High Pressure Gaseous Oxygen Isolation Valve (HP GOx)

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High pressure oxygen leads to serious safety concerns. NASA takes the design of oxygen hardware very seriously to minimize the risk of ignition and provide a safe environment for the crew. Since the space shuttle was retired, NASA has worked with private industry to develop crew transport to and from the international space station, but a new vehicle needed to be designed for the harsher environments and longer durations associated with deep space missions. This new vehicle, now named Orion, needed a breathable oxygen system design to support the crew. Lockheed Martin developed the Orion Crew module for NASA to support these deep space crewed missions. Moog played a part in designing this system by undertaking many of the fluid valves including the high-pressure oxygen isolation valve. Typically, the oxygen is provided by the service module, except on re-entry. After the module separates from the service module prior to re-entry there is an onboard oxygen tank that takes over the supply of oxygen to the crew. There are parallel regulators that support the flow of oxygen from the high-pressure tank, each of which needs an isolation valve in case of a regulator failure. This valve is needed to stay in its commanded position and only use a small amount of power to actuate quickly should a regulator fail. It needs to be leak tight when closed and have minimal leakage externally. The valve was also required to use seals instead of bellows to reduce cost, schedule, and power. The final design needs less than half of one amp to actuate and weighs less than five pounds. This was accomplished by utilizing a brushless DC motor through a ball screw with a pressure balanced poppet and a closing spring to deliver a high-pressure gaseous-oxygen-safe isolation valve. Artemis II will be the first mission launched with the high-pressure oxygen hardware installed. This design will also be used for NASA on the HALO module of the Gateway space station in orbit around the moon.

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I. Introduction

The HP GOx unit was designed developed and produced by Moog over the last five years. We worked closely with the engineers at Lockheed Martin to refine the specifications and valve design to meet the needs of the crew module. Some of the critical characteristics of the valve included minimal weight to support the overall weight allowance for the vehicle, oxygen compatibility was crucial, minimal power usage to integrate into the vehicle control system, as well as tight leakage requirements without the use of bellows.

Schedule was also critical, therefore we highlighted a few key components that needed to be designed and procured early in the process. We selected components that would give us the most margin to the requirements in order to minimize the risk that they would need to be revised during development. We also performed risk mitigation testing on the seals, filter development, and impact stop development that needed to be completed before we started our development hardware test campaign. This early component testing narrowed down the design of the unit allowing us to more rapidly close on the final design. This testing pushed our development unit to be as flight-like as possible, burning down risk and reducing development time.

A successful development campaign showed compliance to almost all the requirements. Final flight modifications were made based on what was learned in development and the Artemis II units were delivered as quickly as possible, the valve design was qualified and is now being produced for the Artemis and Gateway programs.

II. Early Design Choices

The program team decided early in the design on a few key features. This allowed us to order longer lead materials and finalize the design around the brushless DC motor and the ball screw. The brushless DC motor and planetary gearset provided the torque to the ball screw. We chose a ball screw and the motor ratio based on the margins required for actuation. The motor provided the most torque with-in the closing time allotted and the ball screw was chosen over a standard screw to minimize friction and provide the most force possible to the seals which still needed to be finalized.

These initial components set the limit to the force to open the valve. The rest of the design, including the seals and closing spring, were finalized around these initial decisions. Material choices were also defined to successfully prevent ignition of the valve components.

III. Early Risk Mitigation Testing

A. Seals

A fixture that mimicked the centerline of the valve was manufactured to understand the leakage and force characteristics of different spring energized seal designs. Iterations of the seal configurations helped finalize the seal design for the development unit. Three separate vendors provided seals design for the application which were tested across the range of environmental conditions. The best design was iterated to improve leakage before the development unit was built. Force numbers looked promising, and the spring was able to be designed with adjustment in the build to match the already procured motor and ball screw.

