Magnetically Latching Cryogenic Fluid Coupler for Lunar Surface Operations

Nic Heersema,[1] Shideh Naderi,[2] Scott Stebbins,[3] Paul Bean,[4] and
Andrew Holguin[5]
NASA Armstrong Flight Research Center, Edwards, California, 93523, U.S.A.

Envisioning future lunar exploration and habitation necessitates addressing numerous needs related to sustaining human life and managing resources on the lunar surface. One of these needs is proficient cryogenic fluid management, which is particularly challenging in the dusty lunar environment. To address the need for a robust and environmentally tolerant cryogenic management solution, the CryoMag Coupler was developed as demonstrative solution. The CryoMag is a low-force cryogenic coupler that facilitates the mating, latching, and de-mating of cryogenic connections by way of a magnetic interface, providing a dust-tolerant solution to manage cryogenic fluids in the challenging lunar environment. This paper details the design and testing of this Coupler.

I. Introduction

As humanity looks to the future and envisions exploration and habitation of the lunar surface, many needs relevant to those aspirations have been identified. Life support, in-situ resource utilization, and other systems will require a cryogenic fluid management system to enable transport and storage of various cryogenic fluids. Temporary connections, performed in-situ by an astronaut or rover, will be a necessary aspect of the cryogenic fluid management system but will face unique challenges posed by the austere lunar surface environment. In addition to the usual problems of cryogenic fluid transfer (such as leakage, interface purging, et cetera), dust contamination, low gravity, and a wide temperature range must be accounted for. The CryoMag Coupler Project team developed a prototype of a cryogenic magnetic coupler to address this need and meet these challenges. The primary purpose of this project is to assess the feasibility of the concept and identify areas for potential improvement in future iterations of the design.

Hardware designed for lunar operations must be able to tolerate the harsh environment encountered on the lunar surface. The CryoMag Coupler design took into consideration potential operation in any region of the lunar surface and thus potential exposure to a range of lunar surface temperatures, from 30 K in the permanently shadowed regions of the lunar poles up to 400 K mean temperature at the lunar equator [1]. The CryoMag Coupler is also designed to be tolerant of lunar regolith, a known problem for most mechanisms due to the abrasiveness, high iron content, and electrical charge of the regolith. Other environmental factors, such as radiation and vacuum, were determined to be out of scope for this initial proof of concept, and may be investigated in future phases. Operational design factors that enable the ease and speed of Coupler mating and de-mating through the use of the magnetic interfaces further reduce the exposure of the Coupler to lunar dust intrusion while minimizing the astronaut extravehicular activity (EVA) time spent to operate the CryoMag Coupler.

Development of the CryoMag Coupler was conducted in an iterative fashion, with design and testing performed at the subsystem levels first and then at higher levels of integration. At this stage of development, the design is intentionally modular to enable components to be easily changed out as necessary to support the feasibility assessment; future iterations of the design are expected to be optimized for weight and other factors. System-level testing of the

---

[1] AST Structural Mechanics, Aerostructures Branch, AIAA Member.
[2] AST Avionics Systems, Advanced Systems Development Branch
[3] AST Structural Mechanics, Aerostructures Branch
[4] AST Avionics Systems, Advanced Systems Development Branch
[5] AST Aerospace Flight Systems, Operations Engineering Branch

CryoMag Coupler completed to date includes mechanical/functional evaluation, dust environment exposure, and cryogenic fluid flow. Details about the design of the CryoMag Coupler and results of this testing are discussed in this paper.

A. Concept of Operations

A generic cryogenic fluid management system was envisioned to support the development of the CryoMag Coupler design. This generic system was based in part on the design of the prototype Lunar Electric Rover, with the assumption that a rover designed for longer duration would store the necessary oxygen and nitrogen in cryogenic form for greater volumetric efficiency [2]. A rough sketch of the envisioned system is shown in Fig. 1. Two cryogen storage tanks of any size could be temporarily connected using the CryoMag Coupler to allow transfer of cryogenic fluid between the tanks. Venting and pumping of the cryogenic fluid through the Coupler would be performed by the tank system rather than by the CryoMag Coupler itself. Additionally, for initial development efforts, it is assumed that the socket side of the Coupler is fixed to a panel and that the probe side of the Coupler is attached to a flexible hose that can be manipulated by the user. The envisioned setup is similar to the system used to refuel a vehicle at a gasoline station on Earth.

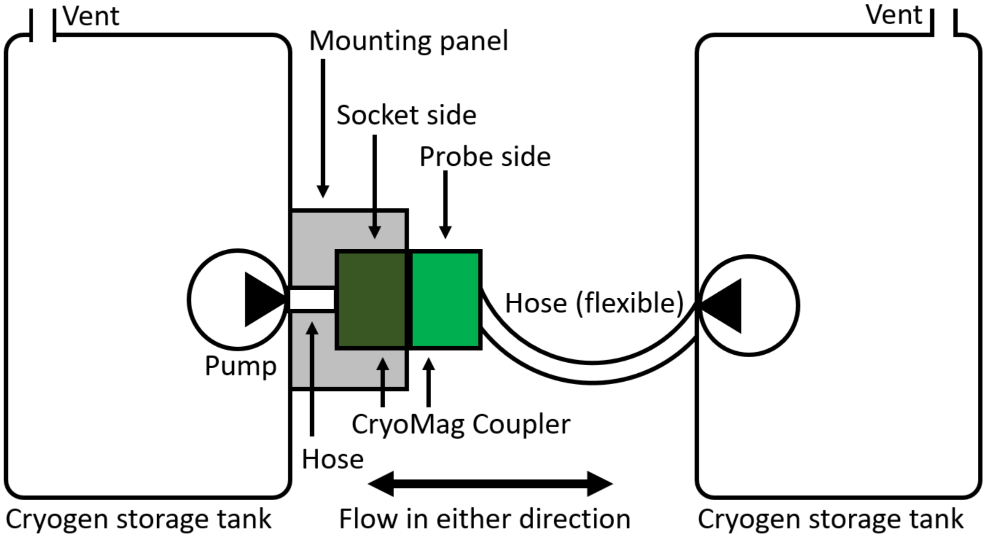

Fig. 1 The envisioned generic cryogenic fluid management system.

The CryoMag Coupler enables the system to rapidly attach and detach the tanks, enhancing the functionality of the system. The interfaces of the system include hose connections, commodity type, fluid pressure, flow rate, allowable leakage, and forces exerted on or by the system during mating, latching, and de-mating. The interfaces of the user with the system include the ability for the user to hold and manipulate the probe side of the Coupler, ease of connection between the probe side and the socket side, and the force required by the user to mate and de-mate the Coupler. The CryoMag Coupler was designed with the intention that a single user wearing bulky gloves (such as those of an EVA spacesuit) could successfully operate it, although the Coupler has not yet been optimized for human factors. Automated operation by a robot was considered and may be viable; further testing and optimization for a robotic-type application would be required.

II. The CryoMag Coupler System Design

The CryoMag Coupler is divided into three subsystems: the Low Force Disconnect (LFD) coupling device that enables cryogenic fluid transfer; the Magnetic subsystem that provides the forces necessary to mate and latch the LFD; and the dust mitigation subsystem (DMS) that reduces the amount of dust that enters the fluid flow path and internal Coupler mechanisms. The subsystems were designed to achieve the capabilities of cryogenic fluid transfer in a dusty lunar environment, and with a high degree of modularity in order to evaluate the feasibility of different component designs. The three subsystems were developed independently with tightly controlled interfaces to ensure that the integrated system would work as expected. The integrated CryoMag Coupler is shown in Fig. 2.

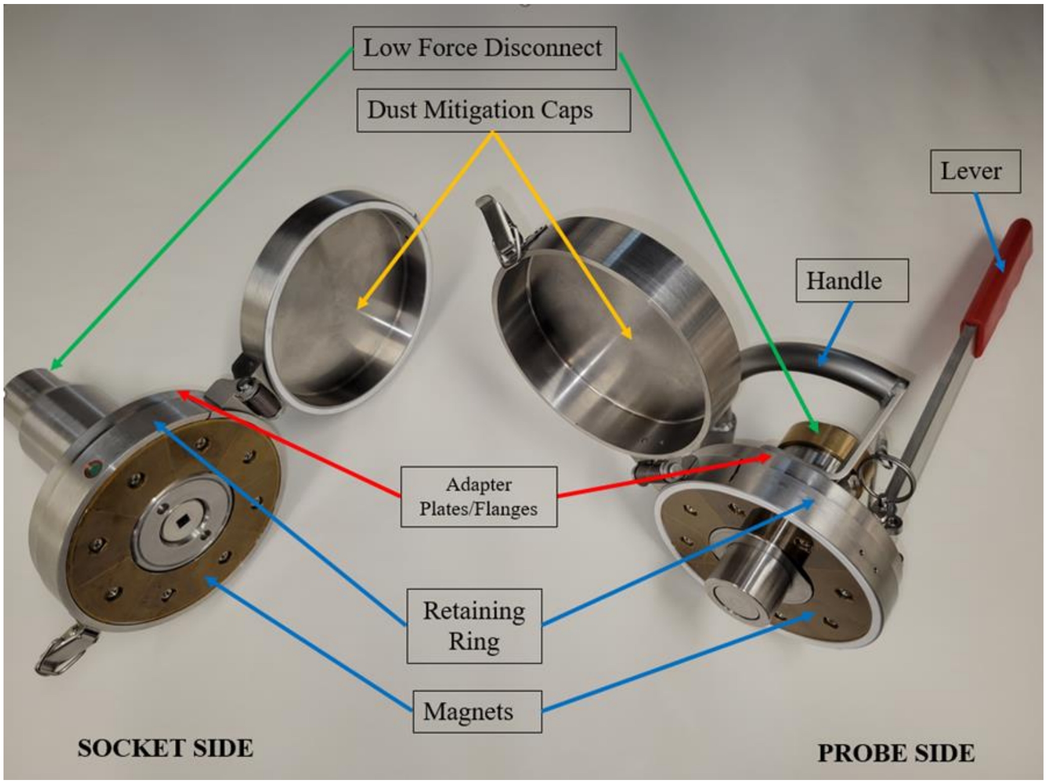

Fig. 2 The fully integrated CryoMag Coupler.

The LFD coupling device developed by the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) (Orlando, Florida) was selected through a comprehensive trade study as the foundation for the CryoMag Coupler design. The LFD subsystem was still under development when it was adopted by this Project team and had previously demonstrated the ability to flow fluids and be mated completely with the external force applied [3], placing the LFD subsystem at a higher maturity level than the Magnetic subsystem and DMS, and defining the interfaces and some of the performance requirements for their designs. The magnet geometry for the Magnetic subsystem was selected based on the initial LFD force profiles for Coupler mating and de-mating. An adapter plate connects the Magnetic subsystem to the LFD Coupler and served as the mounting surface for the DMS. The modular design of the CryoMag Coupler lends itself to the possibility of varying the Coupler itself by swapping out the LFD coupling device for another device. The Magnetic subsystem can use the same magnet geometry but with a variation to the magnetic pattern to accommodate the force profile of the alternative coupling device. The adapter plates and flanges can also serve as potential mounting surfaces for alternative designs for dust mitigation, such as an iris or protective membranes.

These special magnets are of enormous benefit to the CryoMag Coupler because their simplified design offers dust tolerance capabilities by way of design and ease of maintenance. Magnets also provide significant force as well as self-alignment capabilities, significantly reducing the coupling force both for manual and robotic operations. The magnetic characteristics can be customized for various applications, providing flexibility in the amount of force and orientation required.

The DMS was designed based on the geometry of both the LFD and the Magnetic subsystems. The DMS also attaches to the adapter plate; any minor changes to the magnetic pattern, or to the LFD force, will not affect the DMS.

The interface was designed with a strong emphasis on durability and flexibility. Each subsystem was designed to perform independently, but also to integrate flawlessly with the others. The interface was designed to accommodate the physical changes that occur as a result of thermal expansion or contraction. This accommodation was achieved by incorporating flexible or adjustable components that could adapt to these physical changes without compromising the overall functionality of the system. The system was designed using materials that are resistant to extreme temperatures and thermal gradients, so that harsh lunar temperatures can be withstood.

The system was also designed to function properly while withstanding the strong magnetic fields produced by the Magnetic subsystem. The Magnetic Subsystem of the CryoMag Coupler, for example, was designed to provide the necessary forces for mating, while also ensuring that the magnetic fields do not negatively impact other components, particularly those composed of ferrous materials.

The system incorporates sealing features in order to prevent fluid leaks. The LFD of the CryoMag Coupler, for example, utilizes sealing features specific to leak prevention. To combat dust intrusion, the DMS was incorporated into the system. The CryoMag Coupler, even without the DMS, was designed to be moderately dust tolerant; however, the DMS provides additional protection from dust intrusion to the fluid flow path and internal Coupler mechanisms.

