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Low Mass Components for Mars Ascent Propulsion

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The Jet Propulsion Laboratory is planning a sample return mission for early in the next century. To accomplish this, the Mars ascent stage must be landed on the Martian surface and then, after actuation, ascend to Mars orbit. Given this mission profile it is necessary to develop propulsion components of substantially lower mass than were previously available for spacecraft applications. Low mass is especially critical to the Mars ascent stage because mass reduction of this stage affords the greatest leverage for the reduction of the total mission system mass at Earth liftoff. In addition to very low mass, these components must be rugged, reliable, and compatible with fuel, oxidizer, pressurant gas, and environmental extremes. Three separate components were developed for a liquid bipropellant baseline stage propulsion system: A high-flow etched-disk filter with a mass under 90 g, an all-metal miniature fill and drain/vent valve with a mass under 9 g, and a miniature high-flow check valve with a mass under 20 g. The design and development of these components as well as test data are summarized.

Introduction

AN uncrewed sample return mission to Mars is being planned by NASA/Jet Propulsion Laboratory (JPL) for the near future. To accomplish this, the mass of the propulsion systems of various mission vehicle stages must be minimized.

To use liquid propulsion for the Mars ascent stage, the components must have substantially lower mass, increased reliability and durability, and compatibility with fuel, oxidizer, pressurant gas, and the environmental extremes found between Earth and Mars. Low mass of the Mars ascent stage is especially critical because any extra mass here has the greatest compounding effect of all stages on the total vehicle mass at Earth liftoff.

Three separate components were developed for the mission propulsion system: 1) a high-flow etched-disk filter with a mass under 90 g, 2) an all-metal miniature fill and drain and vent valve with a mass under 9 g, and 3) a miniature high-flow check valve with a mass under 20 g.

The high-flow etched-disk filter incorporates a diffusion-bonded element stack that uses a high-efficiency etched disk. Diffusion bonding the element stack substantially reduces the mass of the filter for a given flow and pressure drop. Traditionally, filters with similar flow/pressure drop requirements were approximately 990 g; the high-efficiency filter is only 86 g.

In addition to mass reduction, the high-efficiency filter has fewer internal piece parts than traditional filters and has a greater dirt capacity per filter surface area. Testing verified the expected increase in dirt holding capacity. The proven filtration methodology is the same as used in thousands of other successful etched-disk filters. Briefly, the flow paths' etched depth determines the micron rating of the filter. The main difference between the traditional etched disk and the high-efficiency design is the improved manufacturability and assembly. The new design allows for an increase in open area of the element stack.

The Mars ascent miniature fill and drain valve (FDV) is a simple and lightweight design capable of leakage rates below 1×10^{-6} scch GHe. Because of its nonrotating stem, the valve's seat life is prolonged and particle generation is minimized. The primary valve mechanism is made up of two moving parts (stem and drive) retained in a valve housing. A dowel pin prevents rotation of the stem and limits the stems axial movement. External threads on the stem mate with internal threads on the drive. The drive is trapped between a shoulder in the housing and the retainer. When the drive is turned, the rotation is converted into axial motion by the thread interface with the stem. The opening and closing of the primary seal requires use of specialized ground support equipment (GSE). When the actuation mechanism is located in the GSE tool, the mass of the flight portion is minimized.

The Mars ascent check valve is the latest in a product line that has been improved continuously over the last 15 years. This simple, compact design reduces the mass from 227 g for a typical check valve to just under 20 g. This was accomplished even though the flow requirement increased from 13 SCFM to 87 SCFM, thereby demonstrating a much higher flow to weight ratio than other traditional check valves. The check valve consists of a piston/poppet assembly that is spring loaded against a seat machined into a titanium inlet cap. The inlet cap and housing are joined with a single electron beam weld to form the pressure boundary. A Teflon® poppet is pressed and pinned onto a titanium piston.

All three component designs drew from past designs already qualified and flown on numerous successful missions. Each component was tested to the Mars ascent program requirements with excellent results in each case. The technology developed here has broad applications to other programs where low mass is important.