B. Filter

In parallel to the development of the seal geometry, a pure nickel filter needed to be designed, tested, and qualified to support the inlet flow of the valve. Fine and course mesh were sintered together to provide strength and filtration during the max flow conditions and the rapid pressurization events associated with oxygen slam testing. The mesh was pleated to increase surface area and then multiple designs were tested for pressure drop, both clean and after they had been contaminated with the required dirt capacity. After pressure drop, rapid pressurization testing was performed to induce high pressure drop across the filter showing structural integrity that would be needed for the oxygen testing. This information allowed us to verify pressure drop requirements with the clean filters during the production of the flight units. The initial test campaign needed to be revised after the rapid pressurization test destroyed the filter. A more flight-like test as well as improvements to the filter manufacturing tooling solved the issue and qualified the design.

Fig. 1 Nickel Pleated Disc Filter

C. Impact Stop

The brushless DC motor used HEDs to commutate the phases, but there was no position indication associated with the valve, the valve is commanded open or closed until the ball nut impacts a hard stop. Repeated impacts of the unit against the hard stop introduced a risk of particle generation that could end up in the ball screw. In order to minimize the damage of the hard stop from repeated use, a cushion was developed to slow the ball nut down prior to impact. Viscoelastic material was used in shear to provide the maximum force against the speed of the traveling nut. The figure below shows the impact stop assembly and the test setup used to prove life of the stop.

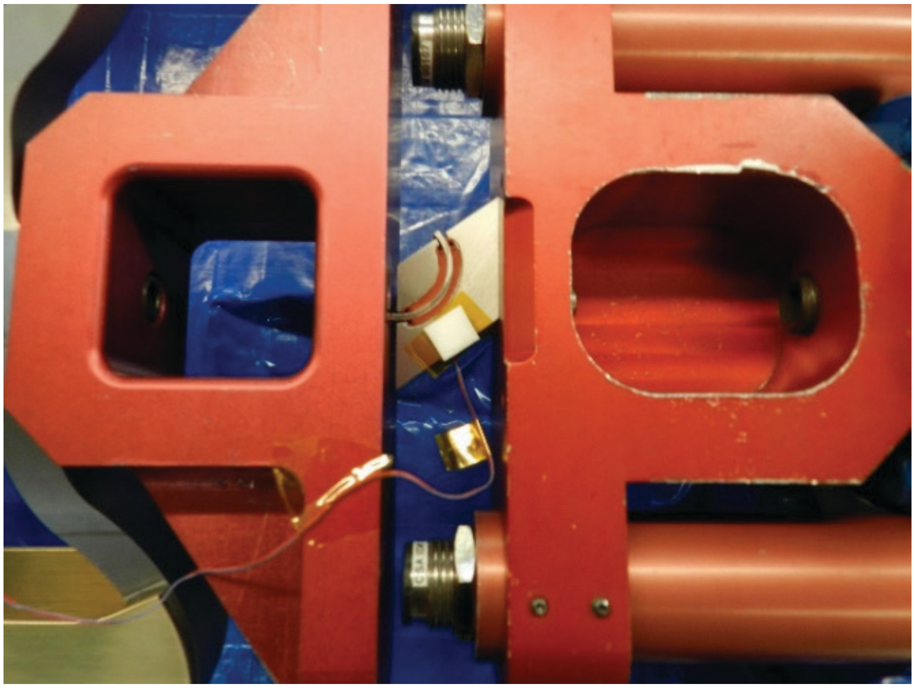

Fig. 2 Impact Stop Cycle Testing

IV. Development Testing

With the seals, filter, and impact stop designed, two development units were built in what was intended to be the flight configuration. The two units were used to run through the qualification testing and finalize the design. This environmental testing included vibration, shock, thermal, and oxygen testing.