The flowchart shown in Fig. 3 summarizes the design and testing process of the CryoMag Coupler. Details of the design and testing of the LFD and DMS are available in Ref. 3 and Ref. 4, respectively.

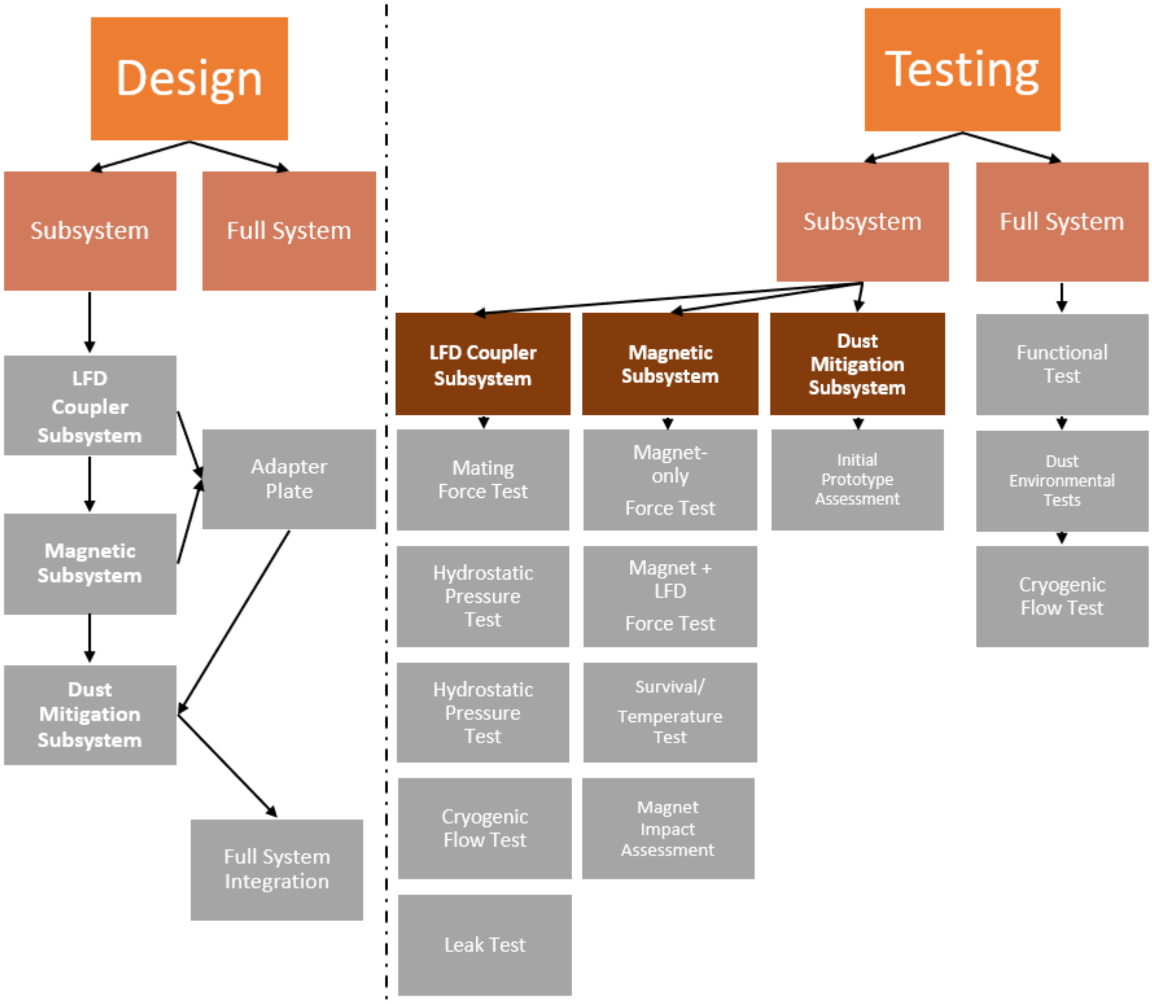

Fig. 3 Overview of the design and testing of the CryoMag Coupler system and subsystems.

In summary, the interface of the CryoMag Coupler system was designed so that small changes in each subsystem could be tolerated without compromising overall functionality. The design process involved a thorough evaluation of each subsystem by taking into account the individual requirements of each subsystem and how those interacted with others.

A. The Low Force Disconnect

The core of the CryoMag Coupler is the Low Force Disconnect (LFD), shown in Fig. 4, which uses a unique seal configuration to nearly eliminate the effect of line pressure on separation load. The LFD is a non-latching quick-disconnect coupler that requires external force to mate and remain latched. Internal springs provide de-mating force and actuate the built-in sealing features. The design and testing of the LFD is detailed in Ref. 3.

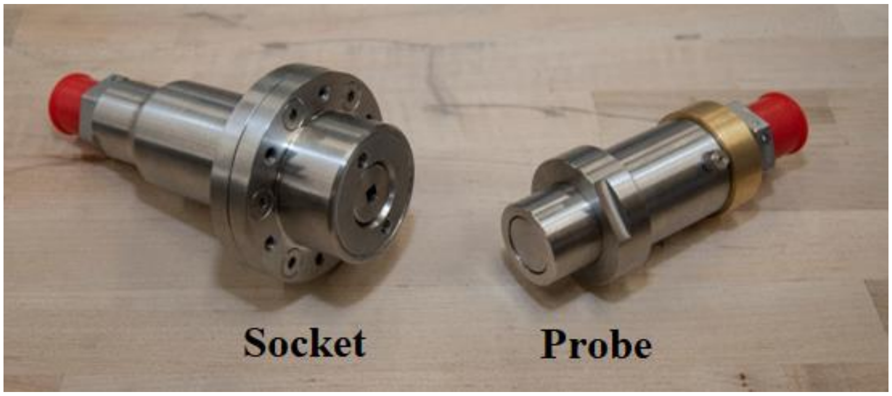

Fig. 4 The Low Force Disconnect (LFD).

Figure 5 depicts the pressure being transferred into the housing by way of the two seals. Typically, this pressure would be axially transferred back to the probe side. Figure 5 also illustrates the method of managing pressure internally using the unique seal configuration after the two halves of the Coupler have been mated. The pressure is being transferred into the housing by way of the two seals during the mate state. Typically, this pressure would be axially transferred back to the probe side, thus the absence of a net separation load due to line pressure.

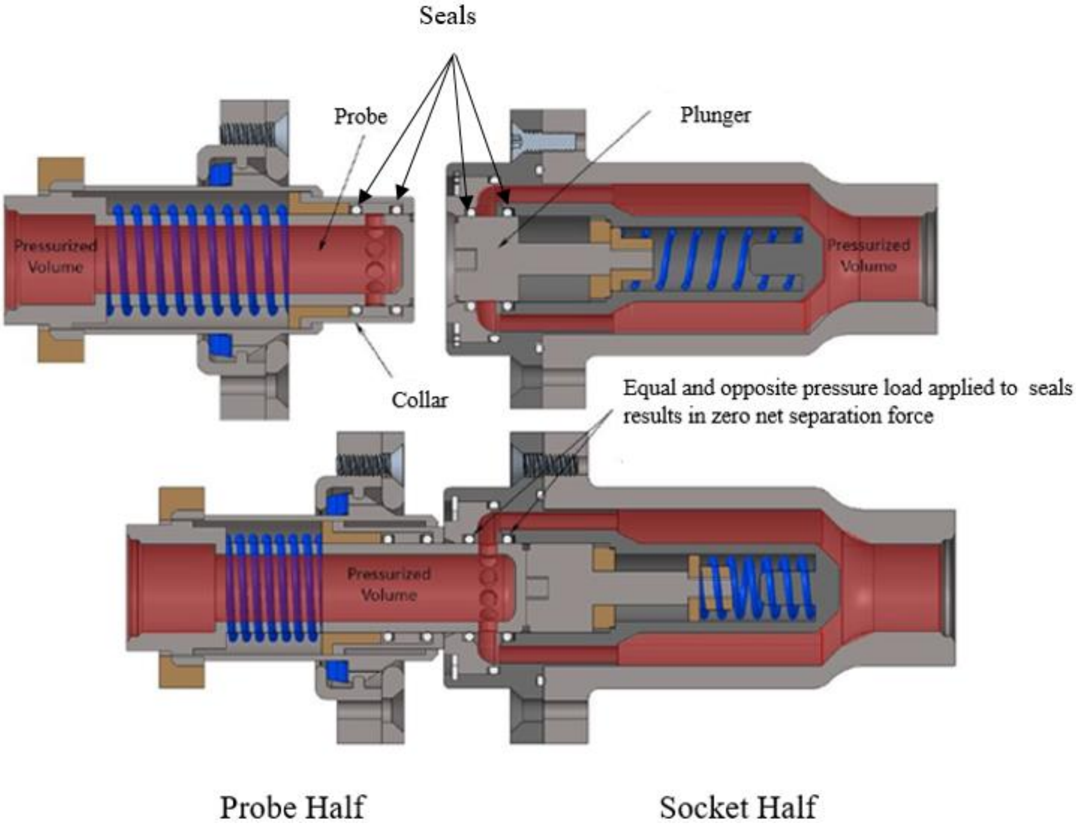

Fig. 5 A pressurized LFD view of the unique seal arrangement.

The collar and plunger sealing additions as shown in Fig. 5 above enhance the contamination protection of the CryoMag Coupler. Unlike traditional-style couplers that use poppet valves further from the interfaces, the near-interface arrangement on the LFD reduces flow path contamination from external sources. The springs enable passive activation of the sealing feature during the mated state of the LFD. The simultaneous action of the springs creates an additive load; for example, if each spring has a 10-lb load during mate, each will have 20-lb load during the mated state. For the probe side-sealing feature to activate, contact must be made between the probe sealing collar and the socket; and for the socket plunger to activate, contact must be made between the socket and the probe. The material for the springs was selected for enhanced resistance to cracking at cryogenic temperatures as well as resilience to corrosion.

Extreme precision is essential to the effectiveness of the sealing of the Coupler. The diameter of the seal must be meticulously matched to avoid enlargement of the seals by the plunger or the probe. A redefined surface texture also proved necessary to minimize friction during the mate state as well as to avoid leakage of small molecules such as hydrogen.

Vent holes are included in the design to prevent pressure buildup in cavities for the seals and springs. Failure to vent these regions could negatively impact operation of the Coupler, and possibly cause uncontrolled separation. These vent holes are shown in Fig. 6.

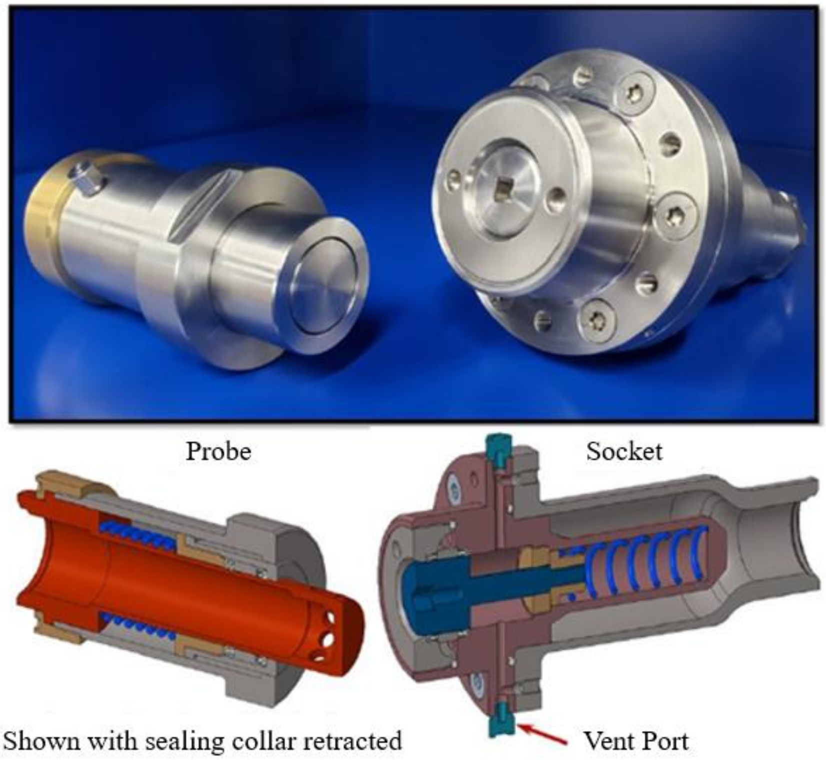

Fig. 6 The modified LFD for the CryoMag Coupler.

Prior to joining and separating the plunger and collar sections, each half must be depressurized. When they are partially joined, the internal sections of each are exposed to the surrounding air; in order to avoid contamination, a low-pressure purge is necessary. Pressurized mate and de-mate may be possible in future iterations of the design.

