un-commanded closure of the thruster valve was detected and attributed to the pressure undershoot. The closing time of the thruster valve appeared to be pulse length dependent.

## 2.0 AA-1 Reaction Control System Developmental Test

A developmental test of the AA-1 RCS cold gas system was constructed to demonstrate performance of the design. A simplified schematic of the flight RCS system can be seen in Figure 1. The black lines indicate the hardware that was included in the developmental test. The test system consisted of four nitrogen propellant tanks pressurized to 3600 psig for a total of 400 lb of nitrogen. A regulator was used to reduce the pressure to 600 psig. Further downstream was a relief valve set at 900 psig, and the thruster valve with an attached nozzle, designed to generate 150 lb thrust at sea level. The thruster valve was a solenoid pilot operated valve. The piloted valve was configured in a manner that requires a differential pressure across the valve for it to stay open. The system was designed with the expectation that the thruster valve could be commanded open and closed for various pulse lengths. Not shown on the schematic is the tank isolation valve and instrumentation. Testing consisted of filling, nominal and emergency blow down operations.

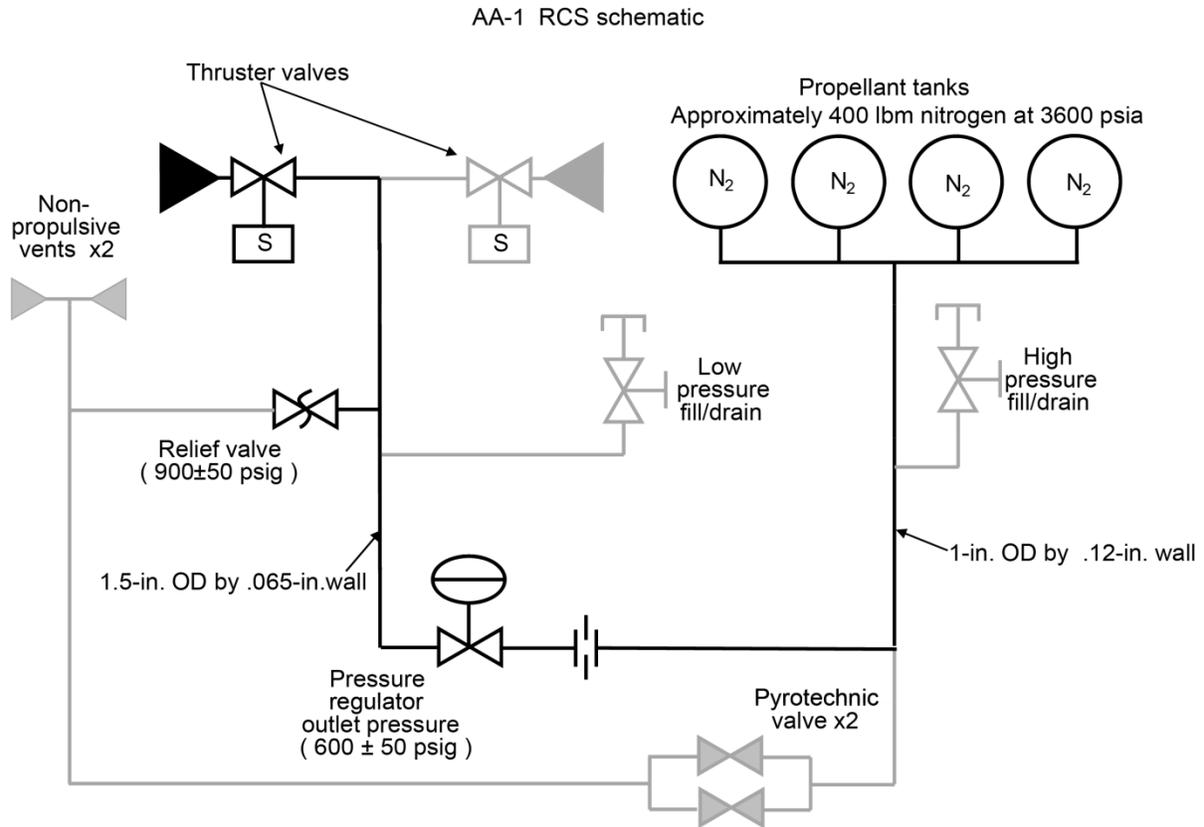


Figure 1.—AA-1 RCS Schematic. Black lines represent hardware included in developmental test.

During the testing of nominal operations the system experienced a large drop and rise in regulator outlet pressure when the thruster valve was opened and closed. In some instances the thruster valve was also shown to close momentarily after the dip in pressure. Another finding was that the valve opening and closing times seemed to be dependent on the thruster valve pulse length. To illustrate the behavior two plots of the test data are presented in Figures 2 and 3.

Figure 2 shows two short (400 ms) pulses followed by one longer pulse (2500 ms). The plots show the regulator inlet and outlet pressure, the command signal to the thruster valve and thruster chamber pressure. Notice that the thruster valve response time for opening is consistent for the three pulses shown. However, the valve closure is nearly immediate for the long pulse whereas it is significantly longer for the two short pulses. Notice that when the regulator outlet overshoot reaches the 1000 psi level the relief valve opens and the pressure drops to near the set point. These characteristics are common throughout the data collected.

As the regulator inlet pressure decreased the response deteriorated further as shown in Figure 3. Shown is a 1500 ms commanded pulse followed by a series of 400 ms pulses separated by 100 ms. During the first pulse shown in Figure 3 the valve opens and closes with similar timing as the long pulses shown in Figure 2. However the valve momentarily closes immediately after opening as determined by the thruster chamber pressure. Also notice that the thruster valve does not respond to the short pulse commands until the third closing command.

