

Low-cost Testing in Representative Lunar Regolith Environment

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Rapid prototyping and testing are key enablers of iterative designs common in early technology research and development. Testing in a dusty environment is critical to prepare the Cryogenic Magnetic Coupler for lunar operations. To enable early and iterative testing of dust mitigation concepts, a low-cost, low-fidelity representative lunar regolith environment was developed at the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California). Based on preliminary testing with this test setup, a similar setup may be of interest to universities and other entities looking to develop the capability to safely test relatively small-scale components with lunar regolith simulant. The development of this lunar regolith test chamber and results from preliminary testing are presented in this paper. Also discussed are further development strategies for the potential improvement of this setup.

I. Introduction

As a new era of lunar exploration arrives, there has been renewed interest in addressing the challenges posed by using equipment and mechanisms in the lunar environment. Significant among these is the vexing nature of lunar regolith dust. First noted during the Apollo missions, lunar dust coated spacesuits, eroded seals, and degraded the performance of thermal control systems [1, 2]. Future missions to the Moon will need equipment tested in a representative dust environment.

One of the many projects that the National Aeronautics and Space Administration (NASA) has funded to address the issue of lunar regolith dust is a proof-of-concept cryogenic-magnetic (CryoMag) fluid coupler, discussed more in the following section. Being developed as part of the Early Career Initiative program, the CryoMag Coupler has a limited scope of 2 years and \$2.5M, requiring the ability to quickly test design iterations and restricting the use of outside facilities. The CryoMag project is primarily staffed and run by early career engineers located at the Armstrong Flight Research Center (AFRC) (Edwards, California). Largely known for its aeronautics research, AFRC has limited space-environment test capabilities and lacked the ability to test components in a dusty environment representative of the lunar surface. As part of the CryoMag project, the capability to test in a dusty environment has now been developed and is the subject of this paper. In the context of the project, other environmental factors such as microgravity, vacuum, and radiation were deemed to have effects that were both quantifiable and outside of scope for this phase of the project.

Other NASA Centers have a variety of capabilities for testing in dusty environments representative of the lunar surface. Some of the more notable laboratories include the Simulated Lunar Operations (SLOPE) Laboratory at the Glenn Research Center (GRC) (Cleveland, Ohio) for testing wheeled propulsion on simulated lunar surfaces, and the GRC Mechanism Exposure to Regolith Simulator for testing mechanisms for survival and function under prescribed surface deposition densities of lunar regolith [3]. The Kennedy Space Center (Merritt Island, Florida) and the Marshall Space Flight Center (Huntsville, Alabama) are both developing or improving regolith laboratories. The Jet Propulsion Laboratory (JPL) (La Cañada Flintridge, California) has several environmental chambers that can support regolith work. While the CryoMag project plans to perform testing of the final design in one of these well-established laboratories, a need was identified to be able to quickly iterate mechanism concepts locally at AFRC to see what worked in a lunar regolith environment without the cost, schedule, and logistical burden of recurring travel to other