The original LFD was modified to meet the requirements of the CryoMag Coupler. The modifications were predominantly external additions to fit with the other the CryoMag subsystems. Other significant alterations were the improved seal design and employing a more gradual lead-in angle for the probe tip. These changes resulted in reducing the possibility of leakage as well as requiring less force to connect the LFD halves, without impacting the flow rate of the LFD.

B. The Magnetic Subsystem

The Magnetic subsystem is designed to attach the magnets to the CryoMag Coupler and enable the user to initiate mating and de-mating of the Coupler. As shown in Fig. 7, the magnets are attached to the LFD through an adapter plate that also allows for the attachment of the DMS. In order to facilitate the maneuvering of the CryoMag Coupler, a handle is located on the probe side, which enables the user to grasp and hold the Coupler securely. A lever enables the user to rotate the probe side of the Coupler relative to the socket side to initiate de-mating. The lever is stowed along the Coupler when not in use and provides a second handhold to the user if needed.

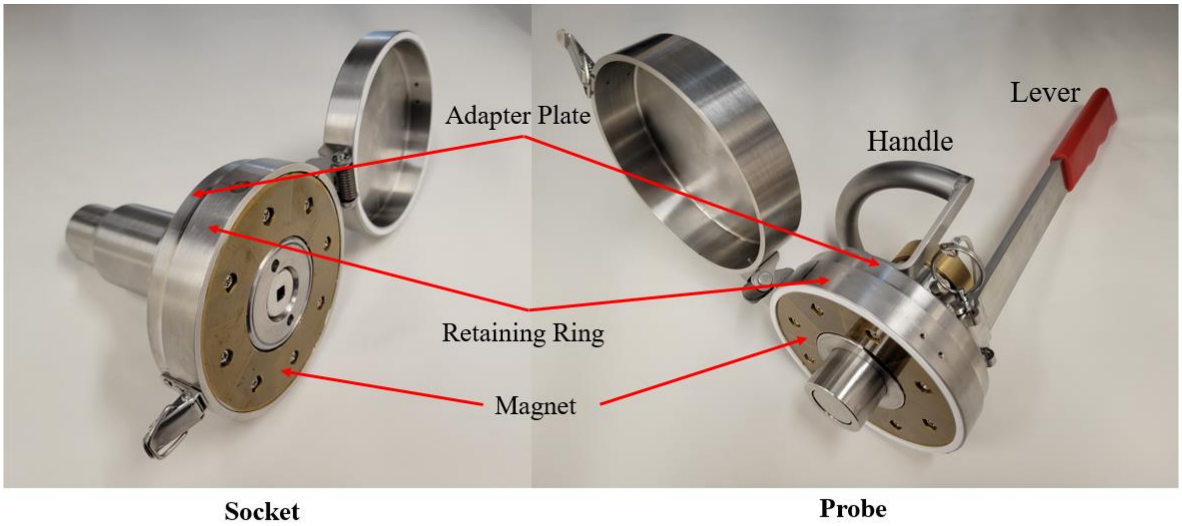

Fig. 7 The CryoMag Coupler with Magnetic subsystem components identified.

The magnets are made from samarium-cobalt (SmCo) to accommodate the temperature extremes and are designed with multiple poles on each face in a particular pattern that achieves the desired characteristics. The design and testing of the Magnetic subsystem is detailed in Ref. [4].

The use of magnets for mate, latch, and de-mate offers numerous advantages for the CryoMag Coupler. One benefit is the reduced physical complexity in the design, making the CryoMag Coupler easier to maintain and operate as well as providing dust tolerance. There are fewer crevices than found in traditional coupler designs, so there is a reduced probability of dust accumulating inside the CryoMag Coupler mechanisms. As well, because of the magnetic properties of lunar dust, some of this dust is captured by the magnet surface, preventing contamination to the cryogenic fluid. The dust accumulated on the surface can easily be removed.

The magnets also provide significant assisting force to the CryoMag Coupler. Mating and latching the Coupler require a substantial amount of force. Although the LFD Coupler requires less force to operate compared to traditional quick-disconnects, using magnets can reduce the external force required to mate and latch the Coupler to near zero. The magnets also have a self-aligning feature that can make the mating process much easier for the operator. The operator simply needs to bring one half of the Coupler close enough to the other half in the correct orientation - the magnets will then self-align and connect. The de-mating process only requires the operator to rotate the Coupler a certain number of degrees in a certain direction.

The tailorable characteristics of these magnets make them a suitable choice for various applications. Depending on the magnetic pole pattern, various magnetic strengths and attraction orientations can be obtained. Three distinct magnetic patterns were developed for the CryoMag Coupler. Before incorporating the magnets into the CryoMag Coupler system, the peak external forces required to mate the Coupler were 45 lbf during mate and 25 lbf to remain mated. After incorporating the magnets, the external forces required to mate the Coupler range between 0 lbf and 22 lbf, depending on the type of magnets selected, where 22 lbf is a project-chosen limit for external human input as discussed in Ref. 4. The strongest magnet set can supply latching forces up to ~245 lbf, which is well above the required forces.

To show flexibility, three patterns were created:

1) Firm-Assist: The magnet is patterned in such a way as to provide a lower magnetic force. When the magnet is integrated into the Coupler, the Coupler requires a stiff external input (near the limit of 22 lbf) to mate the Coupler, such as with a firm push by a human. Firm-Assist would be useful for a strong confirmation action indicating that a connection is truly desired. These magnets attract with ~10 lbf at initial mating distance, reduce the required external forces to 20 lbf during mating, and provide up to ~95 lb of final latching force.
2) Soft-Assist: The magnet is patterned in such a way as to provide a slightly higher magnetic force. When the magnet is integrated into the Coupler, the Coupler requires a lighter external input (well below the limit of 22 lbf) to mate the Coupler, such as with a light push by a human. Soft-Assist would be useful for a momentary slowdown to maintain human control and allow for easier input forces. These magnets attract with ~15 lbf at initial mating distance, reduce the required external forces to 10 lbf during mating, and provide up to ~190 lb of final latching force.

3) Full-Auto: The magnet is patterned in such a way as to provide a high magnetic force. When the magnet is integrated into the Coupler, the Coupler is capable of a fully automatic mate with no external input necessary other than bringing one Coupler half to within mating distance of the other Coupler half. For the CryoMag Coupler, this mating distance is approximately one inch. Full-Auto displays the full potential of a magnetic interface - a true automatic mate with no external human, mechanical, or electrical input necessary. A de-mate requires external input to rotate one magnet with respect to the other. These magnets are the strongest magnets in the CryoMag Coupler magnet collection and attract with ~30 lbf at initial mating distance, eliminate the need of external forces during mating, and provide up to ~270 lb of final latching force.

Magnets also have a few disadvantages. A more notable disadvantage is the brittleness of SmCo. SmCo magnets do not tolerate impact well, and can easily shatter or chip. Initially, concerns were that magnet pieces would be propelled upon breaking due to impact, but a subsequent magnet impact assessment revealed that any broken pieces remained held to the magnet through magnetic attraction, reducing the likelihood of potential harm to nearby people or equipment. The high magnetic strength, while primarily an advantage, also has disadvantages which can pose serious hazards when two magnets come close to each other. The force exerted by these magnets not only can break these magnets, but they can also crush any object that may be situated between the two magnet sides, posing hazards to human operators. Impact resistant gloves thus were required for handling these magnets, as was maintaining the designated hand-hold positions on the CryoMag Coupler. Future design iterations may be able to incorporate features to provide crush protection to the user. Finally, a safety distance was put in place to ensure that electronics were not negatively affected by the magnetic field. Also, a carbon steel backplate was used with the magnets to redirect the magnetic field forward, reducing the magnetic field behind the magnet and increasing the field in front of the magnet, which increased the attraction force. Options for mitigating these deficiencies through design or procedure were demonstrated during this feasibility study.

C. The Dust Mitigation Subsystem

The DMS exists to shield the internals of the CryoMag Coupler from intrusion by lunar regolith dust, which is a known problem for future lunar operations. The Apollo missions highlighted the challenges that lunar dust poses to human health and operation of equipment on the lunar surface [5]. Lunar regolith dust is particularly jagged, abrasive, and difficult to brush off relative to Earth dust. In addition, it has a high iron content and is electrically charged, which characteristics are particularly relevant to the CryoMag Coupler design because of potential interaction with the magnets. Designing systems to be dust-tolerant and protected from dust intrusion in some manner is a key focus area for future lunar operations [5, 6]. Different methods for dust prevention are being developed, including barriers of various types to prevent dust intrusion and methods of removing accumulated dust. Several methods of each type were considered for use in the CryoMag Coupler: mechanical-type barrier methods including cap, iris, sleeve, and flexible membrane; and dust removal methods including a brush, electrodynamic dust shield, electron beam, or use of the Leidenfrost effect. A trade study was conducted to downselect from these options; criteria included the ability to withstand the environment; concept of operations, maintainability and cycle life; and, most importantly, the ability to integrate effectively into the CryoMag Coupler design. The effectiveness of the design in mitigating dust intrusion was not included in the trade study because of inconclusive or unavailable data. For this initial prototype, which focused on proving the concept of the magnetic interface, a simple cap design was selected for dust mitigation. The prototype versions of the cap concept and the iris concept, shown in Fig. 8, were both tested in the Dust Environment Low-fidelity Test Apparatus (DELTA) glovebox and proved to be effective at preventing dust intrusion when closed [7].

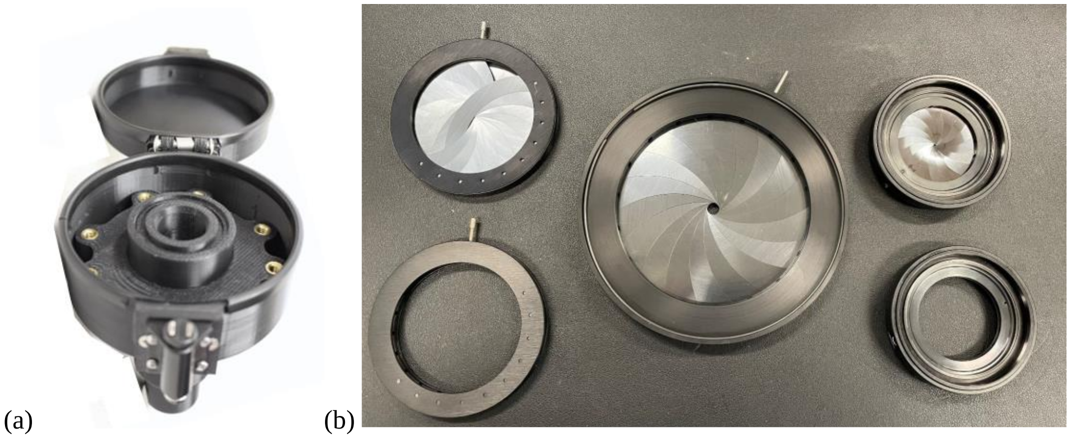

Fig. 8 Prototype versions of the (a) cap and (b) iris concepts for initial testing.

The cap was selected over the iris because of the higher complexity of integration of the iris, which was out of scope for this project. If the cap proves insufficient for future applications and concepts of operation, it may be worth revisiting the iris concept, possibly in combination with the cap. Most of the removal methods are still in development and, as of the start of this project, were not ready for incorporation into a device of this type and scale. Future iterations of the design of the CryoMag Coupler may incorporate some form of dust removal technology once sufficient maturity has been reached.

The dust cap was designed to protect the dust-critical areas of the LFD and Magnetic Subsystem when closed and to be able to be easily opened and closed in order to minimize the time the cap is open during mating and de-mating. The dust cap consists of the cap itself and a sleeve which fits around the LFD and Magnetic Subsystem. When the CryoMag Coupler is fully mated, the caps also mate together to prevent dust accumulation on the inside, which could transfer to other surfaces during de-mating. Figure 9 shows the cap in the closed, open, and mated positions.