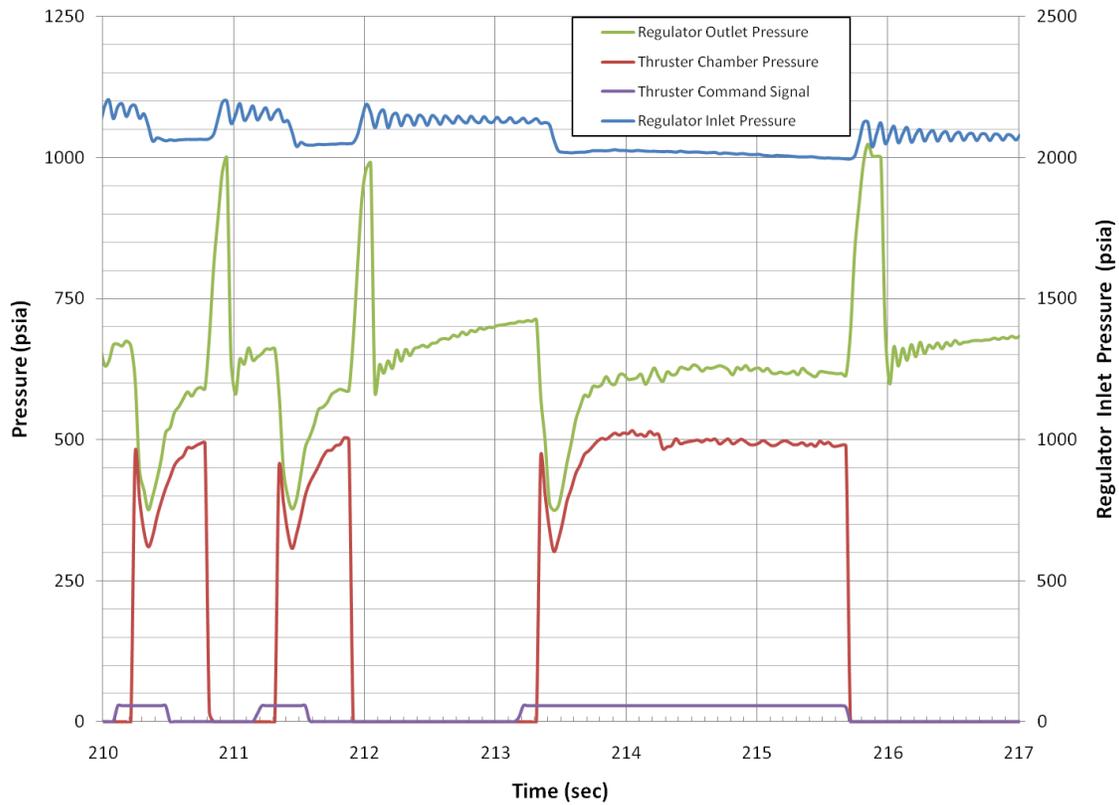


Figure 2.—AA-1 Developmental Test Results. Typical behavior with short and long pulses

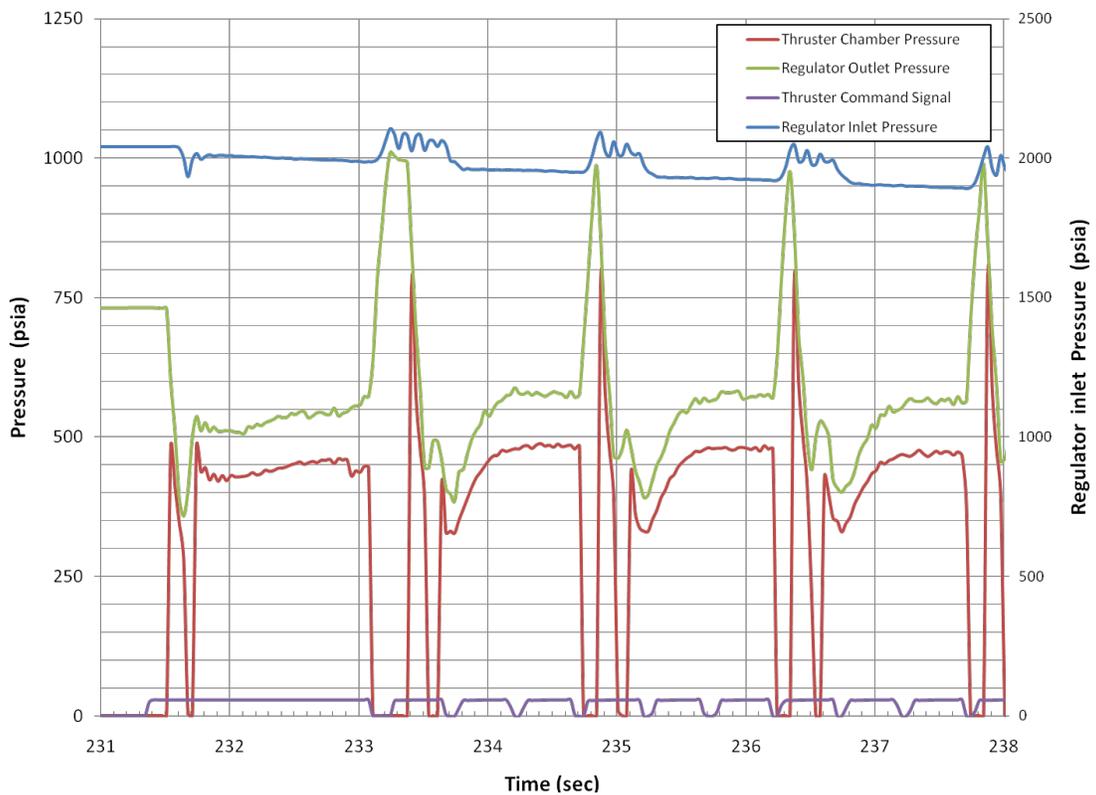


Figure 3.—AA-1 Developmental Test Results Examples of erratic behavior at lower supply pressures.

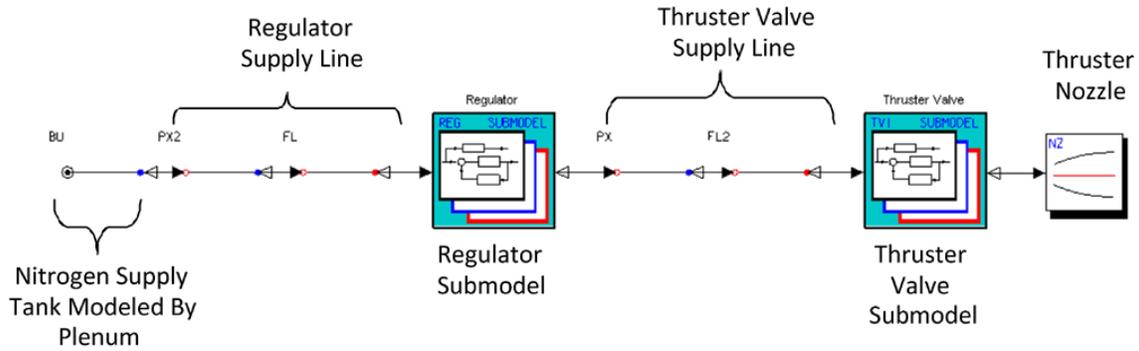


Figure 4.—Overall system model.

