NSTAR Ion Engine Xenon Feed System: Introduction to System Design and Development

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Abstract

The NASA Solar Electric Propulsion (SEP) Technology Application Readiness (NSTAR) program, managed by the Jet Propulsion Laboratory, JPL, includes the NASA Lewis 30 cm Ion engine, power control electronics and a xenon feed system. This paper will examine the design trades and component technology that make up the Xenon Feed System, XFS.

The NSTAR system is unique in that it allows for greater than 5:1 throttling of the engine. This throttling capability will optimize the engine performance to meet the available solar array power over the mission life. In order to accommodate this throttling, the feed system must be able to supply xenon at flow rates over the same 5:1 range. In addition to the throttling requirement, the engine demands that the specified flow rate be controlled to ± 3% of the nominal value. These flow rates needed separate control to the three propellant inlets of the ion engine, the engine, cathode and neutralizer. In addition, xenon purity was to be maintained within the overall xenon feed system. These requirements serve to define the xenon feed system.

The system operational parameters for the XFS were defined by the New Millennium Deep Space One (NMDS1) mission requirements. NMDS1 mission is the first application for the NSTAR XFS.

System Introduction

The major system mission requirements for NMDS1 are summarized below:

1. Store an initial load of 81.5 kg of supercritical xenon.
2. Control engine flow rates to less than ± 3% of nominal requirement at all flow rates and system pressures.
    - Main inlet flow demand range: 6 to 24 scc/min
    - Cathode flow demand range: 2.1 to 3.0 scc/min
    - Neutralizer flow demand range: 2.1 to 3.0 scc/min
3. Provide on/off flow control to the ion engine.
4. Have a design operational life of 24,000 hours of operation.

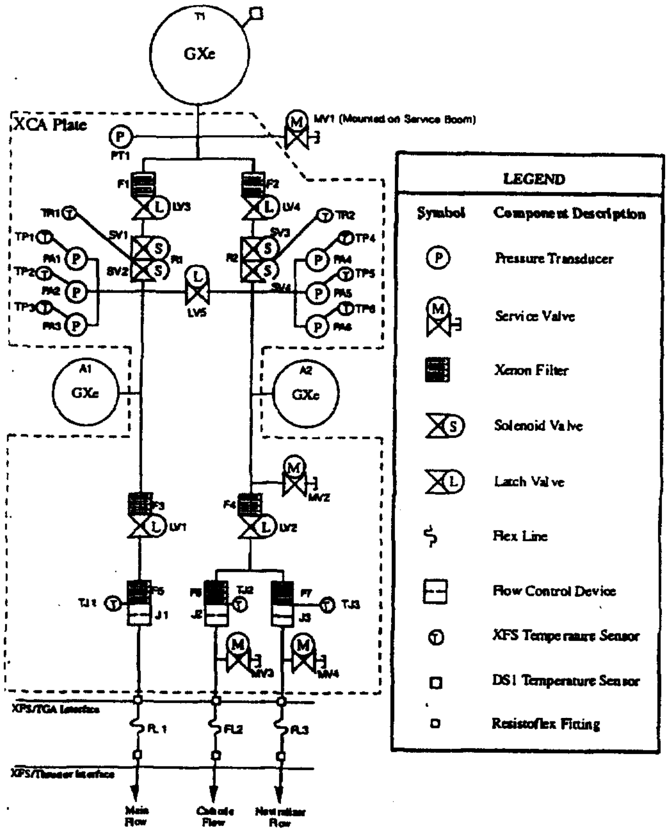

Figure 1 NSTAR XFS Schematic

5. Meet required ion engine point of use purity requirement for the delivered xenon.
6. Minimize mass

Operational environments were established using three sources: 1). Environments from available, previously qualified flight hardware. 2). Temperature constraints consistent with the safe handling of supercritical xenon and 3). Mission environments of NMDS1.