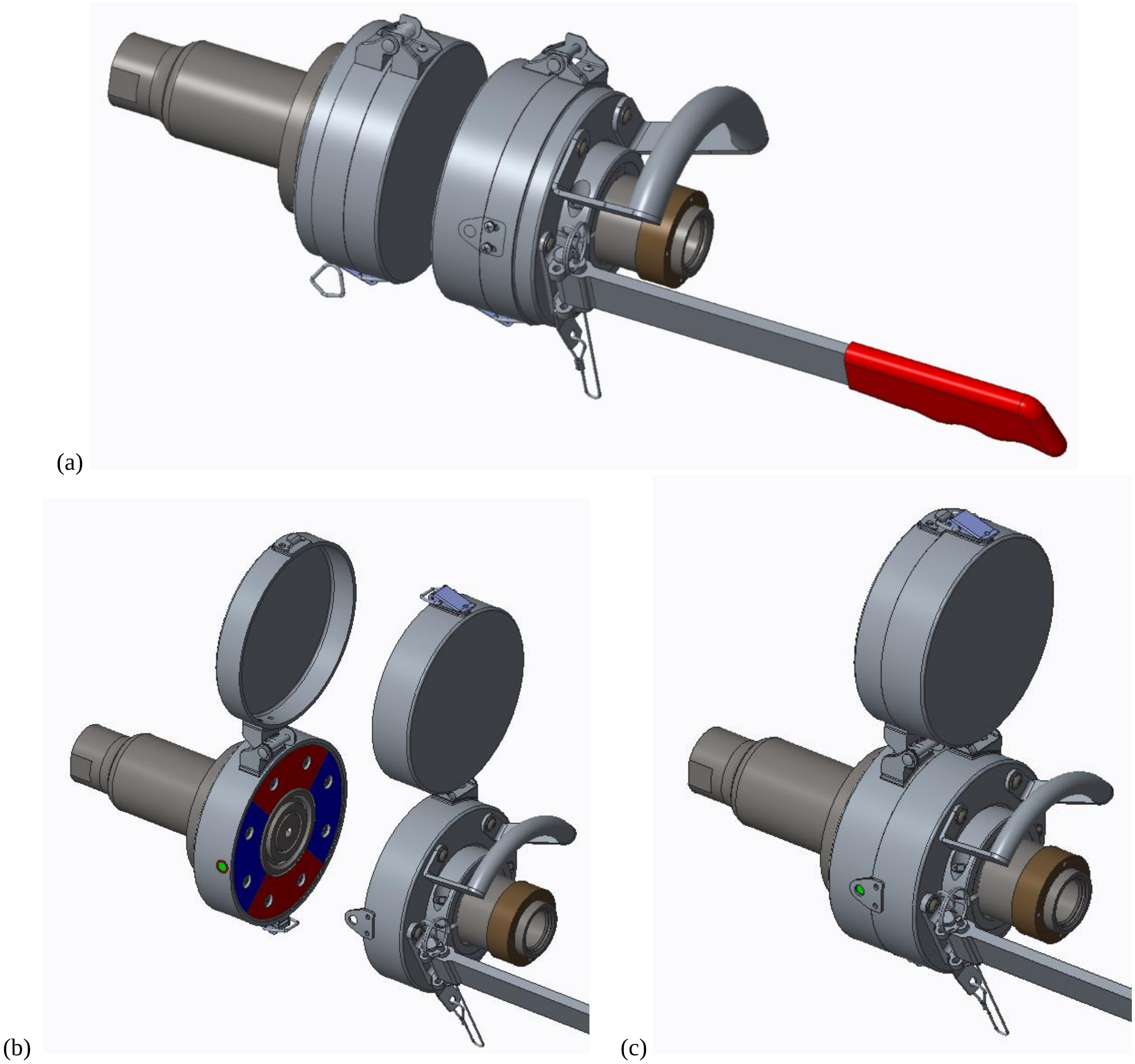

Fig. 9 The Dust Mitigation Subsystem in the: (a) closed, (b) open; and (c) mated, positions.

As part of the design for ease of use, the caps were hinged rather than fully removable. The hinges were specially designed to prevent interference with the mating and de-mating of the Coupler. The offset of the hinges allows for rotation during de-mating. A gap was designed between the hinges to prevent the hinges from becoming a load path during mating, and to account for potential thermal expansion. The caps were designed to be spring-loaded open, although that feature was not tested during this initial prototype development effort. The geometric features of the hinges were designed to tolerate dust intrusion and still operate correctly. As currently installed, the caps open upward, as shown in Fig. 9; the design is flexible to allow the caps to be installed in different configurations as needed for testing. This prototype was designed to be modular; the hinges are easily removable to allow for testing of different hinge designs, or to enable testing of the rest of the Coupler in confined spaces. The caps are held closed by latches, which are also easily removable to allow different latch options to be tested. Initial testing was conducted with a simple mechanical latch; it is desired to test a magnetic latch in the future, along with other latch designs that may be easier to operate when wearing bulky gloves, such as are used on EVA suits.

The mating faces of the caps are a potential dust intrusion point, even if the cap faces have been machined to very tight tolerances. To prevent dust intrusion through the cap faces, seals were added to the design. The seals are staggered such that there is always one seal between the mating faces, as shown in Fig. 10; on the probe side of the Coupler the seal is on the sleeve, and on the socket side the seal is on the cap. Further testing will be required to determine the optimal seal design to achieve the appropriate amount of compression and ensure compatibility with the intended environment.

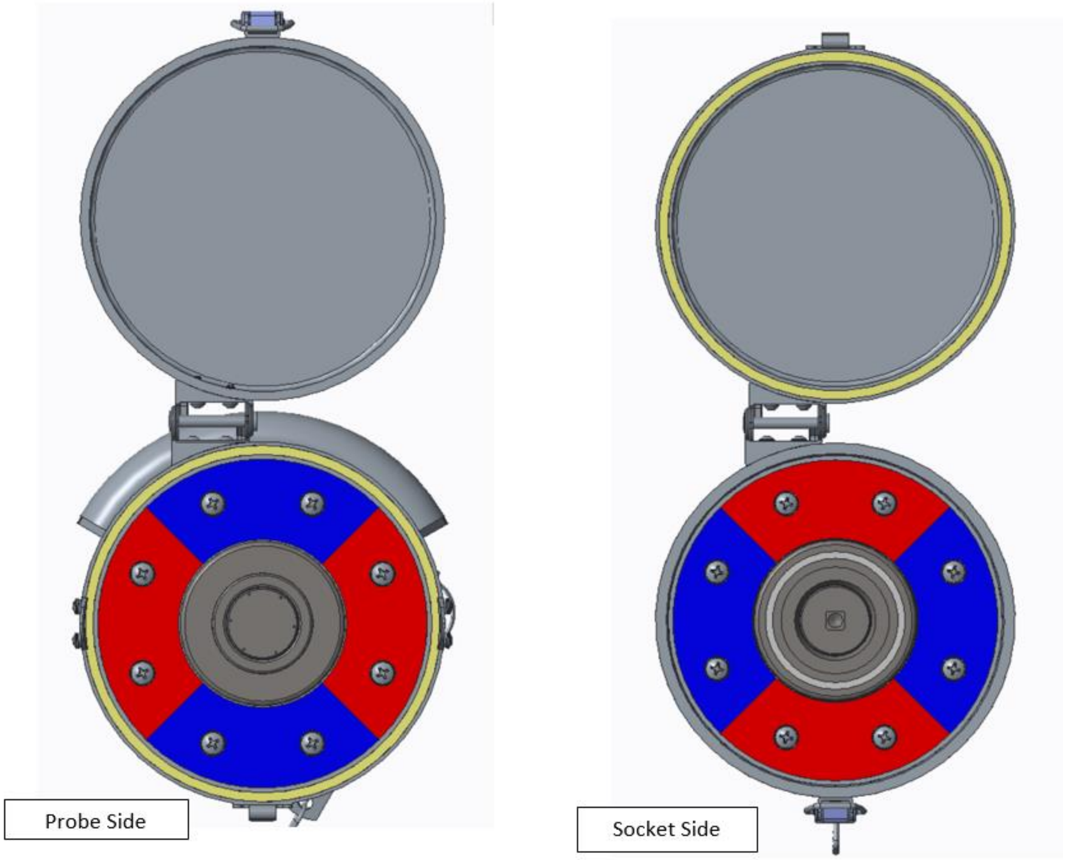

Fig. 10 The seals (yellow) on the Dust Mitigation Subsystem.

The design of the dust caps had to account for the vent holes required by the LFD to prevent fluid or gas buildup in the seals. These vent holes are another potential dust intrusion path and must be covered without interfering with their functionality. The prototype design, shown in Fig. 11, incorporates readily available filter fittings with built-in 40-micron filters, allowing the release of gas but not the intrusion of dust particles.

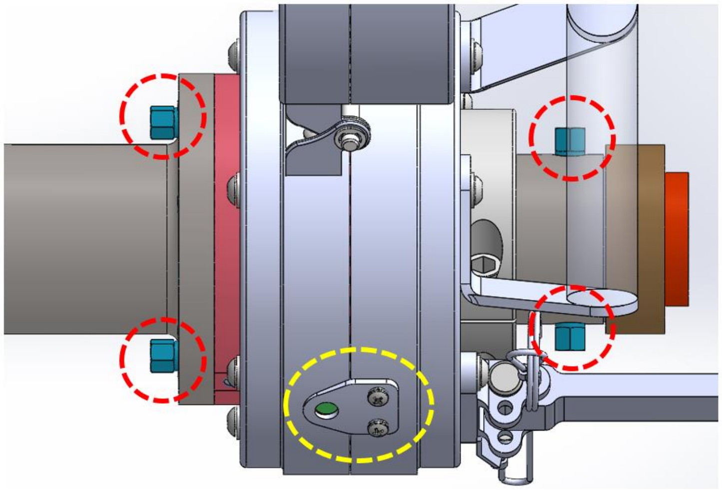

Fig. 11 Dust Mitigation Subsystem detail showing filter fittings (circled, red dashes) and visual indicator tab (circled, yellow dashes).

Future iterations of the design may incorporate filters into the design directly for reduced weight and bulk. Also supporting the functionality of the LFD is a visual indicator tab. The dust sleeves prevent direct observation of the LFD to determine whether it is fully mated, so visual indicator tabs were added. If the CryoMag Coupler is fully mated, only green will be visible; otherwise, a portion of the outer red ring will be visible. The final prototype used for initial functional testing, shown in Fig. 12, did not include the visual indicator. The visual indicator was included for the dust environment testing, as discussed below.

Fig. 12 The Dust Mitigation Subsystem.

The DMS was designed to support the needs of the LFD and the Magnetic subsystems. It is expected that the design will be refined based on the results of testing.

III. Testing and Analysis

Testing at the system level of integration followed a crawl-walk-run approach similar to the subsystem level testing. Previous testing at lower levels of integration included thermal testing of the magnets, characterization of the LFD, force-profile testing of the both the Magnetic subsystem and the LFD, and dust environment testing of the prototype dust mitigation systems [3, 4, 7]. After successful completion of that testing, the system was integrated and underwent system-level testing, detailed herein. This testing included a functional evaluation, structural analysis, dust environment, thermal analysis, and cryogenic fluid flow. The structural and thermal analyses were performed to support the testing and future design iterations.

A. Functional Evaluation

After the three subsystems were successfully integrated, a series of functional evaluations were conducted to assess the handling characteristics of the CryoMag Coupler. The socket side of the Coupler was mounted to a strongback and the probe side of the Coupler was handled by the user, in accordance with the envisioned concept of operations and as shown in Fig. 13. A tether was attached to the probe side to alleviate concerns of significant acceleration during de-mating and to limit the risk of damage if dropped. Impact-resistant gloves were worn by the user, both to protect the user and to simulate the bulky gloves of a spacesuit.

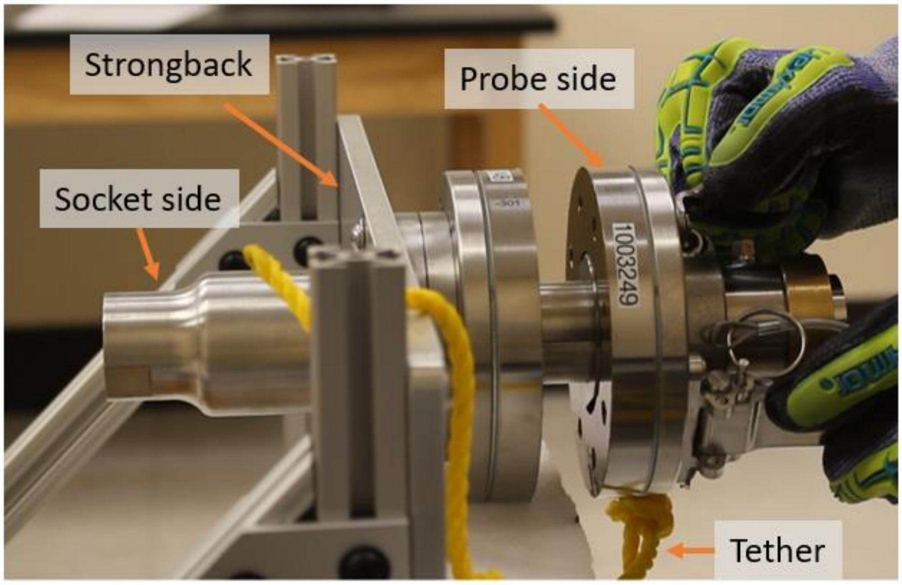

Fig. 13 Functional evaluation demonstration setup.

During these functional tests, multiple users were recruited to help assess the ergonomics and useability of the Coupler, and functional tests were conducted for each magnet set. After each user completed the coupling cycle, they completed out a user's survey for each magnet set evaluated, as specified in Table 1.