### 3.0 Modeling Approach

In response to the unexpected results exhibited by the system during testing, a dynamic model of the system was created with the following goals:

- Determine the cause of the regulator pressure undershoot and overshoot
- Determine the cause of the thruster valve closing during the thruster valve firings
- Determine the cause of the irregular closing times of the thruster valve
- Determine the effectiveness of different design solutions to normalize operation.

The software tool used to model the system was MSC EASY5, a dynamic fluid/mechanical systems modeler. The majority of the components used in the model were built using components in the Gas Dynamics Library (GD) of the EASY5 modeling tool. An overall view of the model can be seen below in Figure 4. The regulator and thruster valve were modeled using a mix of fluid and mechanical components as explained in the following sections. The regulator and thruster valve supply lines included a transient momentum pipe and a generic loss component to account for the losses associated with the bends and fittings. The thruster nozzle was modeled with a generic EASY5 nozzle component that calculates the mass flow rate based on the upstream pressure and temperature.

#### 3.1 Regulator Model

The regulator used in the AA-1 test is a direct acting regulator loaded with a fixed spring. The pressure in the sense volume, connected to the downstream pressure, acts against the spring to close the poppet against its seat as it approaches the set pressure. A schematic representation of the functional components in the regulator can be seen in Figure 5. The pressure forces acting on the poppet were assumed to be balanced and therefore cancelled each other out.

Previous regulator studies in the literature accounted for an additional flow force acting on the regulator poppet (Refs. 1, 2, and 3). The flow force accounts for the uneven pressure acting on the different areas of the poppet. The flow force is typically found by measuring the force at various inlet pressures and poppet positions during a test. Unfortunately, the regulator poppet geometry used in the two previous studies was different than the geometry of the poppet being used in this study. It was decided not to include a flow force in the model since its application would have been arbitrary and would have no basis for its determination.

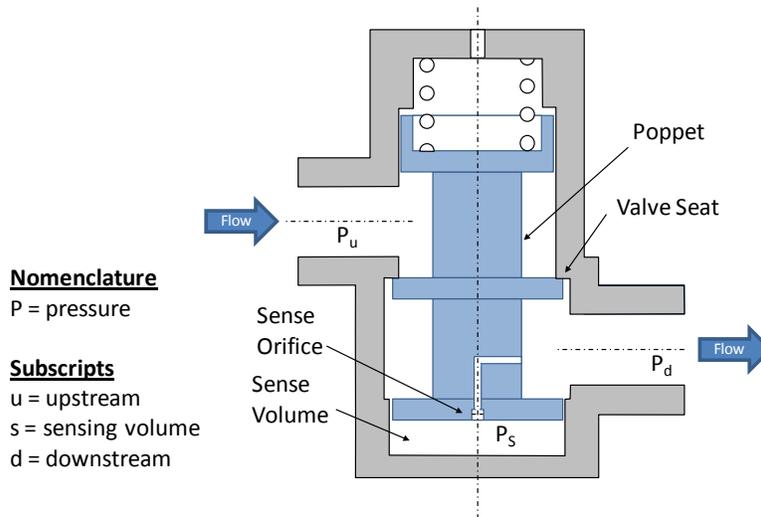


Figure 5.—Regulator schematic.

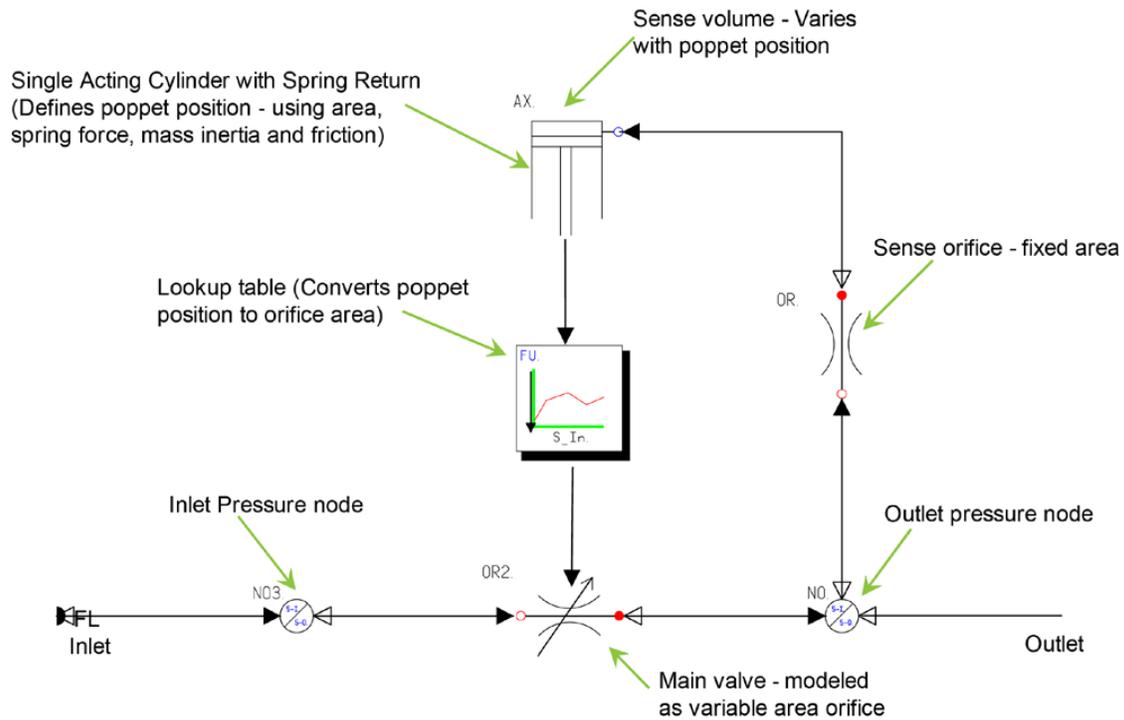


Figure 6.—Regulator model.

