Space Shuttle 750 psi Helium Regulator Application On Mars Science Laboratory Propulsion

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The Mars Science Laboratory (MSL) is NASA's next major mission to Mars, to be launched in September 2009. It is a nuclear powered rover designed for a long duration mission, with an extensive suite of science instruments. The descent and landing uses a unique 'skycrane' concept, where a rocket-powered descent stage decelerates the vehicle, hovers over the ground, lowers the rover to the ground on a bridle, then flies a safe distance away for disposal. This descent stage uses a regulated hydrazine propulsion system. Performance requirements for the pressure regulator were very demanding, with a wide range of flow rates and tight regulated pressure band. These indicated that a piloted regulator would be needed, which are notoriously complex, and time available for development was short. Coincidentally, it was found that the helium regulator used in the Space Shuttle Orbiter main propulsion system came very close to meeting MSL requirements. However, the type was out of production, and fabricating new units would incur long lead times and technical risk. Therefore, the Space Shuttle program graciously furnished three units for use by MSL. Minor modifications were made, and the units were carefully tuned to MSL requirements. Some of the personnel involved had built and tested the original shuttle units. Delta qualification for MSL application was successfully conducted on one of the units. A pyrovalve slam start and shock test was conducted. Dynamic performance analyses for the new application were conducted, using sophisticated tools developed for Shuttle. Because the MSL regulator is a refurbished Shuttle flight regulator, it will be the only part of MSL which has physically already been in space.

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I. Introduction

THE Mars Science Laboratory (MSL) is NASA's next major mission to Mars, to be launched in fall of 2011 and land in spring of 2012. The MSL rover is compact car sized and nuclear powered, carrying a robust suite of scientific experiments (Figure 1). The goals are to determine whether life ever arose on Mars, characterize the climate of Mars, characterize the geology of Mars, and prepare for eventual human exploration. Extended duration and long range mobility are planned for the surface mission.

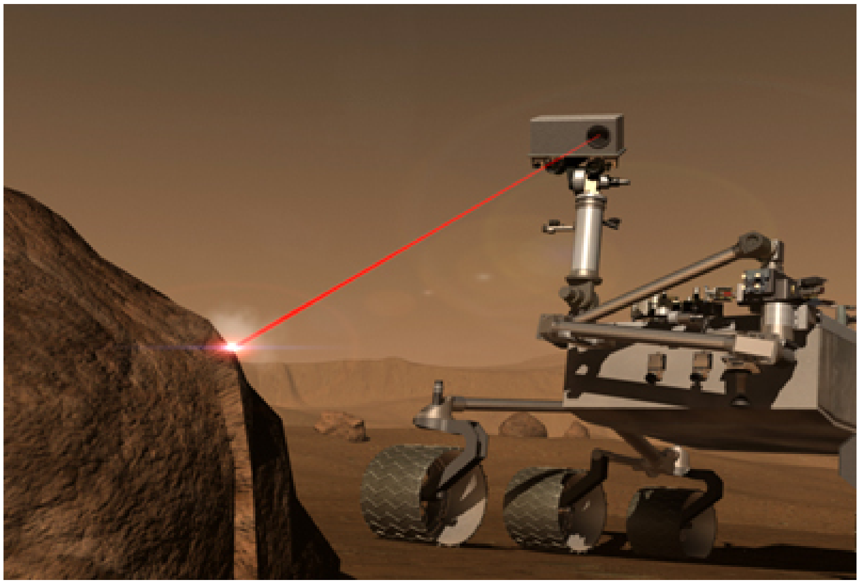

Figure 1. MSL rover conducts a science experiment, artist's concept. Source: Jet Propulsion Laboratory

It was determined that airbag landing, as was used on Mars Pathfinder and Mars Exploration Rovers, was not feasible for a vehicle of this mass. A propulsive landing platform such as was used on Viking and Phoenix, was thought to present difficulties for rover drive-off on rougher terrain with greater scientific interest. Therefore, a unique "skycrane" scheme was devised for descent and landing, where the rover is lowered and placed on the surface by a descent stage, analogous to helicopters used for heavy lifting on Earth (Figure 2).