Table 1 Functional evaluation testers.

Magnet set	Number of testers
Full-Automatic	5
Firm-Assist	6
Soft-Assist	4

Four of the users completed functional evaluation of all three magnet patterns. Although there was a limited sample size, the four users who tried all three patterns preferred the “Soft-Assist” pattern. No one preferred the “Firm-Assist” pattern. Further development of the CryoMag Coupler would be benefited by a repeat of the functional evaluation using a larger sample size.

B. Structural Analysis

As part of the planning for the functional evaluation as well as to show compliance with structural requirements, structural analysis was conducted, for both mated and unmated configurations, in the pressurized configuration.

A finite element analysis (FEA) structural analysis of the LFD was conducted in PTC Creo Simulation (PTC, Boston Massachusetts), with internal fluid Maximum Operating Pressure (MOP) of 1000 psi, as shown in Fig. 14. The load case was imported into finite element software, and simulated, as shown in Fig. 15 and Fig. 16.

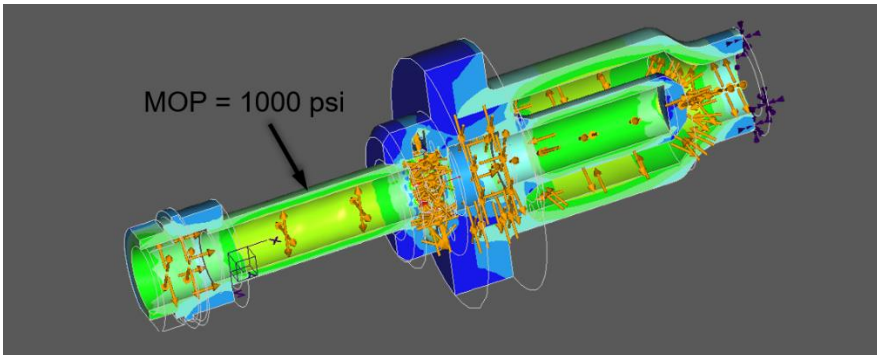

Fig. 14 The LFD assembly (upper) boundary condition of 1000 psi internal pressure.

The finite element model (FEM) used 0.2-in elements by default, and 0.05- to 0.01-in elements in detailed areas, for better resolution of stress concentrations, as shown in Fig. 15.

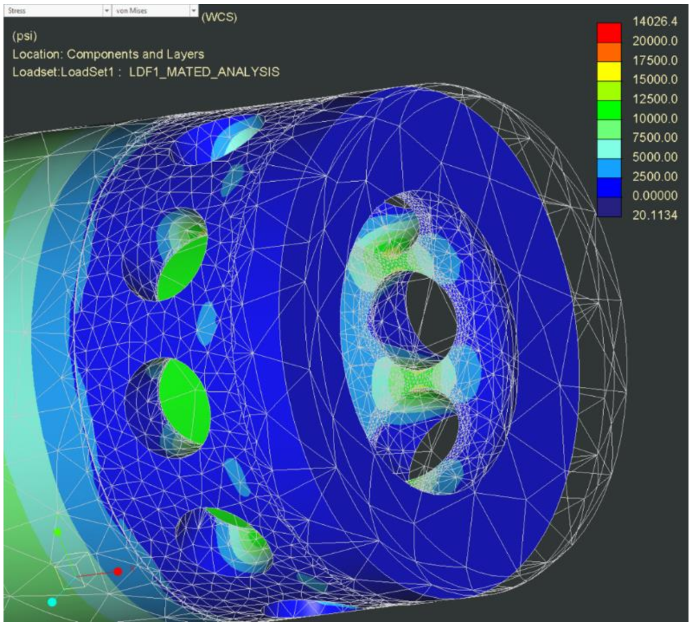

Fig. 15 Detail mesh on the finite element model of the CryoMag Coupler probe.

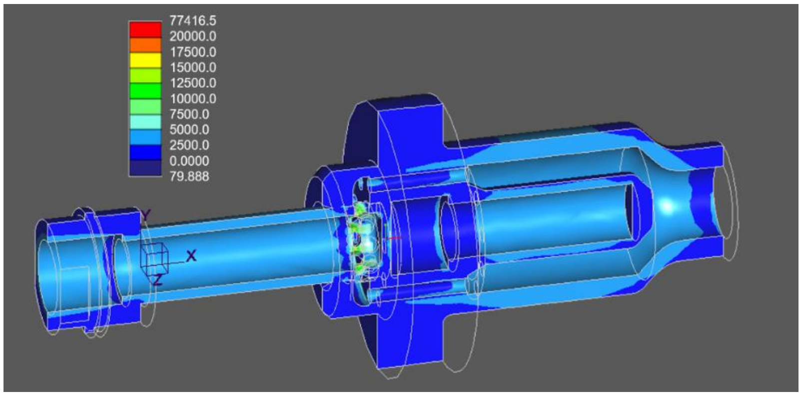

Fig. 16 The finite element analysis results for the LFD assembly of the CryoMag Coupler; red color is set to 20 ksi allowable stress (Sa) limit.

For the Dust Mitigation System and the integrated Coupler, FEM and hand calculations were conducted for several load cases. The load cases covered magnetic mating, latching, and de-mating, including the human interface loads. The FEM models were built in PTC Creo Simulation; the von Mises stress model is shown in Fig. 17. The lowest margin is zero for a worst-case inertial load imparted to cap fasteners at the highest temperature condition.

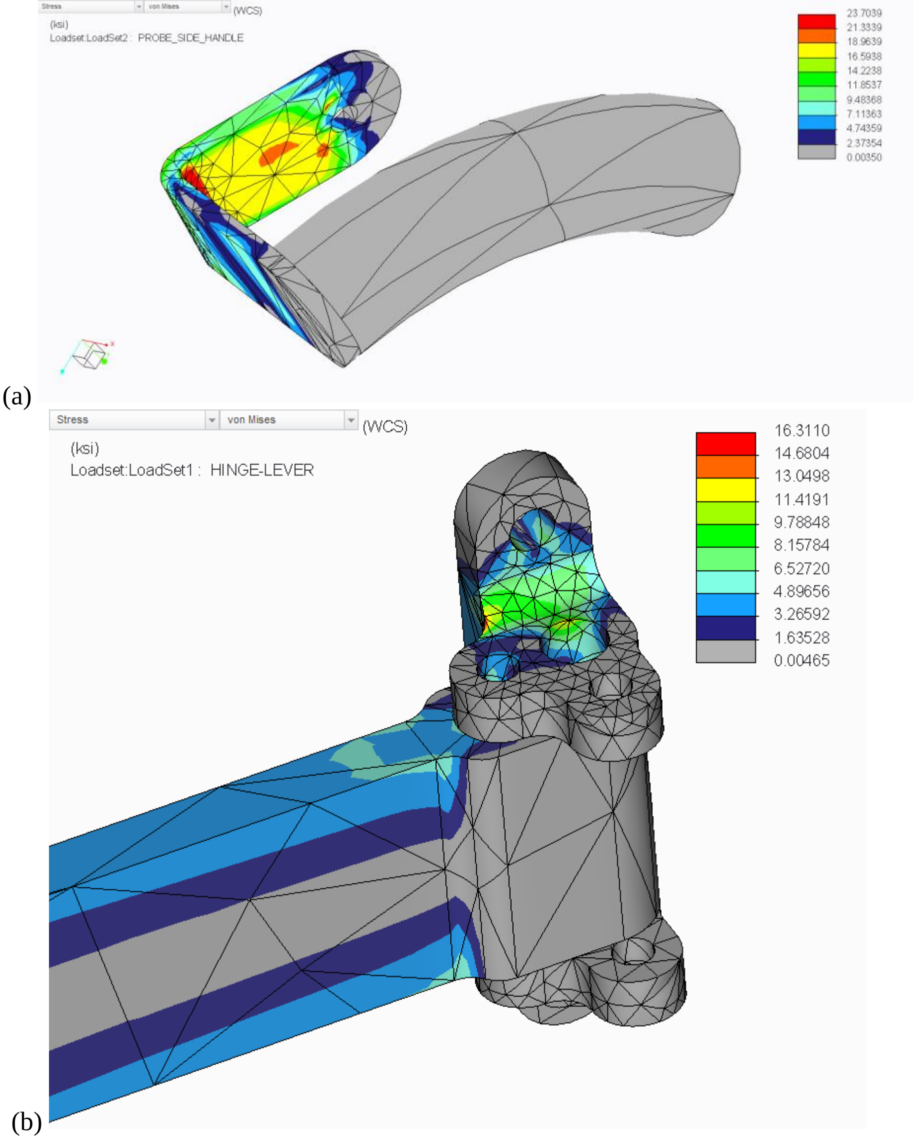

Fig. 17 Finite element analysis detail: (a) the handle; and (b) the lever and hinge; during de-mating; the rainbow scale is in kips per square inch, and the material allowance is 75 ksi.

C. Dust Environment

A major concern for mechanical systems on the lunar surface is exposure to lunar regolith dust. Testing was conducted using lunar regolith simulant JSC-1A to evaluate the effectiveness of the dust mitigation system and characterize potential intrusion points into the mechanism. Initial dust intrusion testing was performed at the NASA Armstrong Flight Research Center (AFRC) (Edwards, California), followed by full dust environment testing at the Glenn Research Center (GRC) (Cleveland, Ohio).

1. Dust intrusion testing

Preliminary testing was conducted in the AFRC DELTA glovebox, described in detail in Ref. [7], to evaluate the seals used in the DMS and to identify potential collection and intrusion points. The limited interior dimensions of the glovebox prevented the use of the DMS caps during the testing, which was acceptable because the seal between the sleeves was the primary focus of the evaluation. Figure 18 shows the test setup. The open ends of the Coupler were sealed with caps and tape prior to the test to prevent dust intrusion; during full system operation, the ends of the Coupler would be connected to fluid hoses, sealing them off from the environment. Further testing with a fully representative setup would be required to determine whether dust could intrude through the connections.

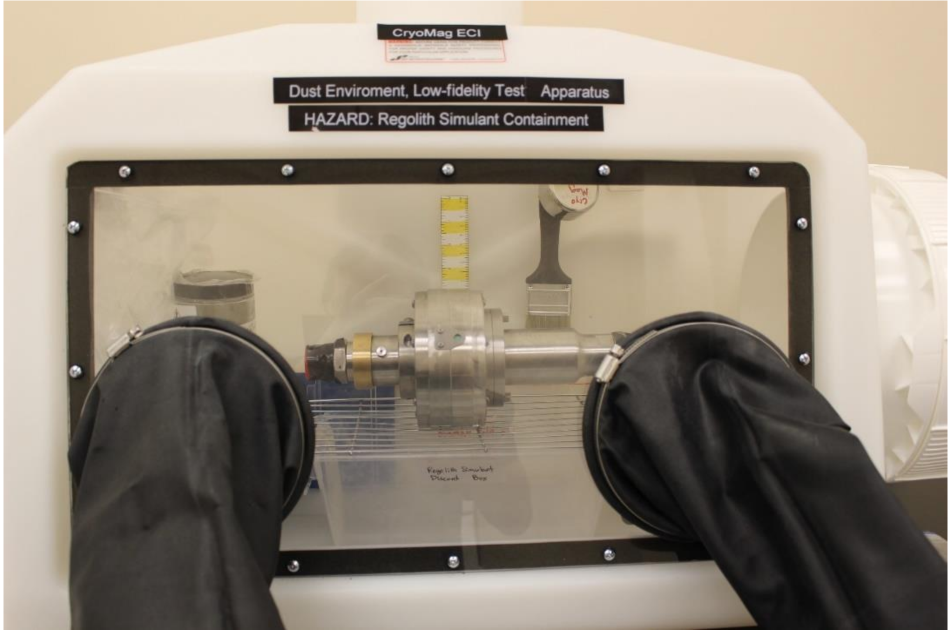

Fig. 18 Dust exposure test setup in the Dust Environment Low-fidelity Test Apparatus glovebox.

The dust loading was applied by hand-sieving in accordance with the procedures developed for the DELTA glovebox [7]. The JSC-1A lunar regolith simulant was used for this testing, sieved to exclude particles larger than 0.10 mm. An example of the resulting dust loading on the CryoMag Coupler is shown in Fig. 19.