Design and Development

The Mars ascent propulsion system components were designed and developed with the goal of reduced weight while meeting the operating requirements of the JPL specification.

Etched-Disk Filter

Typically, a traditional etched-disk filter assembly consists of two main components: a filter body with an inlet port and an element assembly with an outlet port (see Fig. 1). The entire filter assembly may be constructed from either titanium or stainless steel. The filter

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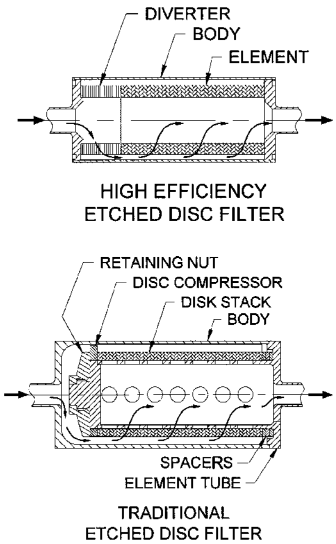

Fig. 1 Traditional and high-efficiency etched-disk filter assemblies and flow paths.

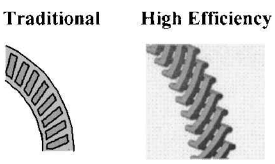

Fig. 2 Etched disks.

body is electron beam welded to the element tube flange to prevent reliably any external leakage during the life of the mission.

A standard round style etched disk is used in a majority of aerospace filter assemblies. Several years ago a high-efficiency etched disk (Fig. 2) was developed for aerospace applications (United States and foreign official patent).[1] This high-efficiency design substantially improves both flow characteristics and dirt capacity for a given filter element size (United States and foreign patent pending),[1] by using the cross-hatch etched pattern, which provides for 50% more open area. To reduce the overall weight of the filter assembly, a diffusion-bonded element stack was used instead of the conventional mechanically compressed element stack. Diffusion bonding is a solid-state process for joining the etched disks permanently by using only heat and pressure to achieve bonding through atomic diffusion. This eliminates the need for the element tube, disk compressor, and retainer. Elimination of these components reduces the mass without compromising the performance of the filter. Employing diffusion bonding maximizes the number of active etched disks in the filter element stack. The nonactive components, such as the disk compressor and the retainer, are eliminated, thereby making the element shorter and lighter.[2]

The diffusion bonded element assembly allows a more aggressive disk design without the restrictions of the compression loading hardware. The absence of large compressive loads allows the disk structure to be less massive. The cross hatch pattern of the high-efficiency etched disk design when stacked generates an element with more flow area and surface area per unit mass. These enhancements are realized while retaining advantages over woven media (wire mesh) such as structural robustness and inherent cleanability.

Fill and Drain/Vent Valve

The miniature FDV discussed here is ideally suited for the Mars mission because of its uniquely simple design, compact size, low mass, outstanding heritage, seal redundancy, and performance. A single configuration is used for both the high- and low-pressure applications. The valve itself is built directly into the 1-in.-long × $\frac{3}{8}$-in.-diam tube with an orbital weld interface at one end and a fill and drain interface at the other. Because the weight of the valve is less than 9 g, the valve can be fully supported at the welded interface with no additional structural support required.

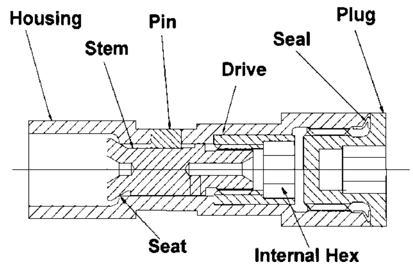

Fig. 3 FDV.

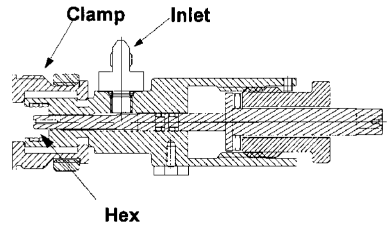

Fig. 4 Ground support tool.

The innovative approach applied to this valve design includes use of a separate nonflight (GSE) valve operating tool. A valve cross section drawing is provided in Fig. 3.