The EASY5 model of the regulator can be seen in Figure 6. A single acting cylinder was used to model the variable volume of the sense chamber and the poppet position. The regulator flow resistance was modeled with the variable orifice component. The orifice area is based on the poppet position and determined using a look-up table. The volume and piston areas of the regulator were determined from drawings supplied by the regulator manufacturer. An orifice was used to model the complicated flow passage connecting the sense volume to the regulator outlet. Since the orifice area was not known, it was varied within the model until the undershoot and overshoot behavior approximated the test results

The regulator poppet force balance equation is shown below in the following equation.

$$m_p \cdot \ddot{x}_p = F_s - K_s \cdot x_p + F_{s,p} - f_s - f_d \cdot \dot{x}_p$$

Where  $\ddot{x}_p$ ,  $\dot{x}_p$ ,  $x_p$  is the regulator poppet acceleration, velocity, and position respectively,  $m_p$  is the poppet mass,  $F_s$  is the force acting on the sensing area due to the pressure in the sensing volume.  $K_s$  and  $F_{s,p}$  are the spring rate and spring preload,  $f_s$  and  $f_d$  are the static and dynamic friction coefficients.

The static friction and dynamic friction coefficients were varied in the simulation model and were not shown to have a significant effect on the response as most of the damping is a result of the pneumatic process occurring in the regulator (Ref. 2).

### 3.2 Thruster Valve Model

The normally closed thruster valve uses upstream pressure in the sensing volume in conjunction with a spring to hold the poppet closed. The closing force on the poppet is opposed by main valve inlet and outlet pressures acting on the poppet. A small direct acting solenoid valve controls a path between the sensing volume and the valve outlet. Similarly a path between the valve inlet and the sensing volume is controlled by a fixed “sense” orifice. When the solenoid valve is initially opened the gas leaves the sense volume reducing the closing force sufficiently for the valve to open. When the solenoid valve is closed, the pressure in the sense volume increases closing the poppet. A schematic of the thruster valve can be seen in Figure 7.

The EASY5 model of the thruster valve can be seen in Figure 8. Similar to the regulator the poppet was modeled by a single acting cylinder with a spring. In this case, the spring acts to extend piston. Gain factors representing the poppet area acted upon were applied to the inlet and outlet pressures with the resulting forces being summed and applied to the cylinder.

The main valve was modeled using a variable area orifice where the effective flow area was determined using the poppet position and a look-up table. Flow into and out of the valve was modeled by orifices. The solenoid orifice area was provided by a time dependent lookup table to simulate operating sequences. The sensing volume and pressure areas were determined from drawings supplied by the thruster valve vendor.

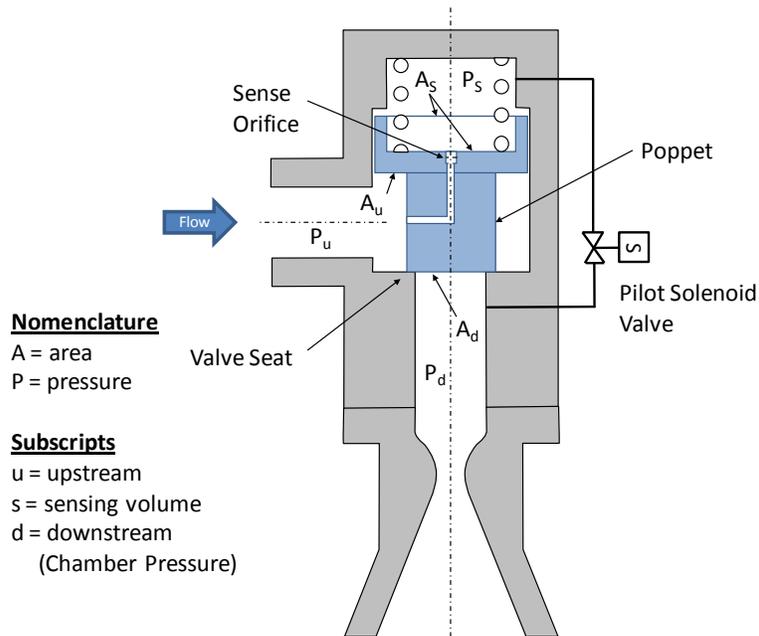


Figure 7.—Thruster valve schematic.