The above operational requirements lead to the decision to use a discrete (Bang-Bang) regulation system which included the use of a solenoid valve pair in conjunction with accumulator tanks. Due to the large difference is throttle ranges demanded by the main flow and the two cathodes, two separate regulation branches are used. Flow control is achieved by regulating the system pressure upstream of the fixed orifices which in turn provide a specified flow rate at a given pressure and temperature. A schematic of the XFS is shown in Figure 1.

Xenon is stored in the main tank (T1) located near the center of the spacecraft. Triple redundant xenon

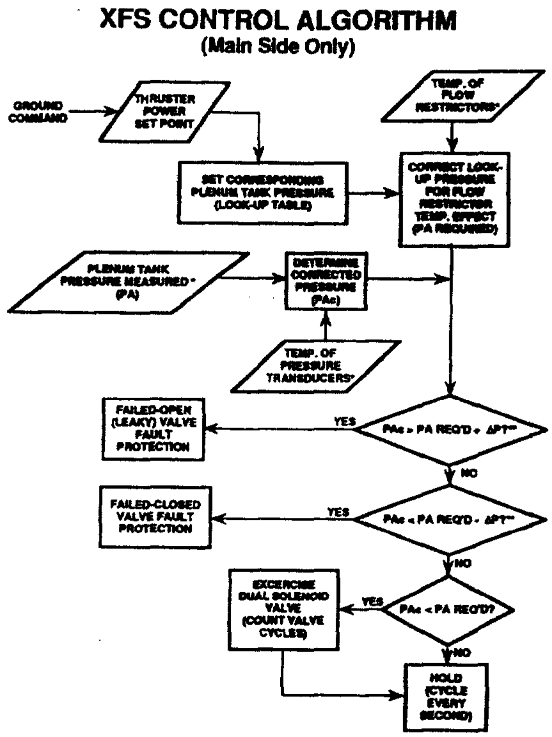

Figure 2 Feed System Control Algorithm

isolation, required by range safety to protect the accumulator tanks, is provided by the high pressure latching valves (LV3, LV4) and the solenoid valve pairs (SV1-SV2 & SV3-SV4). These solenoid valve pairs are commonly referred to as the "regulators" of the system. Pressure feedback in each of the branches is provided by the pressure transducers located downstream of the regulators. Low pressure xenon isolation is provided by the downstream latch valves (LV1, LV2). Flow rate is controlled by Flow Control Devices, FCD's (J1, J2, J3) located downstream of these latch valves. Propellant loading and pressure telemetry is provided by manual valve MV1 and high pressure transducer PT1. Manual valves MV2, MV3 and MV4 serve as test ports for system level testing as well as providing access locations which allow for xenon gas purging during spacecraft integration, test and launch activities. Accumulators (A1, A2) are located downstream of the regulators to allow for the volume needed to expand the high pressure gas into its low pressure range. The cross branch latch valve, LV5, is used to ensure some redundancy in case of a failure of either of the regulation branches. LV5 is closed during normal operation. If either of the regulators were to fail, that branch would be isolated by closing the appropriate high pressure latch valve and LV5 would be opened. This would allow all flow orifices to be operated off of a common regulator. This mode of operation carries with it the penalties associated with common pressurization, i.e. excessive xenon flow rate through the neutralizer and cathode. Temperature sensors, Resistance Thermometer Devices (RTD's), are also located on all critical components such as the regulators, pressure transducers and flow control orifices so that gas temperature can be assessed and temperature corrections can be made in the control algorithms. All components, with the exception of MV1, A1, A2 and T1 are located on a lightweight plate. This entire assembly is called the Xenon Control Assembly (XCA).

Operational Description

The regulation scheme for the XFS uses the difference in the trapped volume between the solenoid valves and the overall volume of the downstream system, basically the accumulator volumes. High pressure gas is allowed to fill the 0.5 cc volume between the two solenoid valves. This is done by opening the upstream solenoid valve and keeping the downstream valve closed. Once xenon has filled the inter-solenoid volume the upstream valve is closed. Approximately 0.5 second later the downstream solenoid valve is opened allowing the high pressure gas to expand into the low pressure side of the system. (Solenoid open times are a function of upstream and downstream pressures. Open times are selected by mission controllers on the ground in order to achieve the most optimum system cycle times.) This process is repeated until the desired pressure setpoint, and therefore the desired flow rate, is achieved.