A. Shock and Vibration Testing

Two of the most difficult environments in space flight are the vibration from the rocket propulsion, and the shock through the structure during separation events. In this case the highest vibration levels came from the launch abort system which provides three rocket motors to pull the crew module safely away from the ascending launch vehicle should anything go wrong, and the astronauts need to abort. A vibration table was used to match the predicted vibration environments for both accent and abort conditions.

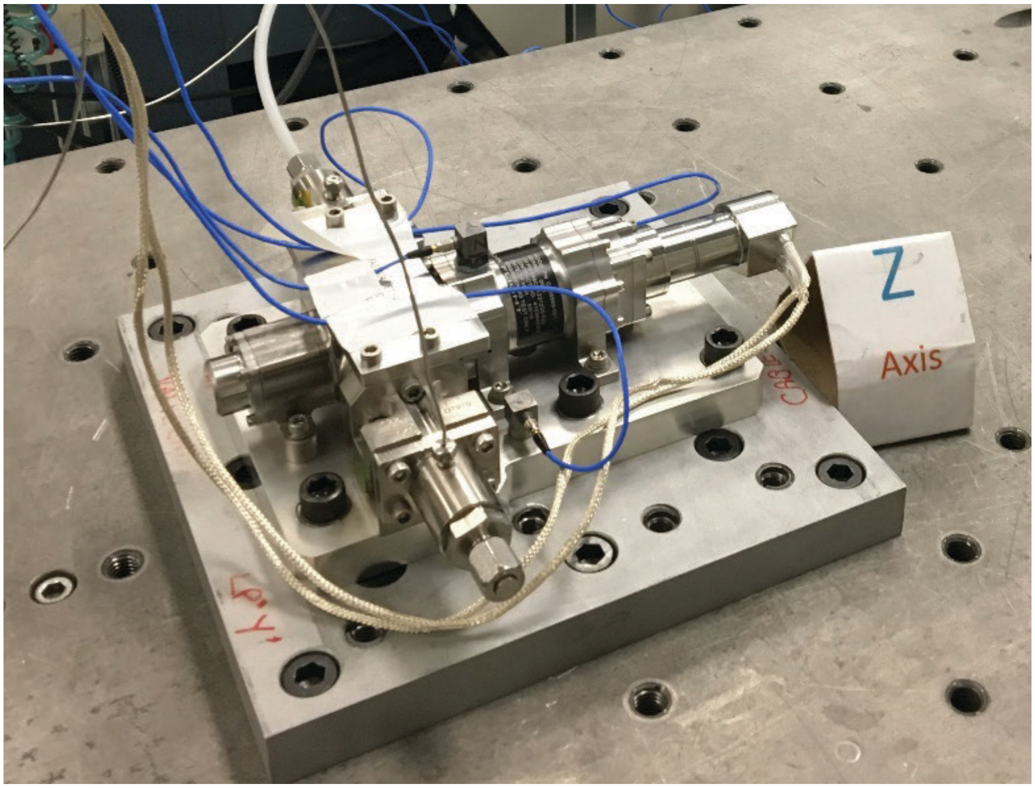

Fig. 3 Random Vibration Testing

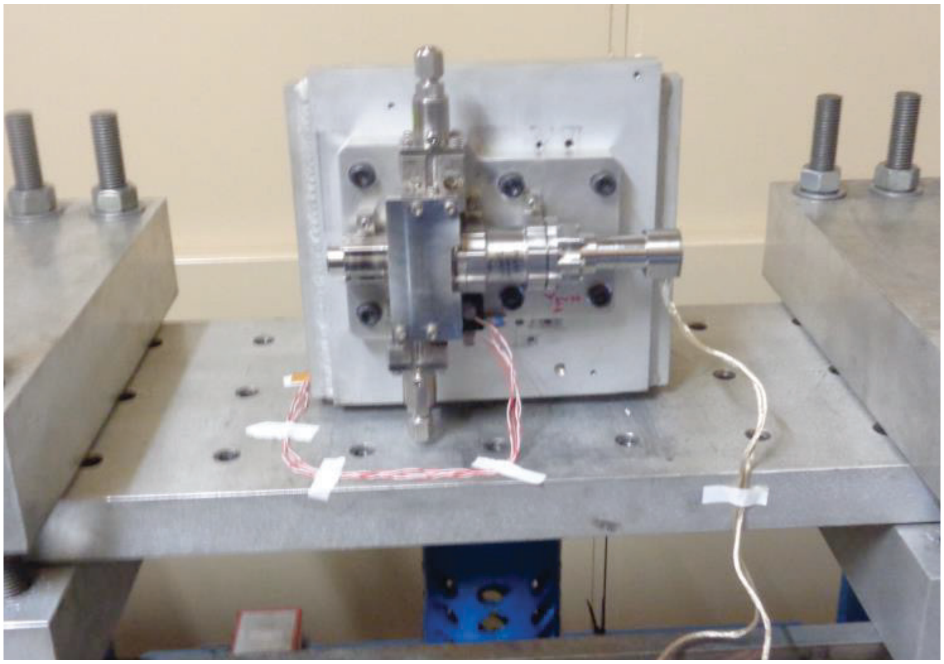

Fig. 4 Pyrotechnic Shock Testing

B. Oxygen Testing

The development units provided an opportunity to design a flight-like oxygen test procedure. The first test required by NASA is a pressure slam test rapidly pressurizing the unit to verify no ignition due to heat of compression. Valve configuration, oxygen temperature, and pressure ramp rate were all finalized and tested during this development phase. The second requirement for oxygen testing was a functional check of the unit. During fill operations the valve is closed, once the tank is full the valve will open and fill the tubing between the valve and the downstream regulator that is locked up with pressure from the service module. This initial opening of the unit creates an important functional inspection due to the initial pressure drop across the valve from a high pressure to atmospheric pressures in the tubing. This creates sonic velocity across the valve seat which can lead to ignition if not properly designed. After this initial stage of the functional test was complete a test of the full flow condition at the design flow and pressures. Finally, the unit was closed during the flow test to simulate an isolation event during re-entry if required. Later it was determined that the design flow did not fully envelope a failure mode of the downstream regulator. When this was found and disseminated to Moog, we were able to incorporate the higher flow rate into the oxygen test and no ignition was ever generated from the testing of the development or flight units.