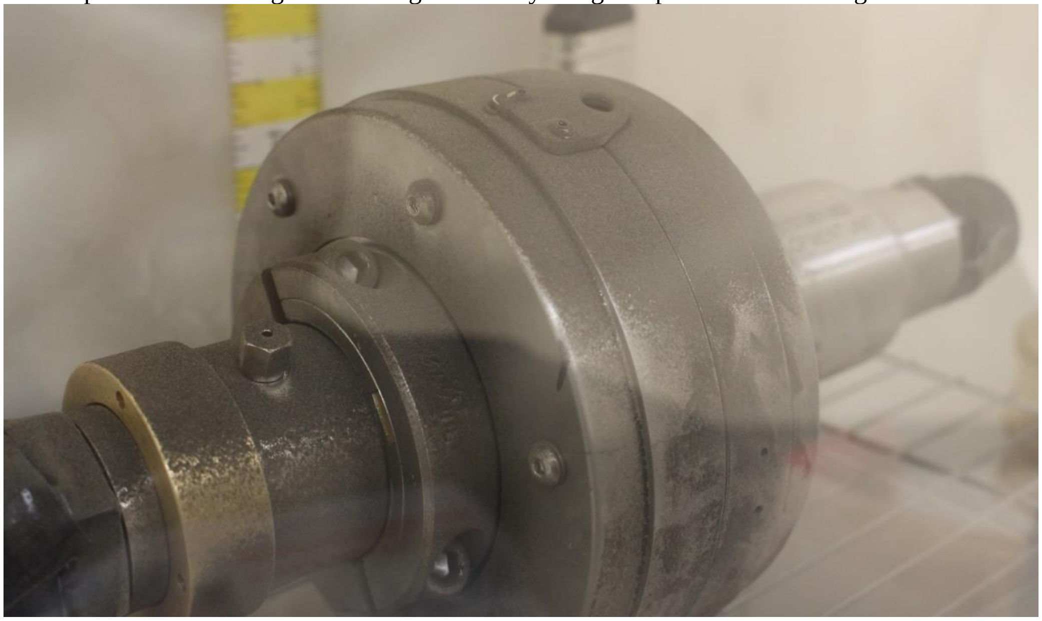

Fig. 19 The CryoMag Coupler (without dust mitigation system caps) after dust exposure.

After application of the dust, the accumulated dust was photographed and then brushed off the surface with a polyester-bristle paintbrush. The Coupler was rotated 90 deg axially and dust was then applied to the newly exposed surface. When all surfaces had been exposed to an estimated worst-case dust loading completely covering all exposed surfaces, photographed, and brushed clean, the exterior surfaces of the Coupler were closely examined for remaining dust, an example of which is shown in Fig. 20. The dust was applied to the surface in a layer sufficient to obscure the visibility of the underlying surface. Many of the areas where the dust could not be removed with the brush correspond with areas to which adhesive tape had previously been applied, indicating that the adhesive residue had not been completely removed by cleaning procedures before the dust intrusion test.

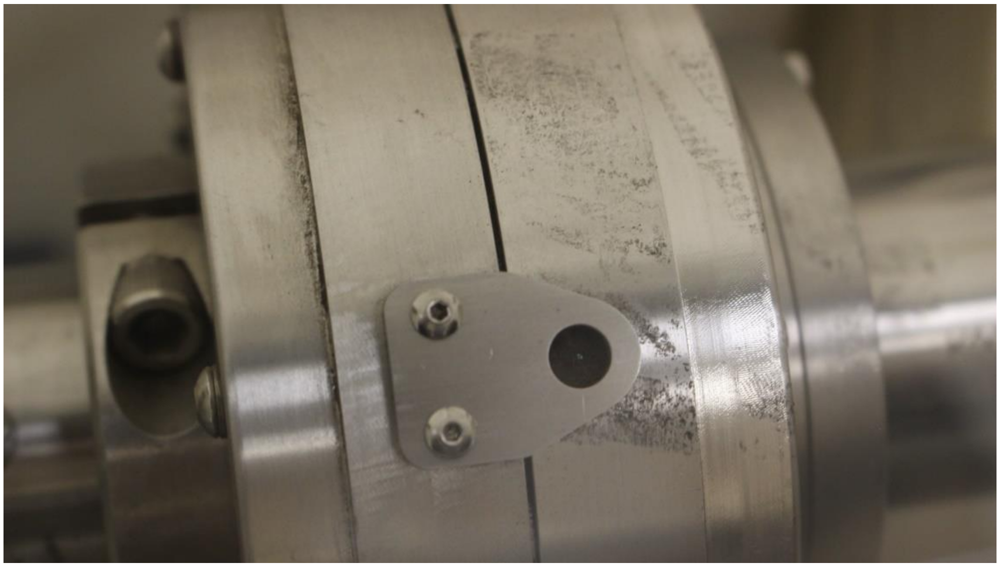

Fig. 20 Dust remaining on the CryoMag Coupler after removal procedures.

The visual indicator was noted to be completely obscured by the accumulated dust, which could not be removed with the brush or with alcohol wipes while the CryoMag Coupler was mated. Once the surface of the Coupler had been cleaned as thoroughly as possible, the Coupler was removed from the DELTA glovebox and installed on the test stand used for functional evaluation so it could be de-mated. (The limited space in the DELTA glovebox precluded the ability to de-mate while the Coupler was sealed inside.) Once the Coupler was de-mated, the visible interior surfaces were examined for dust intrusion. Notable accumulations of dust intrusion are shown in Fig. 21.

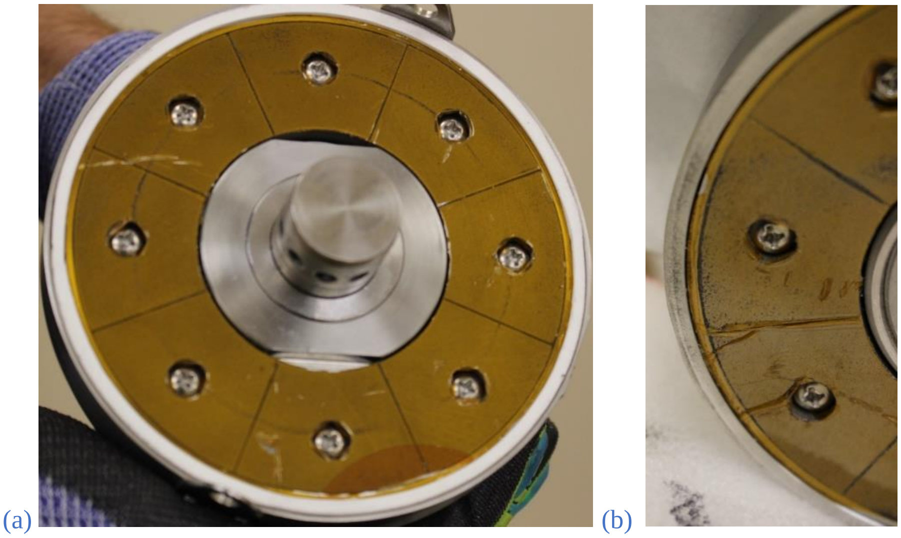

Fig. 21 Dust intrusion into the CryoMag Coupler during the dust intrusion test.

Dust intrusion was noted on the interior surfaces of the Coupler. It is not clear whether this dust was trapped in the visual indicator and migrated in during the de-mating process, or whether the dust intruded during the dust intrusion test itself. The dust appears to have been captured along the magnetic field lines and on the seals of the DMS. The visual indicator was able to be completely cleaned once the Coupler was de-mated; however, the process to clean the dust also removed some of the green and red coloring. A potential design improvement would be to redesign the visual indicator to address the observed issues, such as by filling in the indentation with clear epoxy. Design improvements to the DMS seals would also be desirable to reduce dust intrusion. Observations during the dust intrusion testing helped inform the subsequent dust exposure testing, including removal of the visual indicator tab and a greater emphasis on ensuring that adhesive residue was completely removed from exterior surfaces of the Coupler before testing

2. Dust exposure testing

Following the dust intrusion testing, fully-integrated system-level dust environment testing was conducted at GRC in the Uniform Dust Distribution System (UDDS) chamber using the JSC-1A simulant [8]. The UDDS chamber is more spacious and has more precise dust deposition capabilities than the DELTA glovebox. This dust exposure testing was performed on an untested assembly of the CryoMag Coupler to prevent dust intrusion during prior testing from potentially skewing the results. Unlike the DELTA glovebox, the UDDS chamber has sufficient room to allow the fully-integrated CryoMag Coupler – with dust caps installed - to be mated and de-mated inside the chamber. Figure 22 shows the CryoMag Coupler in both tested configurations: mated and unmated.

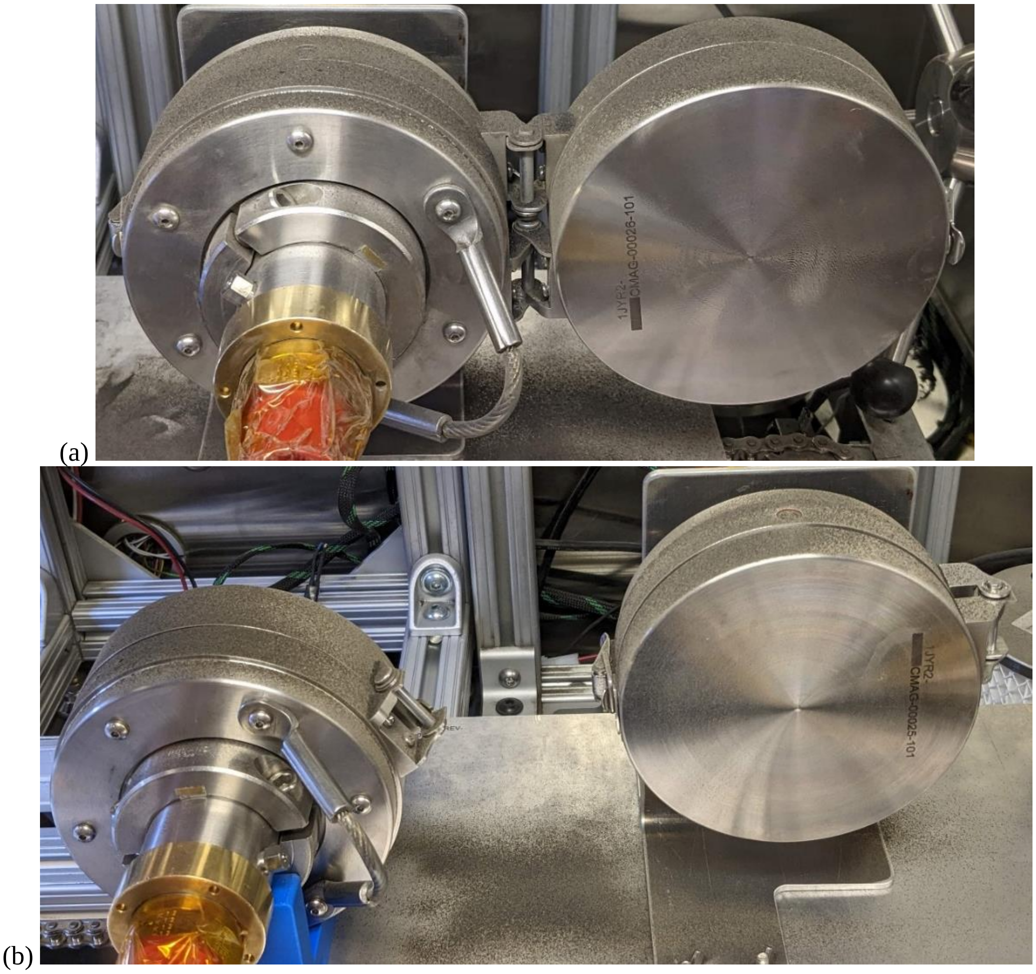

Fig. 22 The CryoMag Coupler configurations after dust exposure: (a) mated; and (b) unmated.

The dust loading, an example of which is shown in Fig. 23, was applied in accordance with typical UDDS chamber procedures, although parameters were altered to enable the heavier dust loading desired to evaluate the DMS under simulated “worst-case” dust loading [9].

Fig. 23 Closeup of dust application on the CryoMag Coupler during testing in the UDDS chamber.

After application of the dust, the accumulated dust was photographed and then brushed off the surface with a fine-bristle, natural-fiber brush. Dust was easily removed from the majority of the outer surfaces, with notable exceptions in area with tight contours (such as hinges). A smaller brush may have been more successful in removing dust from areas of limited access. Following the envisioned concept of operations, dust was applied with the CryoMag Coupler halves unmated, mated, and then unmated again, representing one full cycle of use. At each step, the Coupler was photographed, visually inspected, and then cleaned with the brush. Limitations of the system prevented dust application during the mating and de-mating process - a desired option for future testing. Once the entire dust application process was completed, the CryoMag Coupler was thoroughly cleaned before removal from the chamber, as shown in Fig. 24. It was found that compressed air was very successful at removing the dust from the areas around the hinges where it had previously been trapped. Based on the results of the previous dust intrusion testing, the visual indicator tab was not included on this test article, thus no dust was trapped therein.