The primary feedback to the pressure control system are the three pressure transducers that are in line with each accumulator. These transducers have a total error of less than ± 0.2% full scale in order to meet the pressure accuracy requirements. This accuracy is achieved by providing calibration curves for the transducers at 10 pressures points between 0 and MEOP as well as at three temperature points within operational temperature range of the XCA. Linear interpolation between the pressure points as well as the temperature data is then used to determine the actual pressure in the control branch. This method provides better accuracy over the straight line curve fit approach that is traditionally used with pressure transducers.

Thrust Level	Main Flow	Cathode Flow	Neutralizer Flow	Main Accum Pressure	Cathode / Neutralizer Accum. Pressure
mN	sccm	sccm	sccm	psia	psia
21	6.0	2.1	2.1	42.5	41.3
53	13.0	2.1	2.1	66.4	41.3
93	23.5	3.0	3.0	94.6	50.7

Figure 3 Accumulator Pressures and Associated Flow Rates

The control scheme for the xenon feed system is presented in Figure 2. Several important points about the control algorithm need to be identified:

1. The delta-pressure, identified in the flow algorithm, is the amount of error allowed , both above and below the nominal setpoint P_A, before system fault protection is invoked.
2. Temperature inputs are provided on both the pressure transducers and flow control orifices. This is used to allow for temperature correction on recorded pressure as well FCD temperature to allow for the proper flow.
3. The last block in the flow diagram has the entire system repeated on 1 second intervals. It is not a termination block in the functional diagram.

Pressure Regulation / Mass Flow Regulation System Design

One of the initial design trades was the trade between accumulator tank size and the volume captured between the two solenoid valves. This had a direct impact on the size of the regulator band sawtooth, the number of solenoid valve cycles and the time necessary to increase or decrease the flow rate.

To start the design trade, the number of solenoid valve cycles was determined to be the key characteristic. Moog selected a solenoid design that had previously been qualified to over 1,000,000 cycles. The valve selected has design heritage with several mono-propellant thrusters. With the 1 million cycles as a design nominal point, the accuracy of the flow rate was then selected. Feedback from the engine design team resulted in a flow accuracy requirement of ± 3% in order to maintain stable engine operation. A tank survey was then completed in order to determine what was available in terms of previously designed and qualified accumulator tanks. A 3.7 liter nominal volume tank was selected as the final accumulator tank design. Design calculation resulted in a final inter-solenoid volume of 0.5 cc which resulted in a final overall solenoid valve cycle life of 600,000 minimum, well within the 1 million cycle capability of the solenoid valve.

The pressure regulation scheme required a sawtooth pressure profile that was less than 1% peak to peak. An additional constraint was the need to keep the flow rate above a specified minimum for any given setpoint. Failure to provide a minimum flow rate would result in decreased life of the engine.

In order to determine the setpoint pressure to provide the given flow, the fixed orifices needed to be identified. JPL selected Mott sintered discs for the fixed flow control orifices. The maximum inlet pressure of the low pressure side of the system was selected to be 99 psia. This pressure allows for a more simplistic stress analysis to be used on the accumulator tanks and the low pressure branches of the system. Final Mott orifice selections resulted in the pressure ranges for the desired flow ranges as shown in Figure 3. Only three points are provided in this summary chart.

Since the main objective of the feed system was to provide throttleability of the xenon flow rate, one of the major concerns was the time required to change throttle points. Unfortunately, with the constraints on valve cycle life and flow rate accuracy, the throttle up and down times were not a major design parameter. Instead they were considered a result of the final

Storage Tank Pressure (psia)	**Accum. Tank Pressure (psia)**	**Cycle Time (sec)**	**# of Cycles**	**Total Time (min)**
1096	99	5	168	14
	50		83	6.92
	42		69	5.75
776	99	3.375	562	31.62
	50		277	15.58
	42		231	13.0
244	99	2.625	2846	124.52
	50		1394	61
	42		1166	51.02

Figure 4 Throttle Up Times

design decisions.