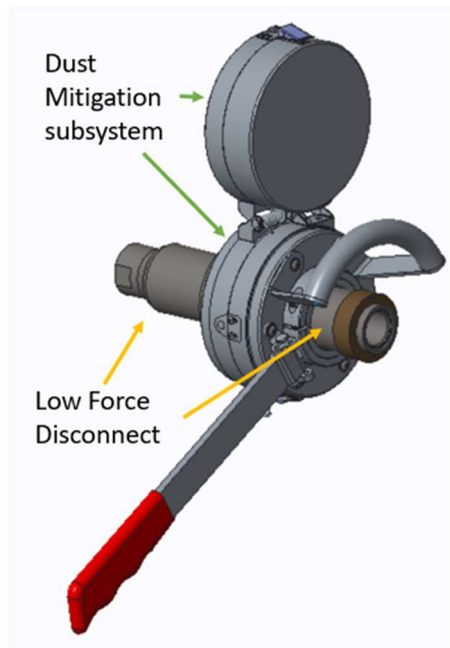
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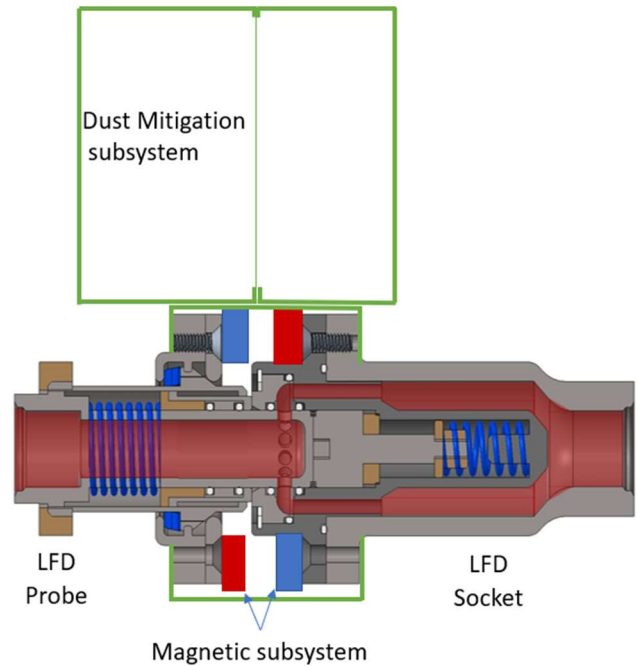
facilities. The team leveraged the knowledge and the work done at the other laboratories to rapidly design and implement a low-cost solution, the Dust Environment Low-fidelity Test Apparatus (DELTA) glovebox, to meet the need for quick, low-fidelity testing. Although the limited precision of surface deposition and quantification methods restrict the usefulness of the DELTA glovebox to low-fidelity testing, the low cost, small size, and rapidly-deployable nature of the design make it potentially adoptable by universities, schools, and other groups seeking to perform dust environment testing on a limited budget. In total, the test apparatus costs less than \$3,300 USD (2022 dollars) - approximately the cost of travel for one engineer for one week to another NASA facility. This cost does not include the optional equipment (a digital single-lens reflex (DSLR) camera and a miniature air particulate tester) which were shared with other projects. This paper describes the development of the low-fidelity DELTA glovebox to support preliminary testing of dust mitigation technologies to support the CryoMag Coupler. A brief overview of the CryoMag Coupler is included to provide context for the testing. Development of the DELTA glovebox is described, including selection of lunar regolith simulant, containment, and dust deposition system. Methods of testing are described in detail including preparation of the test articles, application of the dust, cleaning, and measurement. Results from initial testing are included as verification of the capabilities of the DELTA glovebox. Ideas for improvement based on the initial tests are included along with lessons learned.

II. Overview of the CryoMag Coupler

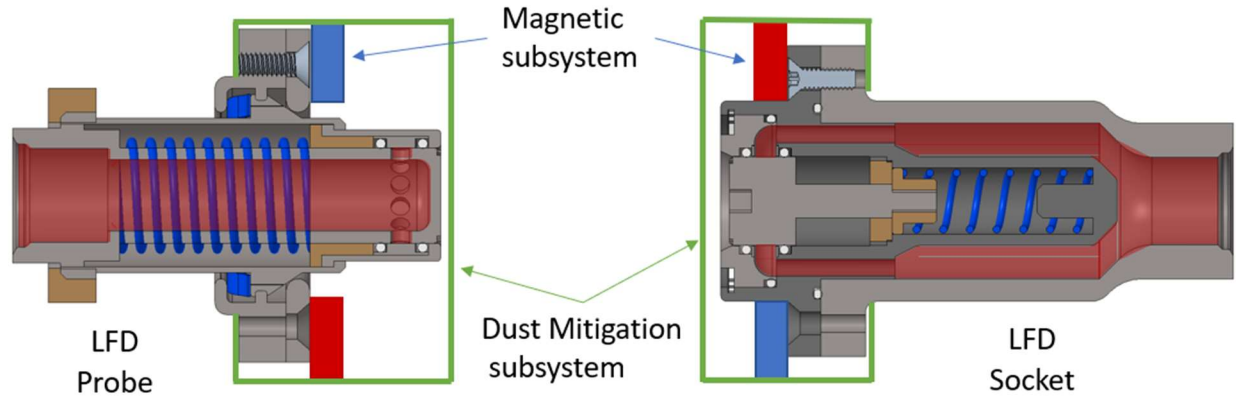
Many needs have been identified for future long-term habitation and exploration on the lunar surface, among them the need for cryogenic fluid management. The CryoMag Coupler is envisioned for use in a cryogenic fluid management system for a temporary connection between cryogen storage tanks. Liquid nitrogen (LN₂) was chosen as the cryogenic fluid of interest for initial development, although the ultimate goal of the CryoMag coupler is to accommodate a wider range of aerospace cryogenic fluids. To achieve the capabilities of cryogenic fluid transfer in a dusty lunar environment, the CryoMag Coupler, shown in Fig. 1, is divided into three subsystems: the Low Force Disconnect (LFD) forms the base of the CryoMag Coupler and enables cryogenic fluid transfer, the Magnetic subsystem provides the forces necessary to mate the LFD, and the Dust Mitigation subsystem (DMS) protects the fluid flow path and internal coupler mechanisms from dust intrusion. The focus of this paper is on preliminary testing to support the design of the DMS; information on the Magnetic subsystem is available in Ref. [4] and details on the LFD are available in Ref. [5].



a)



b)



c)

Fig. 1 The CryoMag Coupler mated: (a) CAD model and (b) cross-section; unmated: (c) cross-section.