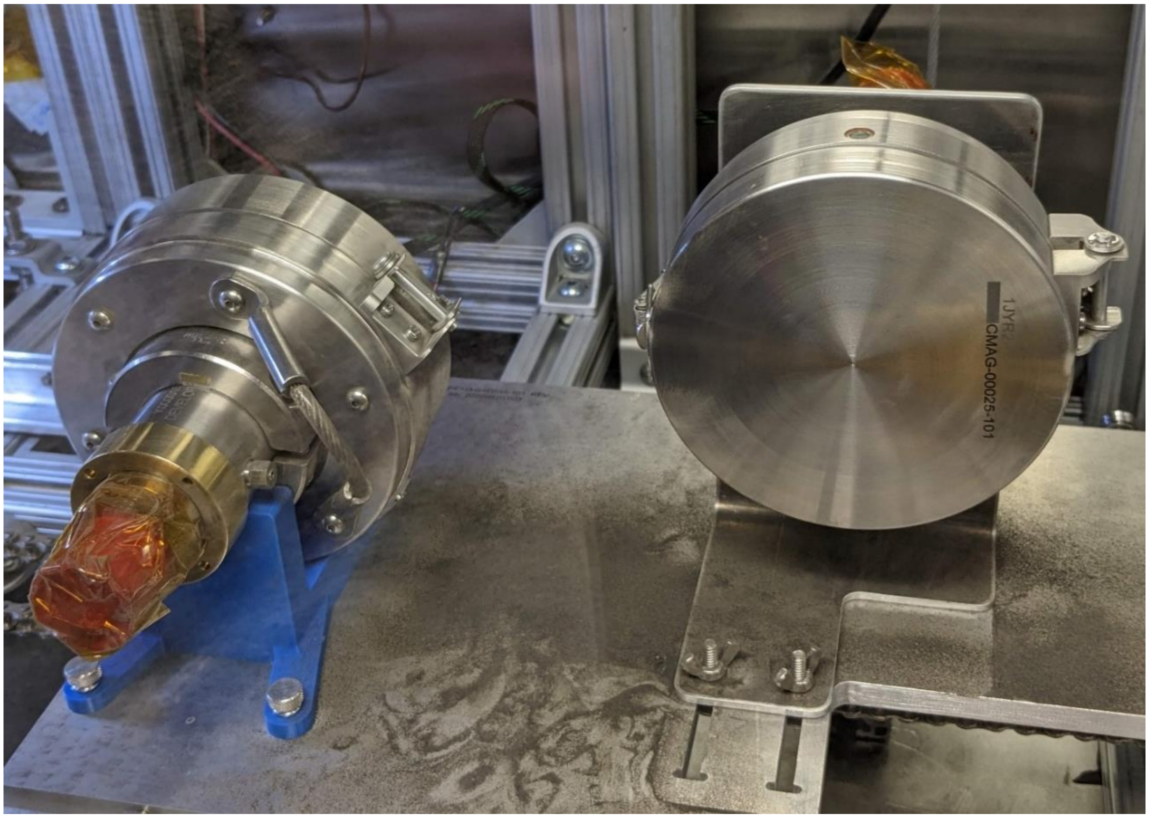

Fig. 24 The CryoMag Coupler after dust removal procedures.

Once the CryoMag Coupler was removed from the UDDS chamber, dust intrusion into the flow path was measured as described in Ref. 7. The DMS and other dust-tolerant features of the CryoMag Coupler proved adequate to prevent dust intrusion into the flow path under the conditions tested. Some dust did intrude past the DMS only to be captured by the magnets, as shown in Fig. 25, confirming the need for an improved seal design, notably to ensure proper and consistent compression of the seal element in the mated and de-mated configurations.

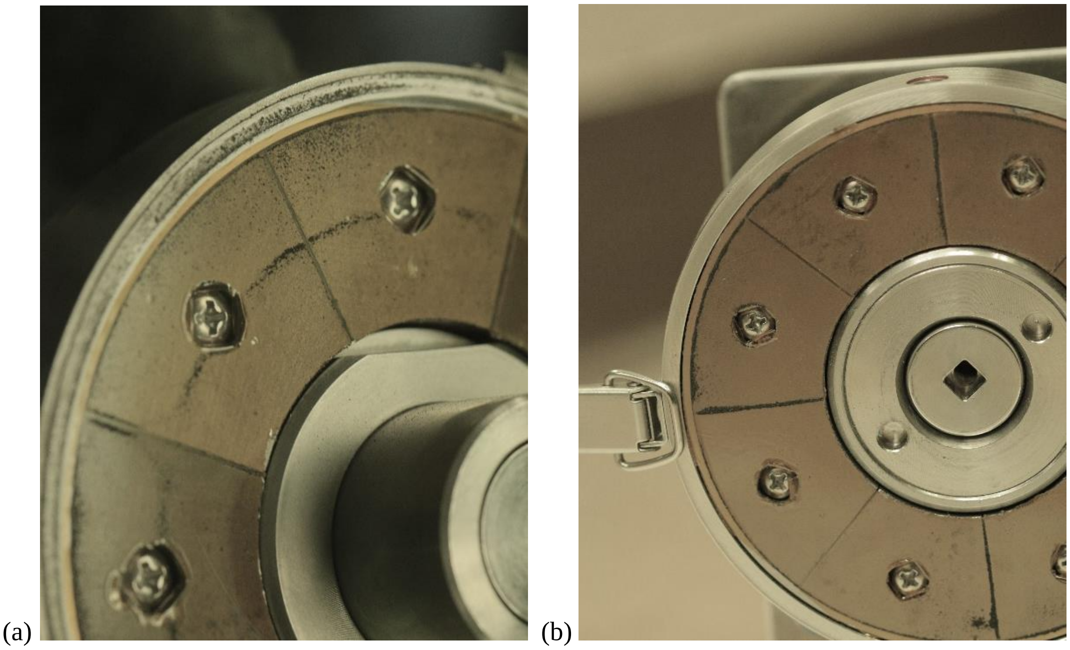

Fig. 25 Dust captured by magnetic mating faces on the: (a) probe; and (b) socket sides of the CryoMag Coupler.

Also visible in Fig. 25(b) is a problem encountered with the current latch design: part of the latch can become trapped in between the mating faces, preventing the Coupler from fully mating. Lessons learned during the dust exposure testing can be used to inform future design iterations. Desired future testing in dusty environments would include multiple cycles of mating and de-mating as well as cryogenic fluid flow after mating.

D. Thermal Analysis

Testing in temperature environments representative of the lunar equatorial region was conducted at the subsystem level and is detailed in Ref. [4]. Testing of the fully-integrated system in a representative thermal environment was beyond the scope of this project and has been identified as a potential future effort. Analysis was performed both to assess the design and to assist with determining future test efforts. Steady-state analyses were performed to evaluate coefficient of thermal expansion (CTE) mismatch and thermal stresses. Transient analysis was performed to understand thermal response during the cryoflow test. Transient analyses at lunar operating conditions were unfortunately also beyond the scope of this project and should be conducted during future efforts.

Operations on the lunar surface have the potential to expose the CryoMag Coupler to significant temperature extremes. The difference in temperature between the liquid nitrogen or other commodity flowing through the internal flow channel and the temperature of the surrounding environment can be as large as 590 K at the lunar equator. While it is expected that limitations may be placed on the overall cryogenic fluid transfer system, proscribing at what environmental temperatures cryogenic fluid may be transferred, in order to limit boil-off or freezing of the cryogenic fluid, it was desired to design the CryoMag Coupler to be usable in any lunar surface environment. Thermal analysis was conducted to address concerns about stresses caused by the thermal gradient through the Coupler in scenarios having significant temperature differences. Although initial testing of the CryoMag Coupler would not include thermal testing at the system level, the cryogenic flow test exposes the CryoMag Coupler to a potential temperature difference of 473 K or more. Gaps were designed into selected areas of the Coupler to account for potential CTE mismatch; the analysis was conducted to evaluate the adequacy of the gaps. The analysis also supports future testing, which would need to include evaluation at representative environmental temperatures.

Evaluated as part of the analysis were both linear thermal expansion (Eq.1):

$$\Delta L = \alpha L \Delta T \tag{1}$$

and thermal stress (Eq. 2):

$$\sigma_{Th} = E\alpha\Delta T \tag{2}$$

where L is the length, α is the CTE, T is the temperature, σTh is the thermal stress, and E is the modulus of elasticity. The temperature of the inner flow path was assumed to be a constant 80 K, which is the temperature of the liquid nitrogen provided by the cryoflow test facility. The outer surface of the Coupler was set to the temperature of different environmental conditions based on recorded lunar surface temperatures and planned tests, documented in Table 2 [1,10,11]. Updates to recorded lunar temperature extremes will require additional analysis to be conducted or operational limits to be defined. Temperature was used instead of radiative energy balance because of limitations on project budget and schedule.

Table 2. Temperatures used for thermal analysis.

Location	Temperature, K
Lunar equatorial maximum	400
Lunar equatorial minimum	95
Lunar polar minimum	26
Cryoflow test facility	311

Steady-state analysis was conducted at each of the environmental temperatures. Sample results for the equatorial and polar minimum temperatures are shown in Fig. 26.

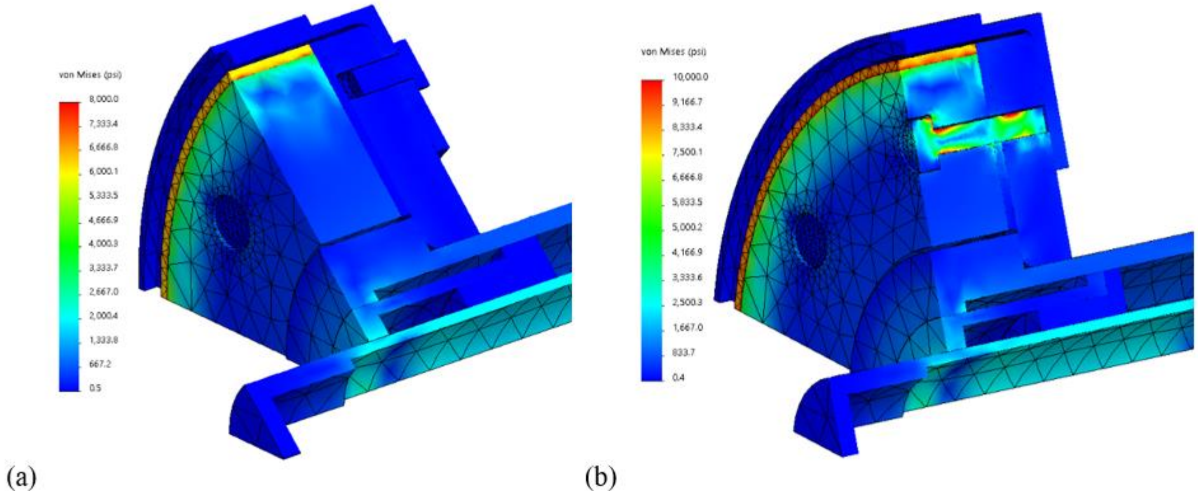

Fig. 26 Von mises stress results (in psi) from steady-state thermal analysis at: (a) equatorial minimum; and (b) polar minimum temperatures.

Results indicate that the thermal stresses for the equatorial minimum case are within allowable bounds. Thermal stresses on the bolts for the polar minimum case have negative margin with a 3-times factor of safety. Future efforts will need to evaluate whether the factor of safety is appropriate and potential design changes to the bolts. Alternatively, an operational temperature limit could be set based on the results of further analysis to determine the minimum temperature at which the margin remains positive.

Additionally, a transient study was conducted to provide initial estimates for understanding what was expected to occur during the cryoflow test. The study was run assuming up to 20 min of cryogenic flow, based on previous cryoflow testing for the LFD. The cryoflow testing is conducted at KSC and was planned for the summer, so an external temperature of 311 K was assumed. Results of the study at 8 min and 20 min are shown in Fig. 27.