The final design resulted in throttle up cycle times listed in Figure 4. The cycle times listed Figure 4 represent the total solenoid open times. (Inlet valve open , wait time before outlet valve opens, and outlet valve open time.) The cycle times change throughout the mission as commanded by mission control.

These times present some operational constraints on the overall system usage. 1). Since excess xenon flowing to the engine will not effect engine life, the engine voltage level point cannot be changed until the xenon flow rate has been stabilized. (2) Throttle up times are a function of upstream pressure, the higher the pressure the faster the throttle up time.

Throttle down times are a function of how fast the pressure can be bled through the flow control devices on each of the pressure branches. These times are shown in Figure 5. These times could have been improved by allowing for a direct overboard vent of the gas. The added isolation valves required to complete this, as well as the reduced reliability due to an added overboard leak path, made overboard venting unattractive. Because excess xenon flow to the engine will not damage the engine, engine voltage levels can be changed prior to the flow being stabilized during throttle down operation

The throttle times that resulted from the pressure and flow regulation components provided acceptable performance for NASA planetary missions, and specifically the New Millennium Deep Space One Mission.

Component Selections

The baseline selection criteria for all components on the XCA was to use previously qualified components to the greatest extent possible. Components that required development/qualification testing in order to meet the requirements of the feed system were the solenoid valves and the flow control devices. The flow control devices were selected, development tested and qualified by JPL. A detailed paper will be written later to describe all of the operational characteristics as well as the development and qualification test plans.

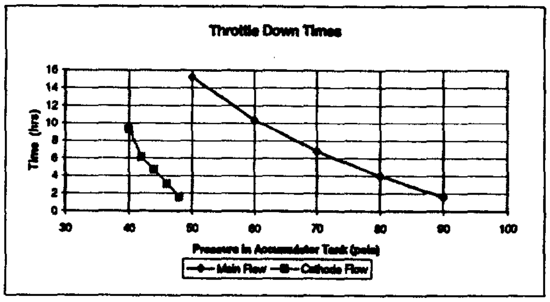

Figure 5 Throttle Down Times

Condition	Range
Inlet Pressure Range	0 to 2175 psia high pressure side 0 to 100 psia low pressure side
Internal leakage Solenoid Valves Latch Valves	Less than 3 scc/hr GHe at MEOP (Both high and low pressure)
Internal Leakage Fill / Drain Valve	$< 1 \times 10^{-5}$ sccs GHe closed $< 1 \times 10^{-6}$ sccs GHe closed and capped
Response Solenoid Valves Latch Valves	 < 20 ms opening and closing < 50 ms opening and closing
Input Voltage	28 ± 6 vdc
Random Vibration Level	17.3 Grms Qualification 12.48 Grms Acceptance
Non-Operational Temperature Range	-40°C (Exposure Only)
Operational Temperature Range	20°C to 50°C
System External Leakage	$< 1 \times 10^{-6}$ scc/sec

Figure 6 General Performance and Environmental Parameters

The NSTAR mission objective also put most of the allowable risk at the engine and the xenon feed system was to be a low risk approach. Therefore, the XFS contains components which represent the lowest risk approach to the needed function.

Components were also selected to minimize the amount of soft goods contained within the hardware. This was necessary in order to achieve the xenon gas purity requirements.

All components were qualified to a set of requirements that exceeded the NSTAR operational requirements. A summary of the environmental conditions and key operational parameters for the selected hardware is listed in Figure 6:

Solenoid Valve

The solenoid valve was designed, developed and qualified for NSTAR by Moog. Desired key parameters of the selected valve design were: 1). High cycle life, 2). No particulate or contamination generation, 3) High pressure capability and 4). Ability to control a small 0.5 cc inter-solenoid volume. Moog selected a baseline design that is part of Moog's standard thruster valve product line. This valve has no sliding fits and therefore meets the high cycle life requirement. The current NSTAR system design requires only 600,000 solenoid cycles in order to operate one engine. Future applications for this system may require more engines and therefore more solenoid cycles. Moog's selection has demonstrated acceptable performance through 1.2 million cycles. The solenoid valve was fully qualified to operational and environmental levels that were in excess of the NSTAR requirements.