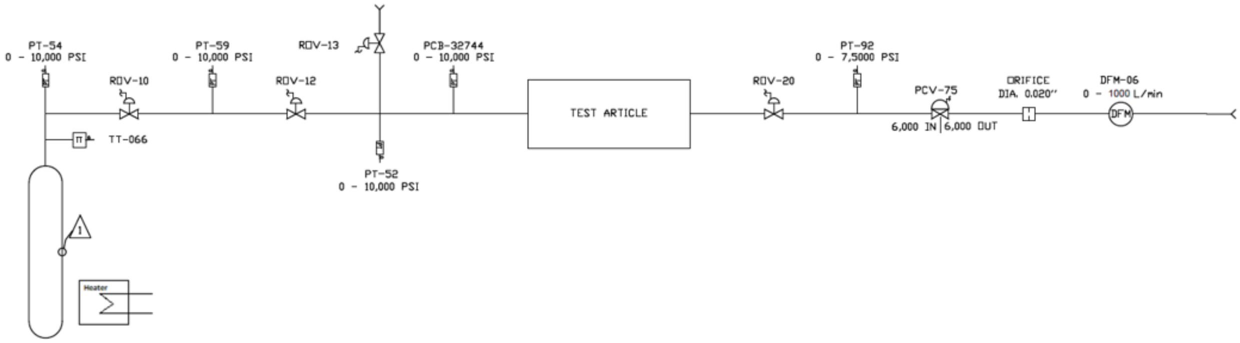

Fig. 5 Oxygen Testing Schematic

C. Thermal Testing

During thermal testing, the external leakage at the cold temperatures were highlighted as an issue due to the seal performance at the cold extremes. From risk mitigation it was already determined a new seal design was required. The newest design continued to lose performance at lower temperatures. There are multiple seals that contain the internal flow from external leakage. External leakage tests are cumulative reading the total leakage from the unit and fixturing. It was critical to develop a new method to isolate the leakage and redesign the critical areas of leakage. Test media was converted from helium to nitrogen to more accurately represent the oxygen molecules that valve is designed to contain. Additional seals were added to minimize the leakage points out of the unit and special ports were added to each end of the hardware to differentiate leakage from the fixture, inlet end, and outlet end of the valve. This along with other failure investigation strategies determined a failure of the dynamic seals and damage to one of the static seals. A new design of the dynamic seals significantly improved the cold leakage as well as an additional shim to protect the static seal from damage. During these updates work with our customer of the requirements of the vehicle set the lower temperature limit as high as possible allowing the unit to meet the leakage requirements for the mission.

V. Major Challenges

A. Seat Retainer

The part of the valve that holds the valve seat in place was originally designed to align to the flow path, this provided the lowest pressure drop configuration. During assembly it was determined that the alignment pin was difficult to install and greatly increased the risk of damaging critical sealing surfaces. With the pressure drop data that showed significant margin to the requirement, we were able to redesign the seat retainer to be axisymmetric and performance became independent of orientation. This allowed us to remove the alignment pin from the assembly and greatly increase our assembly success.

B. External Leakage

More than ten iterations of seals were tested throughout the campaign, this steady improvement from the initial seal testing though development and up to the flight hardware was difficult but ultimately successful. An added component to protect the static seals from back-pressure as well as coordination on the pressure temperature relationship of the tank allowed us to meet the external leakage without the need for bellows. This persistent dedication to improving the external leakage significantly reduced the cost and lead time of the hardware and provides a robust solution by removing the need for bellows.

VI. Future

A. Current Applications

The same design is being used for the oxygen tanks on the HALO module of the Gateway space station that will orbit the moon, providing a docking point for exploration of deep space and the moon surface. This valve is also being proposed for the oxygen tanks on the lunar lander.

B. Position Indication and Reverse Flow

The design could easily be modified to allow for position indication, by adding a linear variable differential transformer (LVDT) into the design, feedback on the valve position could be established with relatively minor design changes. The poppet is pressure balanced, which means the force exerted on the valve by the fluid pressure does not act on the poppet in the direction of actuation. Therefore, the margin on leakage and actuation force would not be reduced if the flow was in the reverse direction. This makes the valve ideal for use in a cross-over application between multiple oxygen tanks. By connecting these tanks together with an isolation valve, should any downstream equipment fail, the commodity could be used through the isolation valve and into the redundant line. A filter could be installed in line with the outlet, or minor modifications could be made to the design to incorporate a filter on both inlet and outlet. This would allow the unit to operate in either flow direction.

C. Re-use Qualification

The valve was recently qualified for a second mission. This will allow NASA to keep much of the fluid hardware in place after the Orion capsule lands and significantly reduce the cost of the next mission by reusing the capsule with the fluid hardware installed. Hundreds of additional cycles were added to the hardware without detrimental impact on external leakage. The surface finish of the poppet inside the valve as well as the special design of the dynamic seals allow the unit to handle significant cycle life requirements and maintain critical external leakage performance. Any external leakage would result in loss of commodity, breathable oxygen, that is required for re-entry.

VII. Conclusion

It has been many decades since humans explored deeper into space beyond earth orbit. As NASA and humanity push to expand our understanding by sending people further from Earth new hardware needs to be designed to support these missions. The high-pressure oxygen isolation valve is just one example of the many achievements Moog and engineers everywhere have achieved for this goal. We continue to work hard to make the hardware more reliable, more efficient, and cost conscious as we expand our horizons and meet the needs of NASA and space missions around the globe.