Figure 2. Skycrane in action, artist's concept. Source: Jet Propulsion Laboratory

The overall transition from space flight to a landed configuration on a foreign body is called "entry, descent and landing," (EDL) and it is one of the most demanding phases of a lander mission. In the MSL EDL scheme, first the cruise stage that flies the vehicle through space from Earth to Mars separates from the aeroshell. The aeroshell enters the Mars atmosphere and decelerates. Precision guidance is used to achieve safe insertion into potentially rough terrain. Lower in the atmosphere, a parachute deploys to further slow the vehicle. Then the heat shield separates, allowing the Mars surface to be seen, and the propulsion system to be started. The descent stage separates from the upper backshell, then descends under rocket power. The rover is lowered from the descent stage on a bridle. The descent stage hovers over the planet surface, suspending the rover like a crane. After rover touchdown on the surface, the bridle is cut, and the descent stage flies off for disposal a safe distance away (Figure 3). [1]

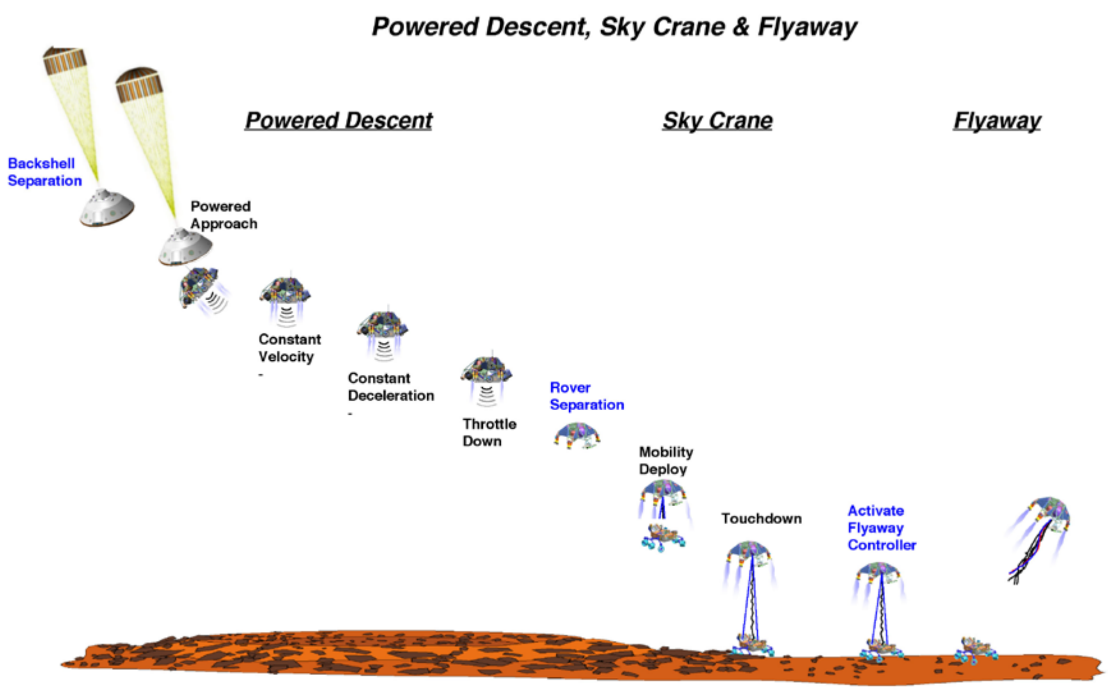

Figure 3. Entry, descent and landing sequence. Source: Jet Propulsion Laboratory

The descent propulsion system is a monopropellant hydrazine type. There are eight large main landing engines, and eight smaller reaction control engines for attitude control. Helium pressurant is regulated to assure consistent performance during the entire propulsive phase of EDL.

Pressure regulation of the descent propulsion system helium supply presents a challenge, because of the very demanding requirements. A tight pressure band must be maintained to assure predictable and controlled performance of the engines. The flow rate demand varies from the low level of a single RCS thruster firing, to a very high level of all eight lander engines at full throttle. The helium supply gas becomes extremely cold as it depressurizes over just a few minutes. The internal pressure drop must be as low as possible to make maximum use of the available helium supply. The hardware should be as light as possible, because mass allocation is at a premium especially for lander missions. The unit must be reliable enough for a single string application on this major Mars mission. Flow will be initiated with a slam start by opening an upstream pyrovalve, which is expected to produce a sharp pressure wave impinging on the regulator. To make matters more interesting, due to previous programmatic events, the lead time to required delivery was short. In this report, the path to delivery of this MSL pressure regulator is described, and the solution included use of some hardware flown on the Space Shuttle.