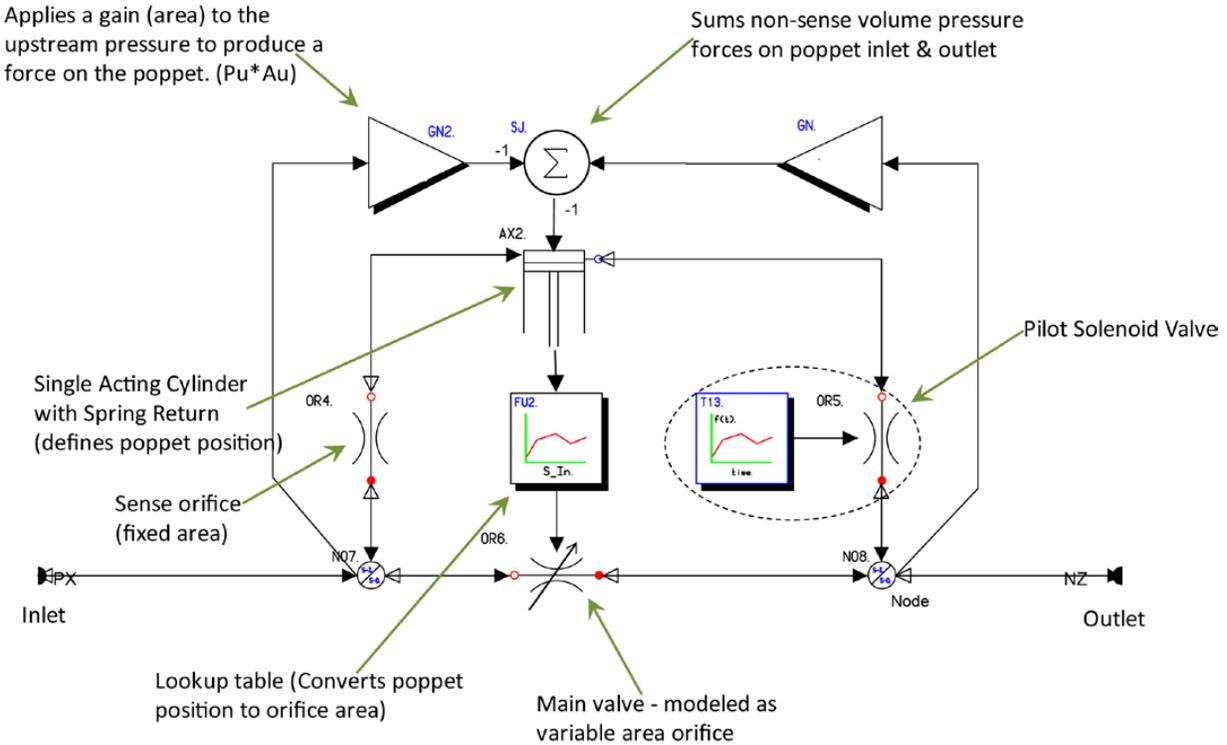


Figure 8.—Thruster valve model.

The upstream and downstream pressure forces were included in the force acting on the poppet. The poppet acceleration can then be calculated through the following equation after accounting for the static and dynamic friction as well as the inertia or poppet mass.

$$\ddot{x}_p = \frac{F_d + F_u - F_s - K_s \cdot x_p + F_{s,p} - f_s - f_d \cdot \dot{x}_p}{m_p}$$

Where  $F_d$ ,  $F_u$ , and  $F_s$  are the pressure forces acting on the downstream, upstream and sense pressure areas,  $\ddot{x}_p$ ,  $\dot{x}_p$ ,  $x_p$  are the valve poppet acceleration, velocity, and position respectively,  $m_p$  is the poppet mass,  $K_s$  and  $F_{s,p}$  are the spring rate and spring preload  $f_s$  and  $f_d$  are the static and dynamic friction coefficients.

## 4.0 Simulation Results

Simulations were run in EASY5 with short segments of thruster firing profiles conducted during testing. The thruster valve was commanded open (2.0 sec) and closed (3.57 sec) in the simulation by adjusting the pilot valve orifice area via the time based look-up table. A comparison of the simulated regulator outlet pressure with the test data can be seen in Figure 9. The simulation is of a “long” thruster firing of 1.6 sec. The regulator outlet pressure experiences a large undershoot when the thruster valve is opened. Similar behavior is seen as the thruster valve is commanded closed, the downstream pressure overshoots to a pressure close to or above the relief valve set pressure. It should be noted that the relief

valve is not part of the model. The measured steady state pressure at the high flow rate is less than the steady state pressure in the simulation. One explanation for this difference is due to the flow force not being included in the model. As discussed previously in Section 3.0 the flow force can become significant and lower or raise the regulator steady state outlet pressure.

A plot of the simulation thruster chamber pressure ( $P_d$ ) is shown against the measured chamber pressure during tests in Figure 10. The chamber pressure increases after the valve is opened but then decreases tracking the regulator outlet pressure. The thruster pressure drops momentarily to 14.7 psia indicating that the valve closes. The valve is commanded closed at 3.57 sec and closes within 40 ms. The measured steady state pressure at the high flow rate is less than the simulated pressure because the model was tuned to approximate both the undershoot and overshoot sacrificing the steady state accuracy.

A plot of the poppet positions of both the regulator and the thruster valve relative to each other is can be seen in Figure 11. Notice that the thruster valve opens and closes before the regulator poppet starts to move. This suggest that the response time of the regulator needs to be improved or the gas stored downstream of the regulator needs to be increased enough to allow the regulator extra time to react before the thruster valve closes. A plot of the thruster valve inlet, outlet and sense pressures can be seen in Figure 12. Note that at two points in time the flow reverses through the pilot valve, as determined by the downstream pressure being higher than the sense pressure. This occurs when the thruster valve first opens, at the 2.1 and 2.27 sec on the timeline.

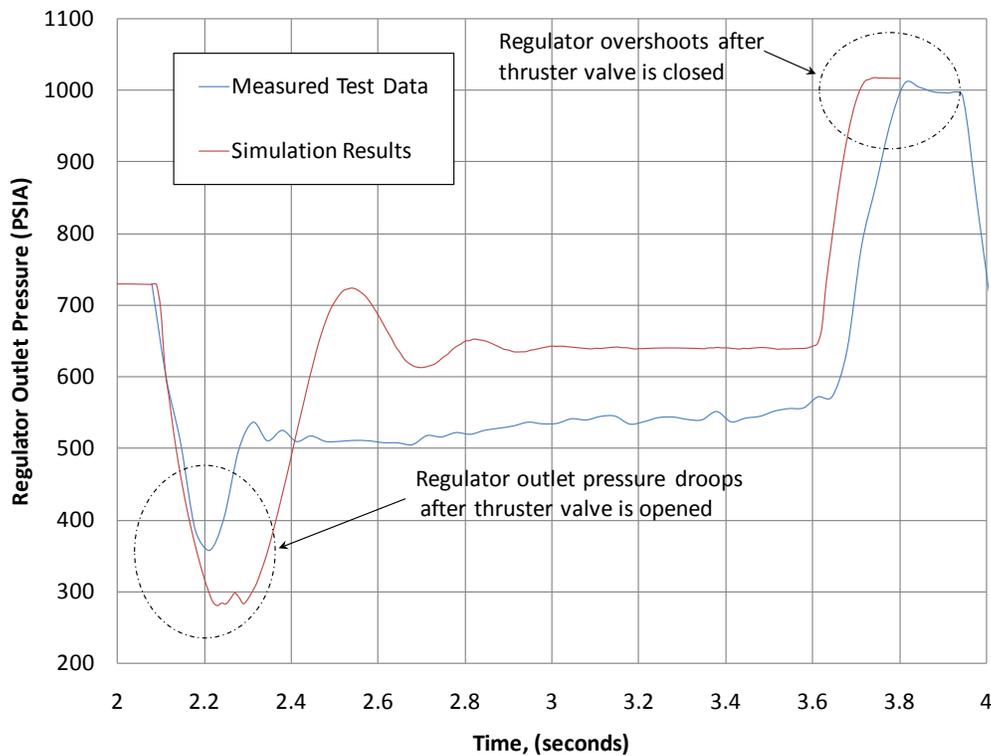


Figure 9.—Regulator outlet pressure, test versus simulation.