Designing dust mitigation into a system is a two-part problem: what the system needs versus what protection can be provided with the current state-of-the-art approaches. Although the focus of this paper is on testing the capabilities of providing protection to the system, a brief discussion of what the system needs is helpful to understanding the design of the test setup. The primary requirement for the dust mitigation subsystem is to prevent dust intrusion into the fluid path of the LFD. Allowable contamination levels are ultimately determined by the cryogenic fluid management system, which is yet to be determined for CryoMag, so a typical value of 2.5 mg/L (for LN₂ used as a cooling fluid for terrestrial rocket launches, a similar potential application) was used for this phase of development [6]. In addition to contaminating the cryogenic fluid, dust intrusion has the potential to interfere with the mechanisms of the coupler itself, reducing the usable life or preventing proper operation. Similar to fluid contamination levels, allowable intrusion of dust into the mechanisms is determined by the system design. The CryoMag coupler is designed to be moderately dust-tolerant even without the dust mitigation subsystem. The LFD has sealing features that help prevent dust intrusion into the fluid path, but the seals are vulnerable to accelerated wear from the abrasive characteristics of lunar regolith. The magnetic subsystem is designed with smooth faces and a gap that allows for some dust buildup without reduction in mating force or wear on the magnetic faces, but the nanophase iron present in lunar regolith may be preferentially attracted to the magnets. Testing of the unprotected system is planned to confirm identified dust intrusion paths and dust-critical areas as well as determine the effect of dust intrusion on the mechanisms and identify dust buildup and entrapment areas. This test is planned to be conducted in the DELTA glovebox and will also serve as an evaluation of the ability of the DELTA glovebox to accommodate a larger test article.

The dust-tolerant features of the LFD and magnetic subsystem, while helpful, were determined to provide insufficient protection against the dusty lunar environment; additional dust mitigation was required. Despite knowledge of the problem since the Apollo era, dust mitigation technologies are still rated at relatively low Technology Readiness Levels (TRLs) and there exists no readily available solution. A trade study was conducted to evaluate different methods of dust mitigation to determine which method could best be developed for implementation into the CryoMag coupler. The options considered can be grouped into broad categories: mechanical shielding, advanced materials (including coatings), and dust removal. The ability of each technology to mitigate dust contamination has not been evaluated in a consistent manner so other criteria, developed from the system requirements, were used for evaluation instead. These criteria included compatibility with the cryogenic fluid, compatibility with lunar external temperatures, mechanical interference with the other subsystems, complexity of design and integration, the technology development required, and a timeline for implementation. Using this approach, mechanical shielding was ranked highest and was chosen as the dust mitigation solution for implementation during this initial development phase. Different methods of mechanical shielding were considered, and a subsequent study was necessary to select the option most effective at preventing dust intrusion. The primary candidates were a cap and an iris. Several irises of different types, shown in Fig. 2, were obtained for evaluation. A cap and mock coupler were 3D printed as well to support the evaluation. To determine the effectiveness of each option, testing with lunar regolith simulant was necessary, prompting the development of the DELTA glovebox.



Fig. 2 Iris mechanisms, from left to right, lever-actuated 75-mm blackout aperture, lever-actuated 120-mm aperture, and ring-actuated 50-mm aperture.

III. Test Apparatus Design and Development

To support the development of the CryoMag dust mitigation subsystem, the ability to quickly perform evaluation of mechanism sensitivity and dust occlusion capability was necessary. Assessing the impact of dust on a system requires an understanding of the type of environment to which the system will be exposed, the particle size range of interest, and the surface density of accumulated dust exposure [7]. Testing in a representative dusty environment, therefore, requires the appropriate kind of dust and the ability to apply it in a manner representative of reality. Development of the DELTA glovebox leveraged the experience of other NASA Centers to balance the need for representing reality with sufficient accuracy and the need for low-cost and rapid implementation. This section discusses the selection of the simulant, containment apparatus, and deposition system which achieved a level of fidelity suitable for early characterization and development.

A. Lunar Regolith Simulant

While it would be ideal to test with actual lunar dust, lunar material on Earth is quite rare; however, lunar regolith simulants are available, with mineralogy formulations that mimic different regions of the Moon or different characteristics of actual lunar regolith dust. Selection of the appropriate simulant depends on the desired characteristics; for this application, hardness, morphology, and Particle Size Distribution (PSD) were the most important characteristics. Electrostatic charge and magnetic response are also desirable characteristics for this application but were considered to be of secondary importance. The region of the lunar surface (for example, highlands versus mare) that the simulant seeks to mimic was not a factor in the selection of simulant because the CryoMag coupler is intended to be capable of use anywhere on the Moon. Table 1 contains a selection of lunar regolith simulants considered for this testing; Table 2 contains selected relevant properties of actual lunar regolith samples for comparison.