II. Description

The short lead time to delivery indicated that an off-the shelf design would be the only feasible approach. The single unit, single vehicle application also indicated that an existing design would be preferred. However, the requirements indicated that a piloted type regulator would most likely be needed. Piloted regulators are typically custom engineered to each application, and adaptations to different applications incur significant technical risk, with the prospects of re-engineering and extended development testing. An extensive survey of available designs was conducted. It was found that one design, amazingly met nearly all of the MSL requirements as is.

On the Space Shuttle Orbiter main propulsion system, a helium system is used to provide purge gas and to actuate pneumatic valves.[2] Helium gas is stored at high pressure to save volume, and is regulated down to approximately 750 psia for use. Seven regulators are used, in three redundant pairs of two, and a single unit. This was the regulator design found to meet nearly all of the MSL performance requirements.

The shuttle 750 psi helium regulator is of a piloted type. A schematic cross section is shown in Figure 4. Outlet pressure is sensed by the controller. The pressure difference over the effective bellows area is balanced by the various spring forces. The internal position of the controller is translated through a pin to the pilot valve. The pilot valve position controls the pressure behind the main piston and positions it. The position of the main piston controls the flow rate through the main valve. A complex series of orifices and volumes control the dynamic response.

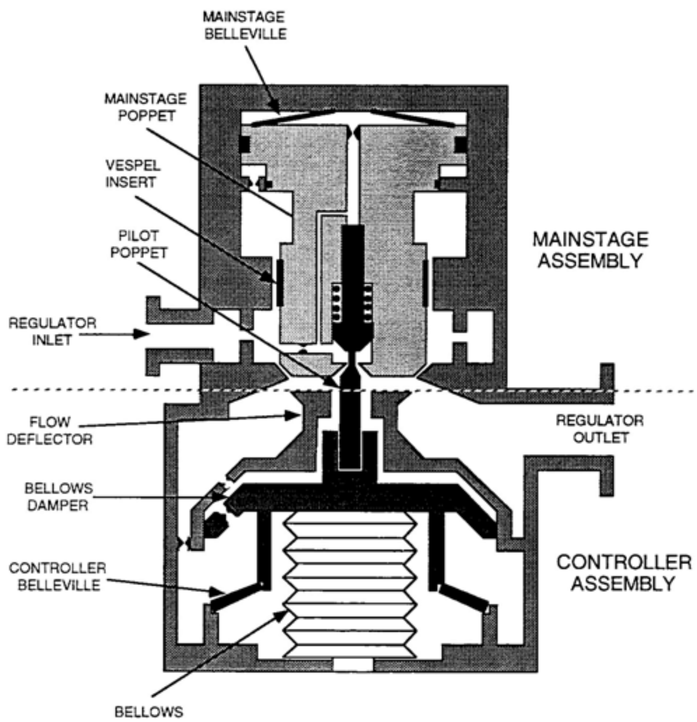

Figure 4. Regulator schematic. Source: AIAA-1990-2749

III. Adaptation to MSL

An integrated product team (IPT) was formed in order to deliver this hardware to the project, bringing in as much existing expertise as possible. JPL was the end user and manager of the overall activity. VACCO modified, assembled and tested the units; the company had acquired the firm that originally made the units, and in fact some of the personnel were involved in manufacture and test of the original units. United Space Alliance (USA), the operator of the Space Shuttle, has deep experience testing and operating these regulators, and facilitated the hardware transfer process described below. An analyst who performed dynamic modeling for the Shuttle program was brought in, working through Indyne.

Additional evaluation of the regulator design, heritage and performance confirmed that the design is indeed suitable for the MSL application. Two notable differences were the pyrovalve slam start, and higher pyro shock environment that are present in MSL but not on Shuttle. These would need to be addressed by test, as mentioned, due to previous programmatic events, time until required delivery was short. It was recognized that fabricating such a complex device in the available time may not be feasible, and would be a significant risk.

An inquiry was made to the Shuttle program to see if it may be possible to obtain spare regulators for use on MSL. Three units were requested, one each for flight, spare and delta-qualification testing. The shuttle program personnel were extremely supportive. Because the regulators would have to be slightly modified and re-tuned in any case, it was proposed to furnish units that had been removed from the orbiters for service and already disassembled. The processes for requesting Shuttle hardware was executed, with the support of senior Shuttle program managers, and the assets were transferred to JPL. This was truly an outstanding example of cooperation between NASA programs and centers.