Latch Valve

The latch valves selected for this application were previously qualified for xenon isolation as part of the Space Systems / Loral Pressure Management Assembly (PMA) which was designed and protoflight tested by Moog. This same latch valve was used on the NSTAR XCA. The XCA was unique with respect to latch valve LV5. This valve is used as the cross branch isolation valve and is used only in the case of a system level failure of one of the solenoid valve pairs. The unique performance requirement of this valve is the need for excellent internal leakage characteristics in both the forward and reverse directions. Moog performed several development tests as well as a delta qualification test to qualify the latch valve for leakage in the reverse direction.

Fill and Drain Valve

The fill and drain valve selected for use on the NSTAR system is the same high pressure valve that has been successfully utilized on other xenon systems, including the Loral PMA. This valve is a metal to metal seat valve and meets all of the operational requirements for both the high pressure and low pressure applications. The fill and drain valves serve 2 purposes, one for xenon filling and second for purge and test operations.

Pressure Transducers

There are two types of pressure transducers on the xenon feed system. One high pressure transducer which is used to determine the amount of xenon remaining and six transducers on the low pressure side for pressure regulation feedback. All transducers on the XCA were manufactured by Taber Industries. Both the high pressure and low pressure transducers are from Taber's satellite product line. Since the high pressure transducer is effectively a fuel gauge, the accuracy of this unit is consistent with standard aerospace pressure transducers. Its operational pressure range is 0 to 3000 psia.

The low pressure transducers have been calibrated with look-up tables to achieve a total error of ± 0.2% of full scale. There are three transducers per regulation branch. These transducers will be polled to determine an average pressure in addition to looking for excessive drift which would discount the use of one the transducer readings. The operational pressure range of the low pressure transducer is 0 to 150 psia with a 3000 psia burst pressure requirement. The high burst pressure requirement is imposed to ensure pressure containment in case the low pressure side of the system is expose to high pressure. It should be noted that this requirement is also imposed on all low pressure components.

Storage and Accumulator Tanks

Tanks selection, procurement and testing was completed by JPL. The main storage tanks is a 49.33 liter, aluminum lined carbon fiber over-wrapped manufactured by Lincoln Composites. The two accumulator tanks are 3.7 liters each and were manufactured by Structural Composites Inc., SCI. These are also aluminum lined, carbon over-wrapped tanks.

System Integration and Layout

Overall integration and test of the XCA was accomplished at Moog. JPL provided the machined baseplate, the FCD's, the electrical connectors and the RTD's. All XCA mechanical and electrical integration was completed by Moog. System integration of the XCA to the tanks and thrusters will be completed by JPL. In addition, full system integration of the XFS to the spacecraft was also completed by JPL.

All tubing used in the system was 0.125 inch OD, with an electropolished ID to ensure cleanliness of the system. All fittings were commercially available, electropolished ID fittings which were compatible with butt welding. All weld joints were orbital butt welded using an automatic butt welding machine.

The overall layout of the XCA was dependent upon the constraints imposed by the DS1 spacecraft. A short list of these constraints are as follows:

- Maximum overall envelope was not to exceed 20 inches long by 15 inches wide by 4 inches tall.
- Latch valves needed to be paired in opposing directions so that the residual magnetic fields from the magnet could be partially canceled.
- Pressure transducers and FCD's need to be located in groups so that their thermal environments are the same.
- All fluid connections to the spacecraft need to be located on the right hand side of the plate.
- All electrical connections needed to be located on the left hand side of the plate.
- Easy access to manual valves had to be provided for xenon ground loading and purge operations.

The flight plate is shown in Figure 7. Once fully integrated, the XCA was subjected to a series of acceptance tests which included baseline functional tests, random vibration, shock testing, thermal cycles and final functional tests. Performance of all components has been acceptable with respect to the DS1 and NSTAR mission requirements.