In the closed position, the stem is forced against the valve seat by the drive. The valve seat is integral to the housing. While the valve seat is closed, the drive is loaded between the stem threads and the housing shoulder in compression.

In the open position, the stem is held away from the valve seat by the drive acting against a shoulder in the ground support tool. Fluid flow passes through the open seat, through two flats on the stem, and through the center of the stem.

The primary valve is composed of two moving parts retained in the valve housing. The internal thread of the drive is threaded to the external thread at the end of the stem. The outer diameter of the drive is free to turn within the inner diameter of the housing. The flat face of the pin is seal welded into the housing and engaged to a flat on the outer diameter of the stem with a minimal running clearance. The pin acts to prevent rotation of the stem, yet allows easy axial motion. When the drive is turned using a hex tool engaged with the internal hex of the drive, the rotational motion is converted to axial motion by the thread interface with the stem. Because the drive is trapped between two fixed shoulders in a way to prevent axial motion of the drive, while the stem is prevented from rotating, the resultant forces cause the stem to move axially. With standard right-hand threads, counterclockwise motion of the drive will force the stem away from the seat, and clockwise motion of the drive will force the stem against the seat. This maintains traditional logic for operating valves. The fact that the stem is not rotating when it is in contact with the seat prevents wear, galling, or smearing at the critical primary seating surface.

After closing the primary valve seat, the ground support tool is removed, and installing the seal and plug to the external end provides a secondary valve seal shown in Fig. 3.

The valve materials were carefully selected for compatibility with the operating and nonoperating environmental conditions, as well as the functional operating requirements. All materials selected are metallic and compatible with all operating and nonoperating fluids and extreme temperature range (−170 to +350°C) specified by JPL.

A unique ground support valve-operating tool was designed to allow for the design of an ultra-low mass flight valve. A cross section is provided in Fig. 4.

The miniature FDV requires a separate specialized ground-support tool for filling and draining operations. The valve-operating tool is nonflight hardware, fully reusable so that a single tool is sufficient to operate all FDVs on a flight system. The valve-operating tool is capable of being disassembled to allow for thorough flushing and cleaning of wetted and nonwetted surfaces as required. All soft goods in the valve operating tool can be replaced whenever necessary. All materials in the tool are chosen to be compatible with all working fluids.

The practical benefits of operating the flight valves with a remote tool are as follows.

1) The total mass of the fill and drain flight valve is reduced by moving certain valve-operating features from the flight valve to the tool.

2) The complexity of the fill and drain flight valve is reduced by moving certain valve-operating features from the flight valve to the tool. This, in turn, improves the valve reliability.

3) The program cost for fill and drain flight valves is reduced because several parts which would otherwise be provided with each valve are provided for with only one tool.

4) The tool design can take advantage of greater design flexibility to reduce cost and improve functionality because mass and size are less critical for the tool.

5) The valve tool is simplified by using soft seals because the valve-operating tool is not exposed to the same environmental temperature extremes as the miniature fill and drain flight valves.

Check Valve

The check valve consists of a two-piece titanium welded housing. The inlet half of the housing contains the seating surface. The seating surface is machined at an angle, different from the poppet sealing surface. The difference in angles between the two sealing surfaces amplifies the seat stress, thus improving the sealing capability of the valve.[3] This type of seat design has been used in other valves for many years. The outlet of the housing retains the spring and guides the sensing piston.

When pressure is applied to the inlet of the valve, a force is created on the poppet/piston assembly, which acts against the spring. When the force created by the inlet pressure exceeds the force of the spring, the poppet lifts off the seat allowing the fluid to flow. As the fluid begins to flow and passes through the valve, the fluid also acts against the sensing piston. The larger area of the piston adds to the force opening the valve. The increased force opening the valve improves the stability of the valve, which in turn increases the life of the seat. The fluid then passes through the metering orifices on the sensing piston and out of the valve. To enhance stability, the pressure downstream of the piston is decoupled from the pressure immediately downstream of the seat.

Two versions of the check valve were initially designed: one with the sensing piston diameter of 0.484 in. and one with the diameter of 0.750 in. The 0.750-in. configuration was decided on because it resulted in a more stable valve with a negligible increase in mass. The check valve is shown in Figs. 5 and 6.