Even with a close match in requirements, some adjustments were still necessary for the MSL application. The required pressure set point was slightly different, but this was fairly easily accommodated using slightly different spring forces. Piece parts expendable during disassembly and assembly, such as seals and shims, were newly fabricated or procured. The external leak rate requirement was much lower on MSL, with a mission duration of many months, than on Shuttle, with a mission duration of a couple weeks. This would require an all-welded external envelope. Therefore, welded-on tube stub inlet and outlet fittings, and a cap with a welded sense port opening were developed. In addition, the existing external welds were changed to the electron beam type to help assure leak tightness. The final MSL regulator configuration is shown in Figure 5. Note the addition of inlet and outlet tube stubs, and the revised all-welded sense port configuration.

Figure 5 MSL high flow pressure regulator

Dynamic performance and stability of piloted regulators are known to be highly dependent on the fluid system configuration the regulator operates in, particularly downstream. Therefore, VACCO modified a test facility to closely replicate the MSL pressurization system configuration, downstream of the regulator to the propellant tank ullage volumes. Coils of tube run through either hot water or liquid nitrogen are used to simulate hot and cold inlet gas conditions, respectively. A bank of orifices with valves controls downstream of the ullage volume controls the flow rate.

The regulators were then tuned to MSL requirements. Tuning of piloted regulators is an art, that can consume months. Experienced hands were a key to success. Delicate shims, different belleville springs and piece parts with barely perceptible dimensional differences were expertly combined to achieve the desired static and dynamic performance characteristics.

An extensive series of tests were run for acceptance and delta-qualification. These included flow cycles, flow performance mapping, hot and cold inlet gases, hot and cold thermal environments, solenoid valve slam starts, representative mission profiles, and flow performance mapping. In addition, random vibration and shock environment tests were conducted. Typical results for a mission profile flow test are shown in Figure 6.