Conclusions

The design, development and qualification testing of the XCA as required for the NSTAR flight program is complete. All original performance objectives have been achieved and the NSTAR system has been fully characterized. Top level performance characteristics have been outlined in this paper.

References

1. E. Bushway III, W. Rogers " Miniature Lightweight Propellant Management Assembly for Stationary Plasma Thrusters", AIAA-97-2788, 33rd Joint Propulsion Conference, Seattle Washington, 1997

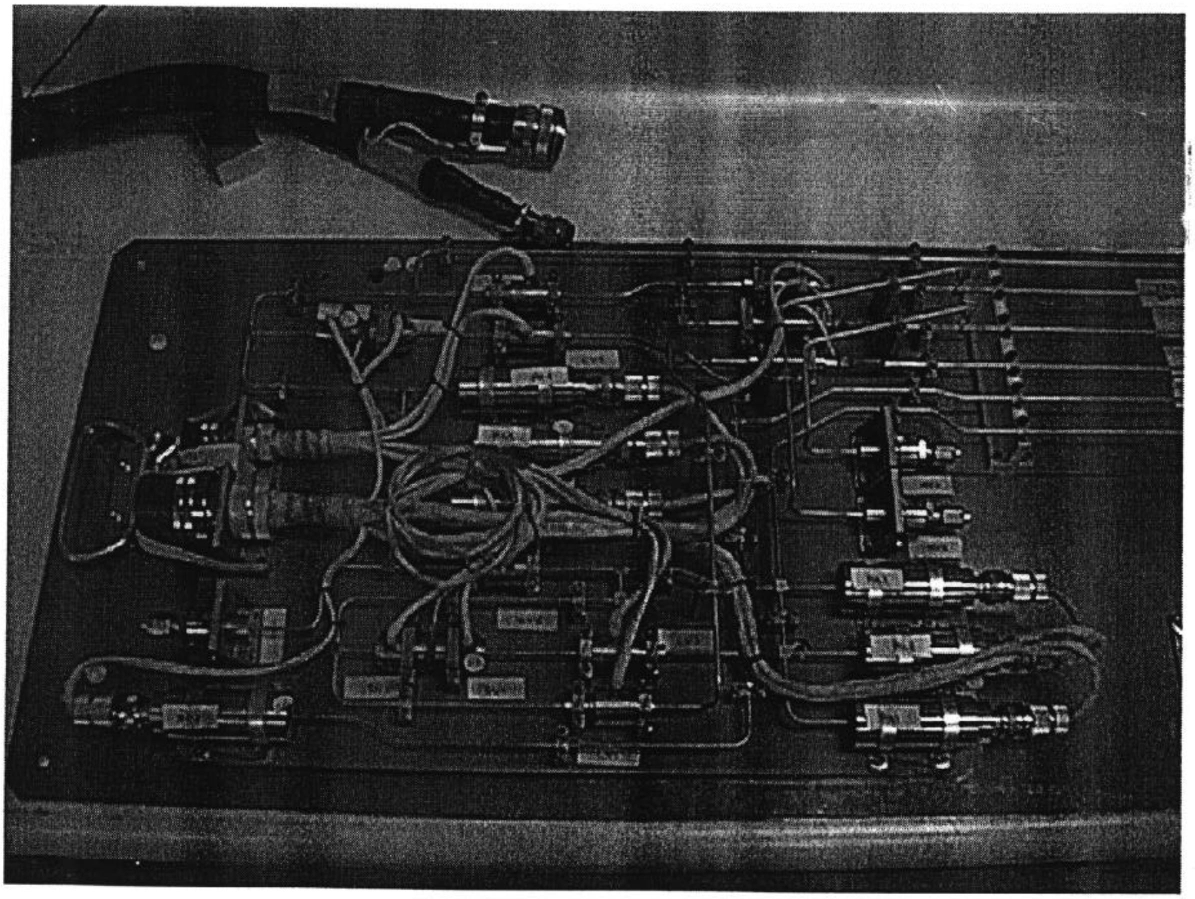

Figure 7 Xenon Control Assembly, Flight System