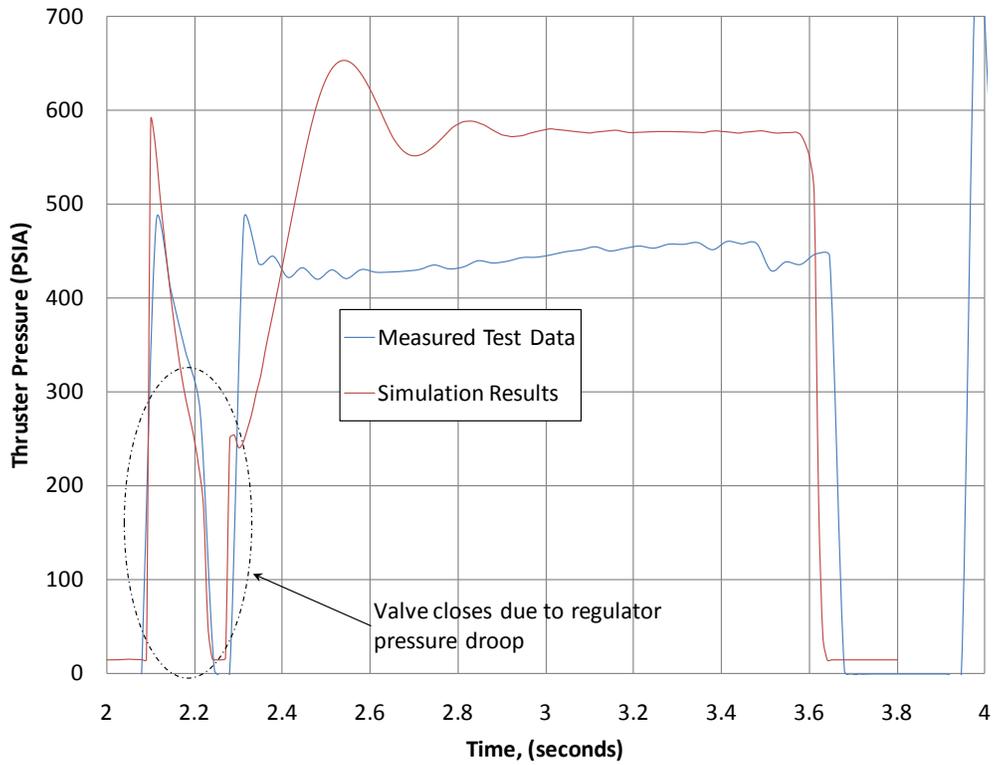


Figure 10.—Thruster chamber pressure, test versus simulation.

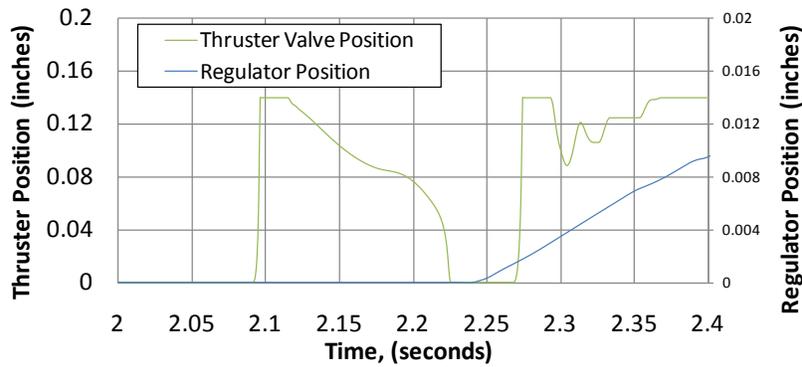


Figure 11.—Regulator and valve poppet position during thruster firings.

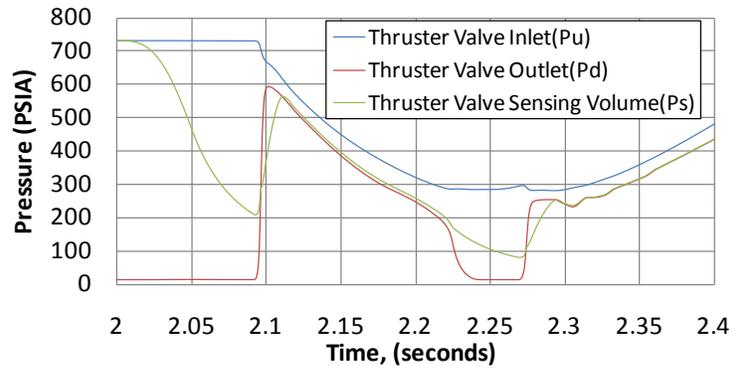


Figure 12.—Valve inlet, outlet, and sensing pressure during thruster firings.

## 5.0 Proposed Design Solutions

Two potential design solutions to reduce the regulator undershoot/overshoot and resulting thruster valve closing were investigated with the EASY5 system model. One was increasing the volume downstream of the regulator perhaps by adding an accumulator. Another approach was to decrease the flow resistance between the regulator sense volume and regulator outlet. These design solutions were easily investigated using the EASY5 model by increasing the node volume downstream of the regulator and increasing the diameter of the orifice used to model the flow resistance into the sense volume of the regulator.

The system volume downstream of the regulator was varied in the simulation to see what impact it had on the pressure undershoot/overshoot, and resulting thruster valve performance. The as tested volume of 110 in<sup>3</sup> was run along with volumes of 1000, 2000, and 5000 in<sup>3</sup>. A plot showing the regulator outlet pressure and thruster valve outlet pressure for the various downstream volumes can be seen in Figures 13 and 14 respectively. As volume increased the regulator outlet undershoot and overshoot pressure also decreased resulting in increasing acceptable thruster pulses. The practical limitations into how much volume can be added to the system due to weight and volume constraints were not determined.

The effect of changing the regulator sense orifice was accomplished by varying the modeled orifice diameter. The sense orifice resistance was varied by changing the orifice diameter from the original 0.0052 in. to values of 0.008, 0.01 and 0.02 in. Figures 15 and 16 show the regulator outlet pressure and thruster valve outlet pressure for the various orifice diameters used in the simulation.