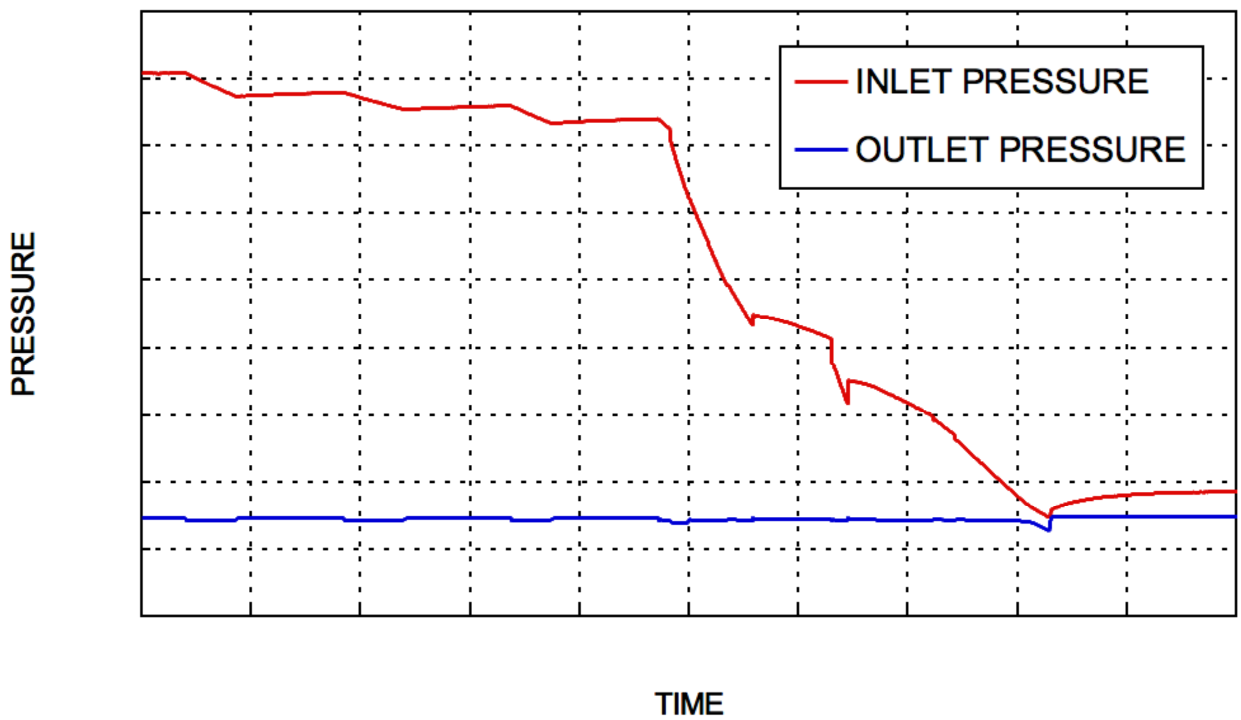

Figure 6. Sample regulator flow test data, typical mission profile

Dynamic analytical modeling was also performed. Objectives were to gain insight and support troubleshooting as needed, and to predict performance in the flight system including the pyrovalve slam start. The model was based on one developed in the late 1980's for the Space Shuttle program. It was used to aid redesign of the shuttle regulator to address dynamic instability issues. The model provides capability to simulate operational transients such as changes in flow demand and slam starts. The regulator fluid system was partitioned into a series of volumes and flow paths. Volumes were varied in size depending on motion of regulator components. Internal flow paths were modeled as orifices, annular flow passages, or short tubing segments, as required. The mechanical system as modeled as a network of springs and masses. Pressure forces combined with the spring forces to determined total force on a given mass. [3]

The model was successfully applied during the development of the MSL regulator. First, the model was re-validated using test data from the present program. Insight was gained into some low frequency oscillatory behavior. Potential causes of a setpoint change were identified. Confidence was gained that the regulator could perform under a pyrovalve slam start (Figure 7), well in advance of the actual test being performed.

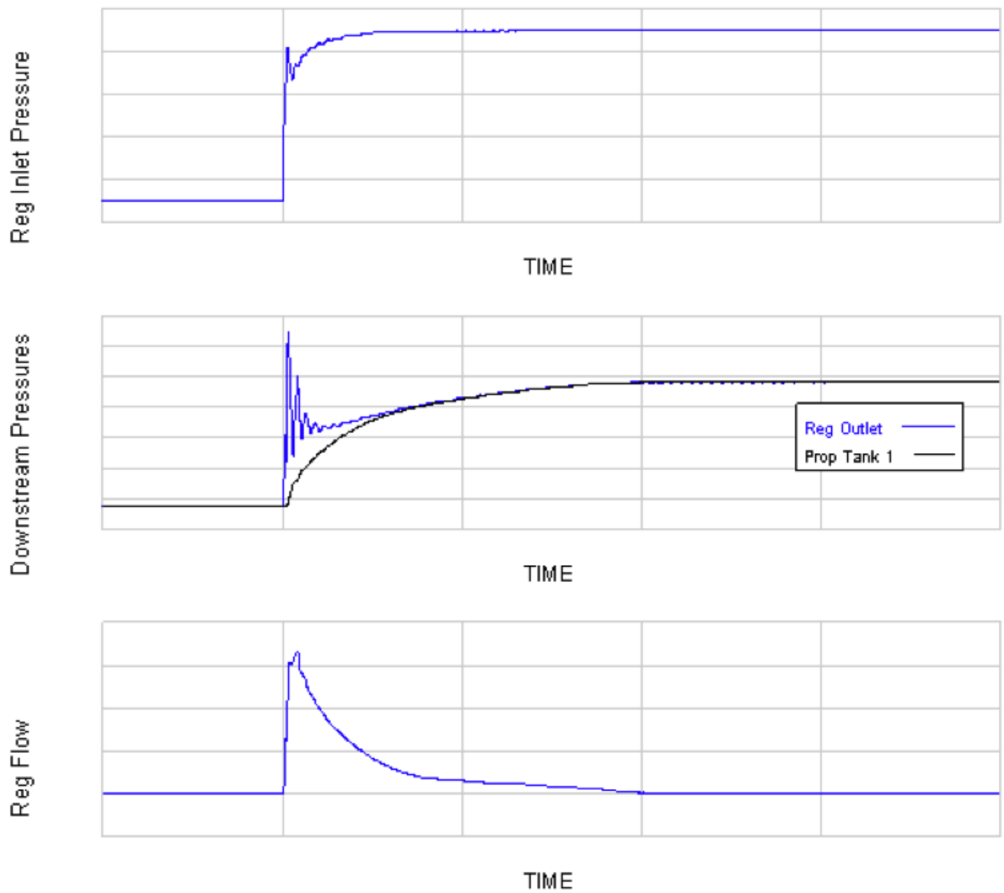

Figure 7 Sample dynamic analysis results, slam start

As mentioned, regulator performance under a pyrovalve shock and slam start was unknown and outside of Shuttle heritage. Therefore, a pyrovalve shock and slam start test was performed at JPL. The test article was a nearly flight like mockup of the pressurant control assembly (PCA). This consisted of two pryovalves in parallel followed in series by a filter and shock attenuator fitting upstream of the regulator; downstream of the regulator another shock attenuating fitting was followed by two pryovalves in parallel. The test was conducted in the MSL propulsion system flow test bed. The test bed was designed for testing MSL descent stage components using water, instead of hydrazine. The test bed can be reconfigured to accommodate a variety of testing and was used to test decent stage flight venturis and trim orifices, as well as a development throttle valve assembly. The test facility was configured to provide high pressure helium to the upstream side of the PCA. Downstream of the PCA the facility was configured to flow into an ullage volume in one of the test bed water tanks. A number of accelerometers were installed on the test PCA, to characterize the shock generated by pyrovalves and shock environment at the regulator.