The seat/seal, constructed of lightweight titanium, is capable of sealing up to 8.3×10^{-4} sccs GHe at from -7 to $+49$°F (internal). This seat/seal configuration is flight qualified and has a demonstrated successful flight heritage of over 10 years. The valve seal is constructed of Teflon for low leakage over a wide temperature range and long life cycle. The all-welded external construction ensures low external leakage better than 1×10^{-6} scch GHe.

Component Test/Acceptance Test Program

Etched-Disk Filter

It was demonstrated that the prototype filter assembly met the acceptance and qualification requirements as specified by JPL. The maximum expected operating pressure (MEOP) is 550 psig, proof pressure is 825 psig, and burst pressure is 1100 psig. See Table 1 for a brief summary of test results.

Fill/Drain Vent Valve

Acceptance testing was performed, that is, visual review and mass measurement; proof pressure testing; cleanliness testing; leakage testing of both primary and secondary seals (leakage test rates were well below 1×10^{-6} scch GHe at 10,000 psi). Flow and pressure drop testing, environmental testing with sine and random vibration and shock testing, and functional testing were also conducted. The MEOP is 6,700 psig, proof pressure is 10,050 psig, and burst pressure is 13,400 psig. Actual proof and burst test pressures were increased to account for elevated temperature conditions.

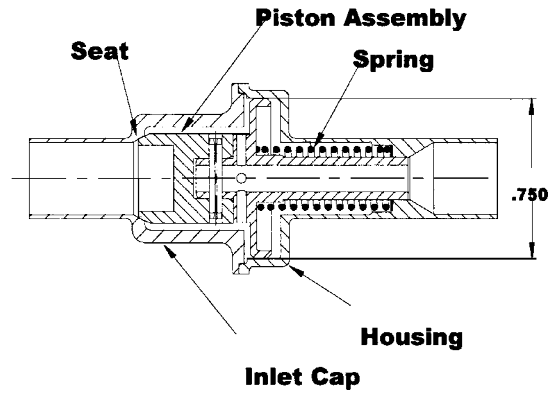

Fig. 6 Check valve cross section.

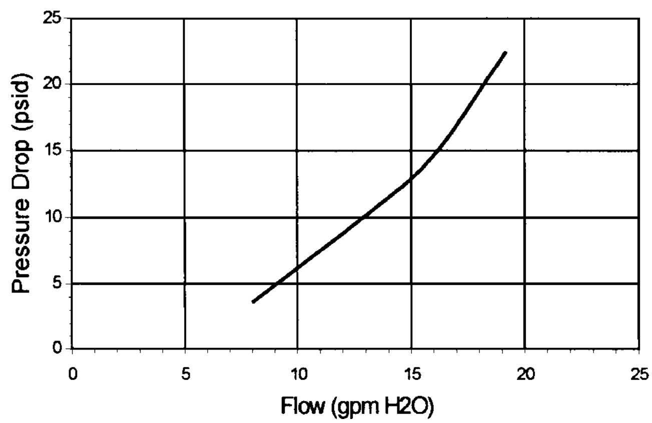

Fig. 7 Filter flow vs pressure drop.

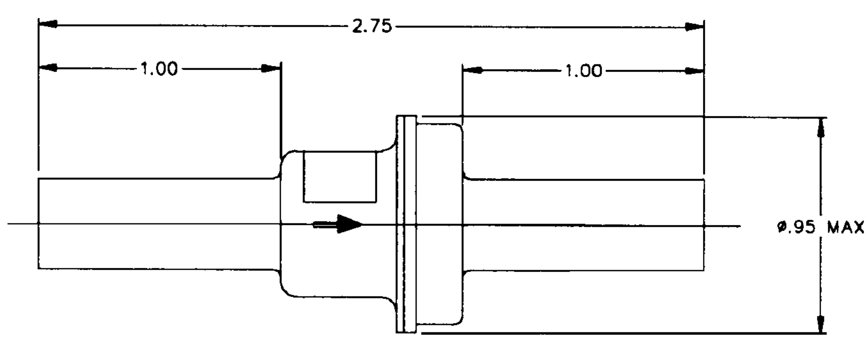

Fig. 5 Check valve envelope (dimensions in inches).