As the orifice diameter increased the regulator response time decreased. The faster response time and corresponding reduction in regulator pressure undershoot resulted in satisfactory thrust impulses. The increased volume approach effectively delayed the rate at which the pressure dropped allowing regulator to recover before the drop in pressure adversely impacted the thruster valve performance. The larger orifice did nothing to change the rate of pressure drop, but did allow the regulator to respond quickly enough to provide satisfactory thruster performance.

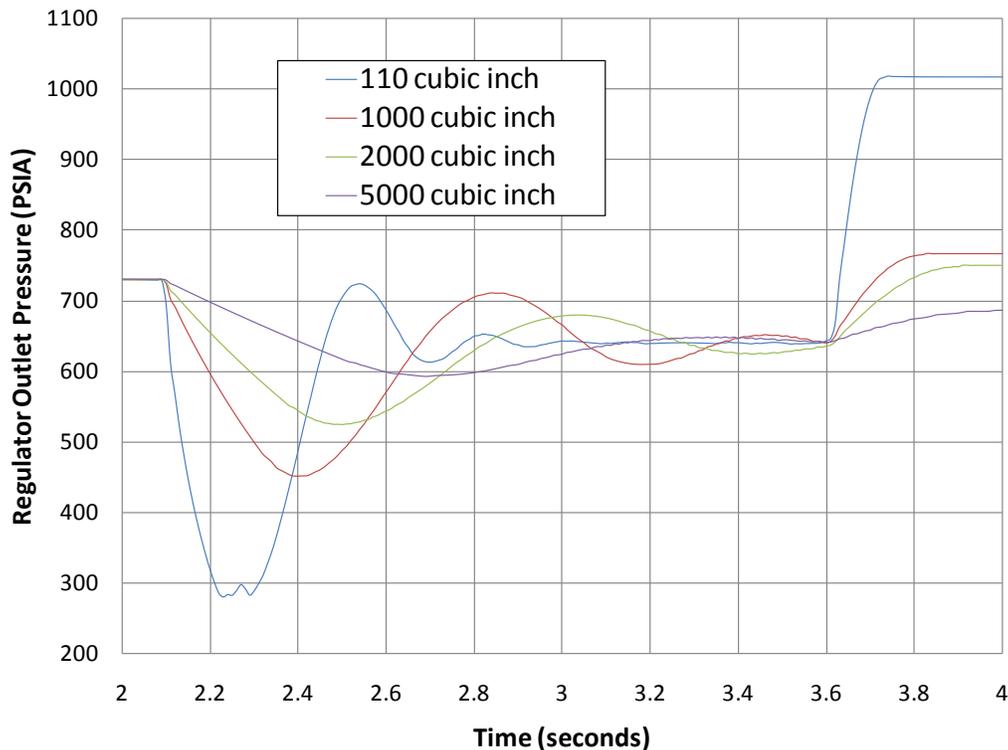


Figure 13.—Regulator outlet pressure.

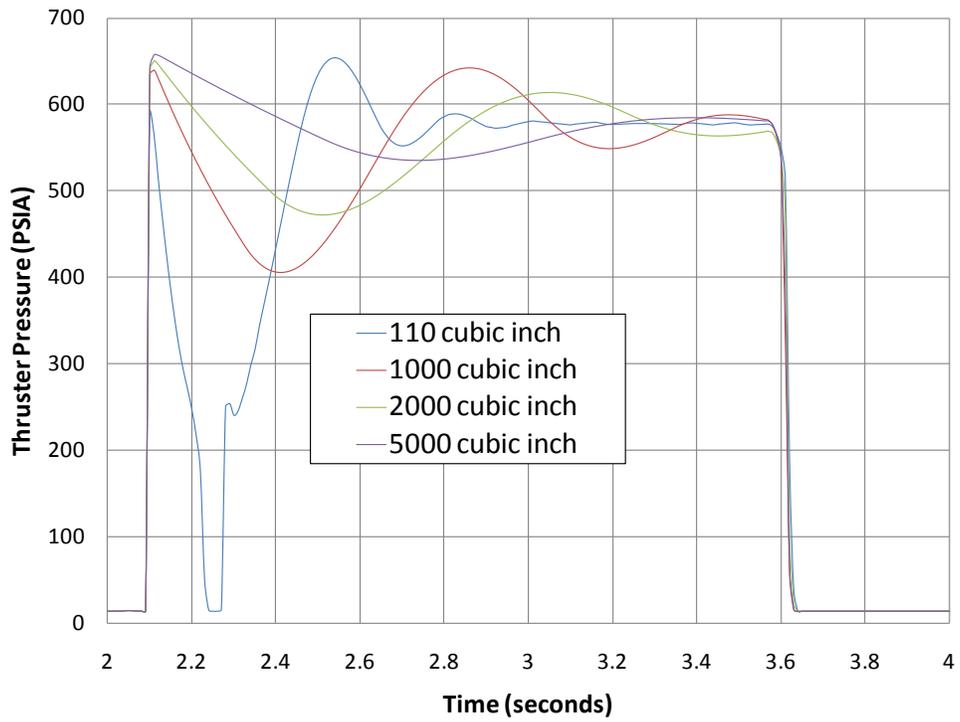


Figure 14.—Thruster valve outlet pressure.