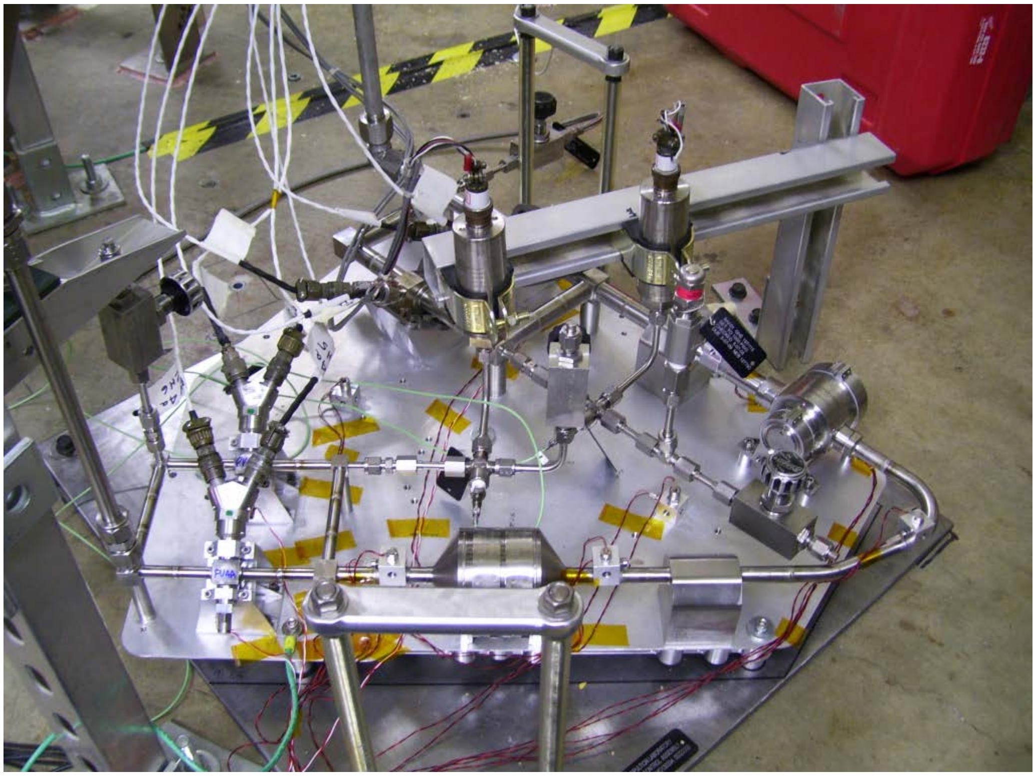

Figure 8. Pyrovalve shock and slam start test configuration

The test was conducted successfully. Although the source shock levels were all significantly high, the levels were well attenuated due to the mass block. The measured shock levels at various locations on the PCA plate were not high enough to raise a concern. To assess possible impact on regulator performance, a representative nominal mission duty cycle flow was run on the regulator before and after this test by VACCO. There was very little change in performance from the run before the test. Dynamic characteristics are very similar. Internal leak rate after slam start were still within specification. Therefore, it can be concluded that the slam start and shock did not negatively impact regulator performance.

IV. Concluding Remarks

The Space Shuttle Orbiter 750 psi helium regulator was successfully adapted for use as the Mars Science Laboratory (MSL) descent propulsion system pressurant regulator. The major achievements and findings were as follows.

- The Shuttle program furnished parts for the regulators from their inventory, which is an outstanding example of cooperation between NASA programs and centers.

- An integrated product team was formed to deliver this hardware, bringing together JPL project personnel, the original manufacturer, Shuttle program personnel, and one of the original analysts.

- Piloted regulators are extremely complex devices, highly customized to each individual application. Even their minor modification, re-tuning, assembly and test constituted a substantial effort.

- Dynamic analyses, based on those originally developed for Shuttle, were used to gain insight and predict performance.

- A special pressurization control assembly test was conducted to verify the regulator can operate with pyrovalve shock and slam start.

Acknowledgements

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