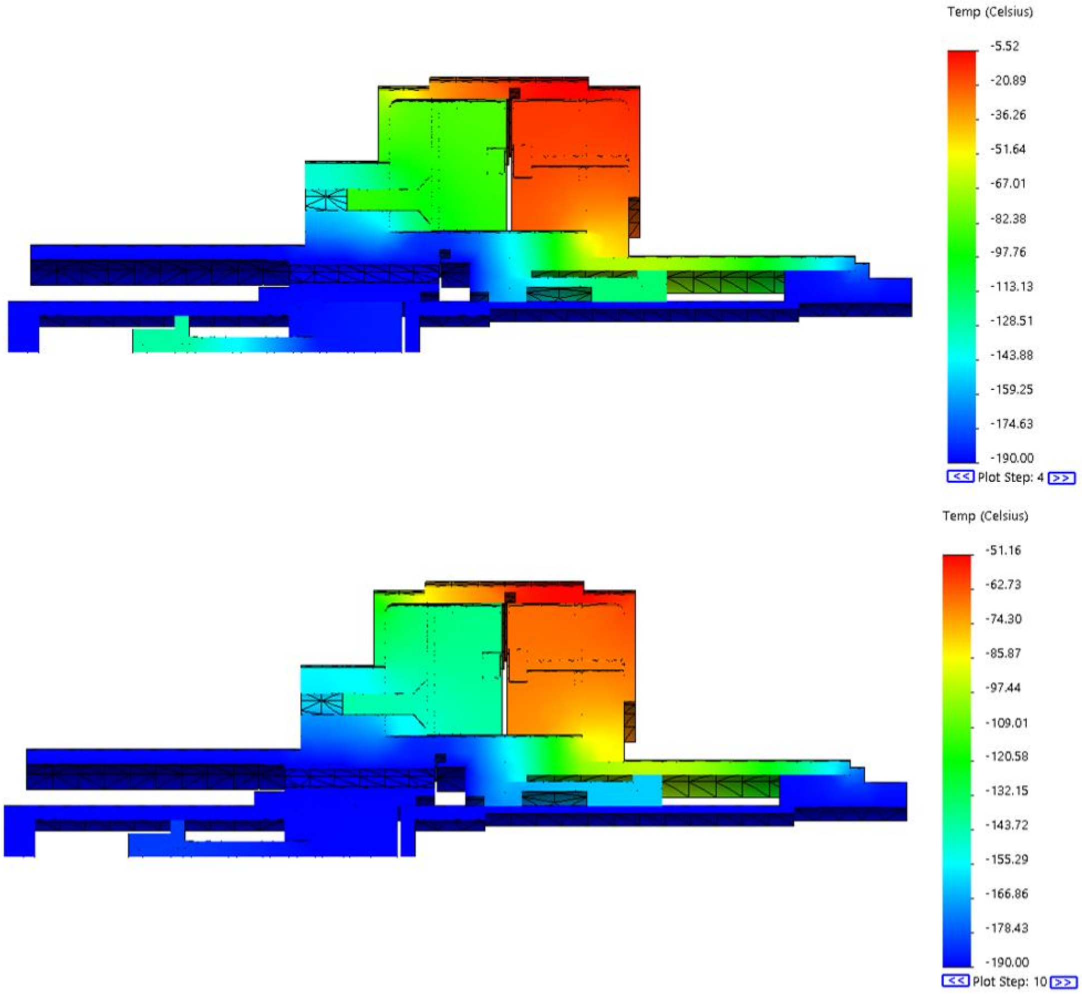

Fig. 27 Temperature (Celsius) results from the transient thermal analysis at: (top) 8 min; and (bottom) 20 min.

Cryogenic fluid flows from left to right, resulting in a difference in temperature between the two halves of the CryoMag Coupler; the upstream half is much colder. Further study is recommended to ensure this temperature differential does not impact the sealing of the DMS, which study was not included in this preliminary analysis. Additional transient analysis should be conducted at the other temperatures presented in Table 2 to evaluate potential thermal stresses in representative operational conditions.

E. Cryogenic Fluid Flow

As a conclusion to the testing effort for this project, a post-dust-exposure cryogenic fluid flow test was conducted. The purpose of this test was to perform a functionality check to ensure that the CryoMag Coupler can successfully flow liquid nitrogen at 50 to 60 psi without leakage and to ensure the successful mate and de-mate of the Coupler. The cryogenic flow test was conducted at the KSC Cryogenic Test Laboratory. The liquid nitrogen was successfully flowed at a rate of 14.06 L/min with a pressure of 72 psi at the inlet of the CryoMag Coupler. Although the LFD can accommodate a higher flow rate, the liquid nitrogen supply tank limited the flow rate during the test to 14.06 L/min. The usage of magnets to mate, latch, and de-mate proved user-friendly and functional for this test.

Figure 28 shows the cryogenic flow test setup. To calculate the flow rate, the weight of the cryogenic storage Dewar was measured before and after one minute of liquid nitrogen flow. The purpose of the wood block support shown in Fig. 28 is to support the hose and avoid any leakage that may be caused by the weight of the liquid nitrogen supply hose.

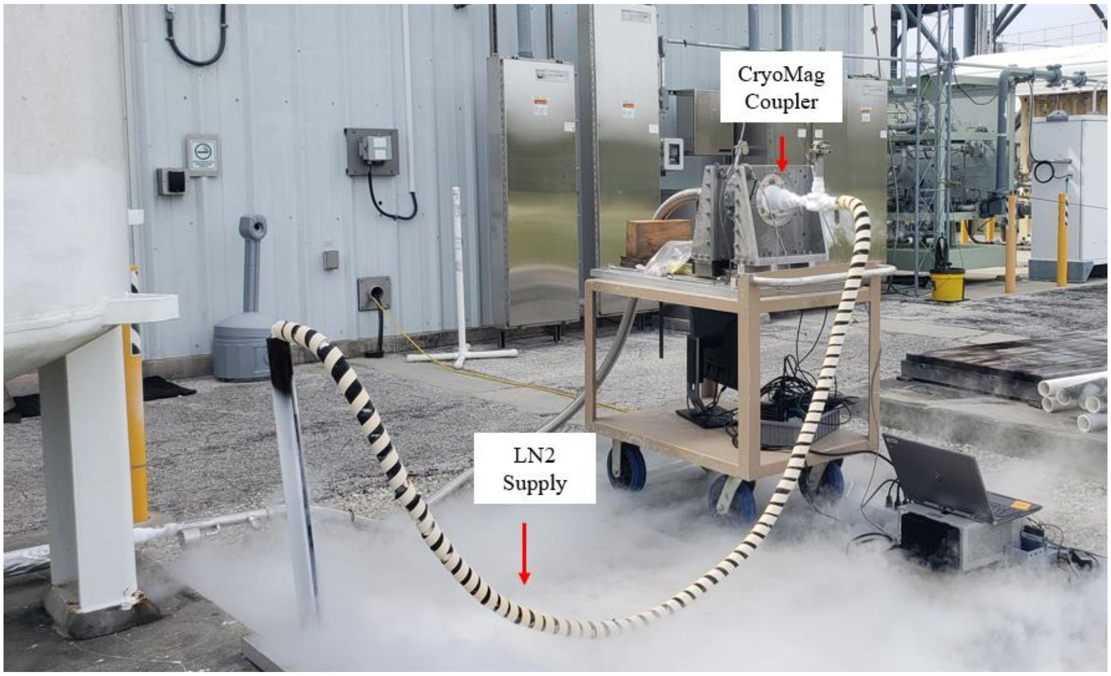

Fig. 28 The Cryoflow test setup at the Kennedy Space Center.

During the prior LFD-only tests, due to water condensation from prior tests and freezing from slow cooling, some icing was formed, which caused some problems during the mating and de-mating of the Coupler. For this test, the Coupler was fully purged to ensure full dryness, preventing the formation of ice. Instead, however, frost formed, which acted as a good insulator as shown in Fig. 29. Frost was a result of the humidity at the test location in Florida, and obviously would not form at the lunar surface.

Fig. 29 Ice formation during the cryoflow test at the Kennedy Space Center.

During the liquid phase flow, no leakage was observed; however, a very small gaseous leak was detected by observing the cloud of water vapor emerging from between the two halves of the LFD. The test was deemed successful because there was no visible leakage of liquid nitrogen.

IV. Conclusion and Next Steps

Development and initial testing of the prototype CryoMag Coupler has been completed, proving the feasibility of the concept of a magnetic-latching cryogenic fluid coupler. The CryoMag Coupler mates, latches, and de-mates successfully, with noticeable differences between the three magnet patterns. The cryogenic flow test demonstrated the capability of the CryoMag Coupler to allow liquid nitrogen to flow through with no visible leaks. Exposure to a representative dust loading proved the capability of the CryoMag Coupler to withstand the dusty lunar surface environment with no dust intrusion into the flow path. Thermal analysis demonstrated the ability of the CryoMag Coupler to survive the temperature range across the lunar surface. The CryoMag Coupler, which began as a concept, has been advanced to a technology readiness level of four: validation in a laboratory environment.

Further development will target increasing the technology readiness level through testing in more representative environments, including vacuum, the full lunar surface temperature range, and a combination of dust, vacuum, and temperature representative of different regions of the lunar surface. Vibration testing to ensure survival of the CryoMag Coupler in a typical launch environment should also be conducted, along with other application-specific testing. All testing to date has been in accordance with the nominal concept of operations. Additional development efforts should include testing of off-nominal scenarios to develop a better understanding of potential failures (for example, from mishandling) and improve the development of operational and handling procedures, as well as the identification of other potential safety hazards and mitigations.

Several design refinements identified during the initial analysis and testing may be incorporated into future design iterations. Work is currently under way to improve sealing of the Low Force Disconnect to support potential transport of smaller-molecule fluids. Improvements are needed to the seals of the Dust Mitigation System as well; testing showed no dust in the fluid, as required, but dust intrusion onto the magnet mating faces is not desirable because continued buildup over many cycles may impact magnet functionality. Other magnet materials and patterns are also worth exploring to create more options for tailoring the magnet force profile to suit a particular application. Improvements based on human factors and ergonomics may also need to be incorporated; for example, the current latching mechanism on the Dust Mitigation System proved challenging to use.

In addition to the envisioned use as part of in-situ resource utilization on the lunar surface, the technology being developed could be useful for similar use on Mars, different types of couplers (other fluids, electronics or electrical, et cetera), terrestrial applications (dusty areas), et cetera. It is expected that the design will require some tailoring to suit the intended application. Additionally, it may be possible to tailor the design to be useable with rovers or other robotic or automated systems, which would be especially useful for in-situ resource utilization applications.

Acknowledgments

The authors thank the Early Career Initiative (ECI) Program in the NASA Space Technology Mission Directorate (STMD) for sponsoring this work. The authors also thank the Armstrong Flight Research Center personnel and the other members of the CryoMag Project team, namely Jonathan Lopez, William Manley, Tanner McDonnell, Ana Osorio-Alvarado, and Kole Pickner, as well as the Project mentors Jeanette Le and Eric Miller for their support of this effort. Finally, the authors thank Nathan Jimenez and the staff of the Glenn Research Center Uniform Dust Distribution System (UDDS) chamber and Gabor Tamasy and the staff of the Kennedy Space Center Cryogenic Test Laboratory for their assistance with the test efforts.

References

[1] National Aeronautics and Space Administration, *Cross-Program Design Specification for Natural Environments,* NASA SLS-SPEC-159, Revision G, December 2019.

[2] Bagdigian, R.M., and Stambaugh, I., “An Environmental Control and Life Support System Concept for a Pressurized Lunar Rover,” AIAA Paper 2010-6256, July 2010.

[3] Manley, W., and Heersema, N., “Low Force Disconnect Cryogenic Coupler Design Development,” AIAA Paper 2023-2128, January 2023.

[4] Bean, P.S., Heersema, N., Holguin, A., Lopez-Zepeda, J., and Stebbins, S.L., “Magnetic Subsystem Design and Testing for the NASA Magnetic Latching Cryogenic Coupler,” AIAA Paper 2023-0069, January 2023.

[5] Wagner, S.A., *The Apollo Experience Lessons Learned for Constellation Lunar Dust Management,* NASA TP-2006-213726. URL: https://history.nasa.gov/alsj/TP-2006-213726.pdf [retrieved 31 October 2023].

[6] Winterhalter, D., Levine, J.S., Kerschmann, R.L., and Brady, T.K., *Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop),* NASA TM-2020-5008219, 2020. URL: https://sservi.nasa.gov/wp-content/uploads/2020/10/NESC-RP-19-01469_NASA-TM-2020-5008219.pdf [retrieved 31 October 2023].

[7] Stebbins, S.L., and Heersema, N., "Low-cost Testing in Representative Lunar Regolith Environment," AIAA Paper 2023-2469, January 2023.

[8] Gerdts, S., Jimenez, N., and Dunlap, P.H. Jr.., *Lunar Simulant Deposition Technique for Dust Tolerance Studies,* NASA/TM-20210024128, 2022. URL: https://ntrs.nasa.gov/api/citations/20210024128/downloads/TM-20210024128.pdf [retrieved 31 October 2023].

[9] National Aeronautics and Space Administration, *Classifications and Requirements for Testing Systems and Hardware to be exposed to dust in Planetary Environments,* NASA-STD-1008, 2021. URL: https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-08-21_nasa-std-1008-approved.pdf [retrieved 31 October 2023].

[10] National Aeronautics and Space Administration, "Lunar Reconnaissance Orbiter: Temperature Variation on the Moon," URL: https://lunar.gsfc.nasa.gov/images/lithos/LROlitho7temperaturevariation27May2014.pdf [retrieved 31 October 2023].

[11] Williams, J.-P., Paige, D.A., Greenhagen, B.T., and Sefton-Nash, E., "The global surface temperatures of the Moon as measured by the Diviner Lunar Radiometer Experiment", Icarus, vol. 283, 2017, pp. 300-325. URL: https://doi.org/10.1016/j.icarus.2016.08.012 [retrieved 31 October 2023].