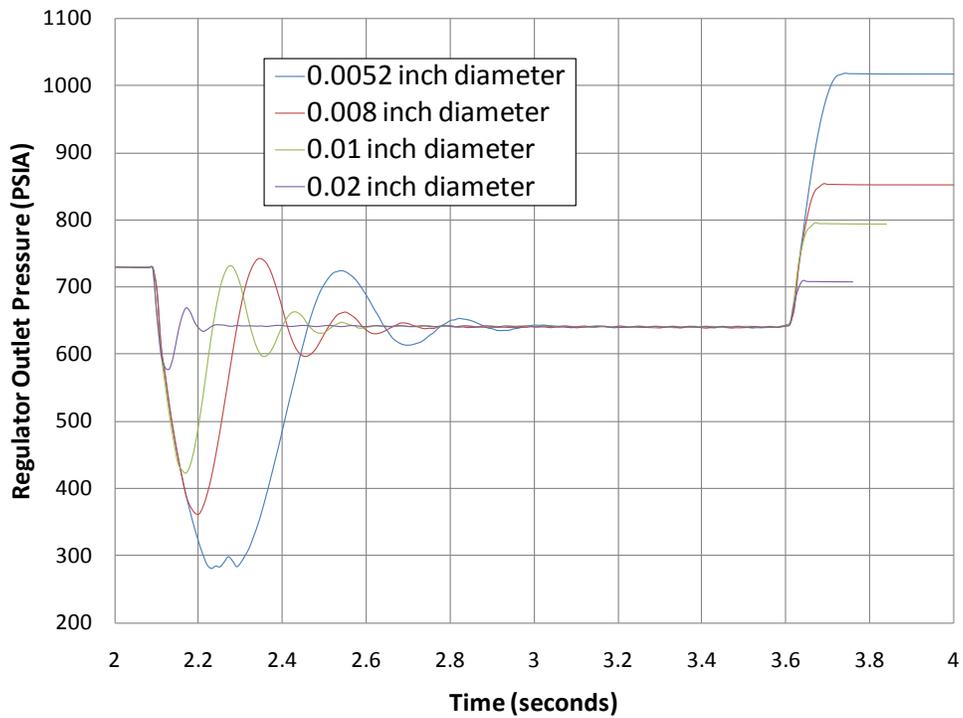


Figure 15.—Regulator outlet pressure.

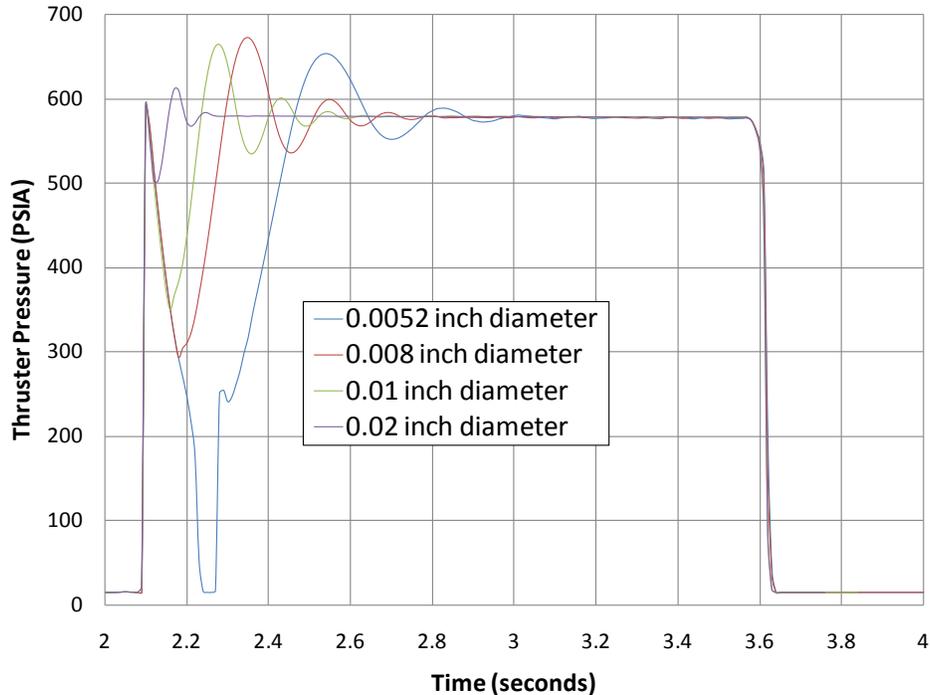


Figure 16.—Thruster valve outlet pressure.

## 6.0 Conclusion

The value of system level developmental testing is illustrated by this investigation of the test results. Models generated using EASY5 provide insight to the component interaction and system level performance. The simulation of the cold gas thruster system compared well with the test data. The fluid/mechanical model of the thruster valve contained enough fidelity to predict the momentarily closing of the valve as a result of the regulator pressure undershoot. The regulator pressure undershoot was determined to be the primary cause of the momentarily closing of the thruster valve. The simulation provided an ideal tool for investigating design modifications for improved performance. The simulation predicted that increasing the regulator downstream volume and/or decreasing the regulator sense flow restriction would reduce the regulator outlet pressure undershoot enough to prevent the momentarily closing of the thruster valve.

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<b>1. REPORT DATE (DD-MM-YYYY)</b> 01-02-2012		<b>2. REPORT TYPE</b> Technical Memorandum		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> Simulation of a Cold Gas Thruster System and Test Data Correlation			<b>5a. CONTRACT NUMBER</b>		
			<b>5b. GRANT NUMBER</b>		
			<b>5c. PROGRAM ELEMENT NUMBER</b>		
<b>6. AUTHOR(S)</b> Hauser, Daniel, M.; Quinn, Frank, D.			<b>5d. PROJECT NUMBER</b>		
			<b>5e. TASK NUMBER</b>		
			<b>5f. WORK UNIT NUMBER</b> WBS 644423.06.032.01.03		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> E-18027		
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING/MONITOR'S ACRONYM(S)</b> NASA		
			<b>11. SPONSORING/MONITORING REPORT NUMBER</b> NASA/TM-2012-217271		
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Unclassified-Unlimited Subject Category: 34 Available electronically at <a href="http://www.sti.nasa.gov">http://www.sti.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> During developmental testing of the Ascent Abort 1 (AA-1) cold gas thruster system, unexpected behavior was detected. Upon further review the design as it existed may not have met the requirements. To determine the best approach for modifying the design, the system was modeled with a dynamic fluid analysis tool (EASY5). The system model consisted of the nitrogen storage tank, pressure regulator, thruster valve, nozzle, and the associated interconnecting line lengths. The regulator and thruster valves were modeled using a combination of the fluid and mechanical modules available in EASY5. The simulation results were then compared against actual system test data. The simulation results exhibited behaviors similar to the test results, such as the pressure regulators response to thruster firings. Potential design solutions were investigated using the analytical model parameters, including increasing the volume downstream of the regulator and increasing the orifice area. Both were shown to improve the regulator response.					
<b>15. SUBJECT TERMS</b> Regulator; Valve; Simulation; Cold gas propulsion system					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UU	<b>18. NUMBER OF PAGES</b>  20	<b>19a. NAME OF RESPONSIBLE PERSON</b> STI Help Desk (email:help@sti.nasa.gov)
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			<b>19b. TELEPHONE NUMBER (include area code)</b> 443-757-5802