Table 1 Summary of test results for filter, fill/drain vent valve, and check valve

Property	Etched disk filter	FDV	Check valve
Proof pressure, psig	825	16,500	825
Flow/DP (see Fig. 7 and 9)	14.6 psid at 16 GPM water	11.5 psid at 0.1 GPM water	13 psid at 87 scfm GHe at MEOP
Random vibration	13.2 Grms	13.2 Grms	13.2 Grms
Mass, g	86	8.9	20
External leakage	0.4×10^{-9}	1.6×10^{-8}	1.0×10^{-8}
Internal leakage	N/A	1.4×10^{-8} sccs GHe	0 scch GHe at 650 psig
Life cycles	N/A	50	5,000
Micron rating	25μ	N/A	N/A
Dirt capacity (see Fig. 8)	700-mg test dust	N/A	N/A

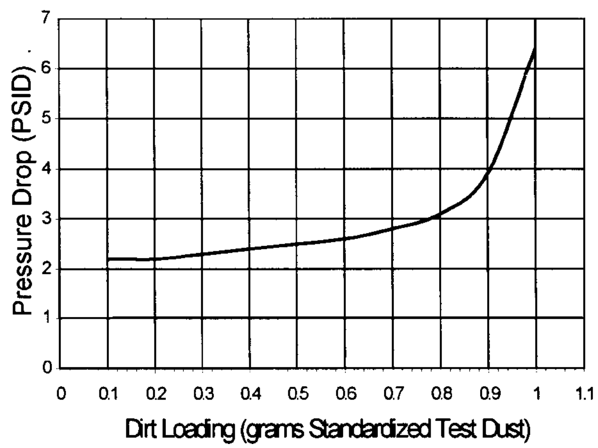

Fig. 8 Filter pressure drop vs dirt loading.

More aggressive development testing consisted of cycle life testing, functional testing, burst pressure testing, and visual review. See Table 1 for a brief summary of test results.

Check Valve

Two check valve units were built, tested, and delivered. The first unit, the proof of concept (POC), was tested to validate that the design met the requirements for crack and reseat pressure, and for flow vs pressure drop. The second unit, a production configuration unit, was tested before welding in a special fixture to verify functional compliance for crack pressure, reseat pressure, flow vs pressure drop, and internal and external leakage. It was then acceptance tested after final welding. A plot of flow rate versus pressure drop for the production unit is shown in Fig. 9.

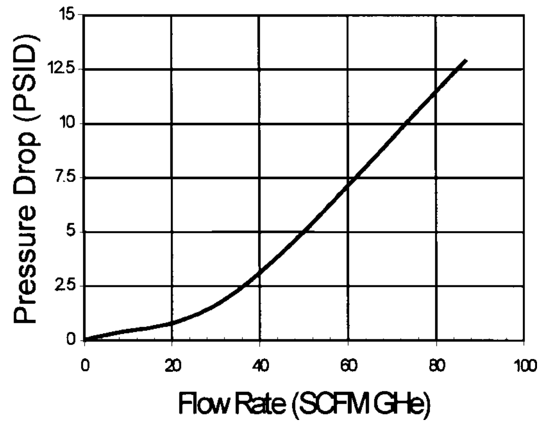

Fig. 9 Check valve flow rate vs pressure drop at MEOP.

The production unit configuration differed from the POC unit in that the flow passages were increased to allow for more flow and reduced pressure drop. With minor modifications to the housing and sensing piston, flow vs pressure drop characteristics were improved. See Table 1 for a brief summary of production unit test results.

Summary

The innovations (use of a ground-based support tool) and new developments to be employed in the pressurant filter assemblies for candidate Mars ascent liquid propulsion systems (increased flow and contaminant collection) do not compromise the performance of the components. The current designs of the three components (high-flow etched-disk filter, miniature fill and drain/vent valve, and miniature check valve) are based on a progression of improvements in technology and materials and evolving customer needs.

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