Table 1 Sampling of available lunar regolith simulants [8, 9].

Simulant	Region	Mean particle size, μm	Density, g/cm^3	Primarily simulates
GRC-3	unknown	105	1.89-1.94	mechanical
JSC-1/1A	Mare	81-105	1.5-1.9	mechanical and mineralogical
NU-LHT-1M/2M/2C	Highlands	~90	1.367-2.057	mechanical and mineralogical
OB-1 / Chenobi	Highlands	82.25	1.815	mineralogical
OPRH2N/H4N	Highlands	tailorable	tailorable	mechanical
CSM-LHT-1	Highlands	122	unknown	mineralogical
CSM-LMT-1	Mare	140.6	unknown	mineralogical

Table 1 Selected properties of lunar regolith [10].

Lunar samples	Region	Mean/median particle size, μm	Bulk density, g/cm^3
Apollo 11	Mare	48-105	1.59-1.71
Apollo 12	Mare	42-94	1.74-1.98
Apollo 14	Highlands with mare ejecta	75-802	1.60-1.75
Apollo 15	Mare	51-108	1.30-1.93
Apollo 16	Highlands	101-268	1.40-1.81
Apollo 17	Mare/highlands	41.5-166	1.57-2.07

The simulants GRC-3 and JSC-1A were provided by the SLOPE Laboratory at GRC to help establish this AFRC capability. The simulant GRC-3 has been used for preliminary testing because of a requirement to have a Safety Data Sheet (SDS); primary interest was in the movement of the dust through the mechanism. Future testing may include higher-fidelity lunar simulants (such as JSC-1A) that better replicate angular particles and the effect of long-term wear. The DELTA glovebox can be used for any simulant, so other simulants may be used in the future. Testing with lunar regolith simulant poses many unique challenges. The mineralogical composition and particle size of most (if not all) of these simulants poses a respiratory hazard that must be addressed before any of the simulants may safely be used in testing.

B. Containment

The simulant needed to be contained during testing to address the hazards of the lunar regolith simulant and protect the test personnel. There is also the added benefit of confining the dust to help with cleanup. A commercially available glovebox was used, with approximate dimensions of 14 inches high, 24 inches wide, and 10 inches deep. All of the necessary equipment for depositions, a scale for post-exposure weight measurements, and all other “dirty” equipment were required to fit inside the glovebox through a 10-inch-diameter port on the right-hand side. The DELTA glovebox, shown in Fig. 3, is made of polyethylene, with an acrylic window and built-in neoprene gloves. As may be apparent from the figure, the glovebox was quite crowded, providing limited room within which to maneuver. The small size, coupled with a concern about static electricity charge from the glovebox, prompted consideration of a slightly larger steel glovebox. On the Moon, a significant deposition mechanism for regolith dust is static charge, and great care is taken to control static in the GRC Mechanism Exposure to Regolith Simulator; however, for this low-cost, low-fidelity test apparatus, it was determined that the potential reduction in static electric charge and the slight increase in available space were not worth the significantly higher (a cost increase of 72 percent to total experimental setup) price of the steel glovebox.



Fig. 3 The DELTA glovebox used for testing, loaded with the necessary equipment: (a) wire rack, (b) paper ruler, (c) temperature/humidity remote control, (d) sieve stack, (e) rechargeable desiccant, and (f) regolith simulant discard box.

In addition to static electric charge, another factor affecting the deposition of the simulant is high humidity, which can cause clumping of the depositing simulant particles. A commercial off-the-shelf (COTS) indoor/outdoor weather station was used to monitor the humidity in the DELTA glovebox, with the “Outside” sensor inside the glovebox to measure temperature and humidity. Different types of silica gel dessicants were used in different combinations to control the humidity: small dessicant packs, bulk silica gel grainuals exposed directly to air, and Molecular Sieve dessicant packs. Silica gel is most useful above 40 percent RH; molecular sleeve dessicant can remove water vapor down to 10 percent [11, 12]. All of these solutions had limited success in controlling the humidity, even in the dry environment of the Mojave desert. Relative humidity of approximately 35 percent was easily achievable.

C. Dust Deposition System

Once the simulant was safely contained and in a humidity-controlled enviornment, the next problem to be tackled was dispersion of the simulant. Dispersion requires a deposition system that can, at a minimum, bound the PSD and volume of the dust loading. Several solutions were considered to tailor the surface dust loading. Initially, some sort of “salt shaker” dispenser was envisioned, but these dispensers only seem to exist as culinary equipment and the holes are not standardized. Stackable sieves, used to separate granular materials by size, work along the same principle, and provide a tailorable PSD. Figure 4 shows the setup and the deposition process during one of the initial tests; the hardware used is labeled. To settle the regolith simulant through the sieves, the stack was tapped on the side with the metal scoop several times while moving the stack over the desired area of deposition.

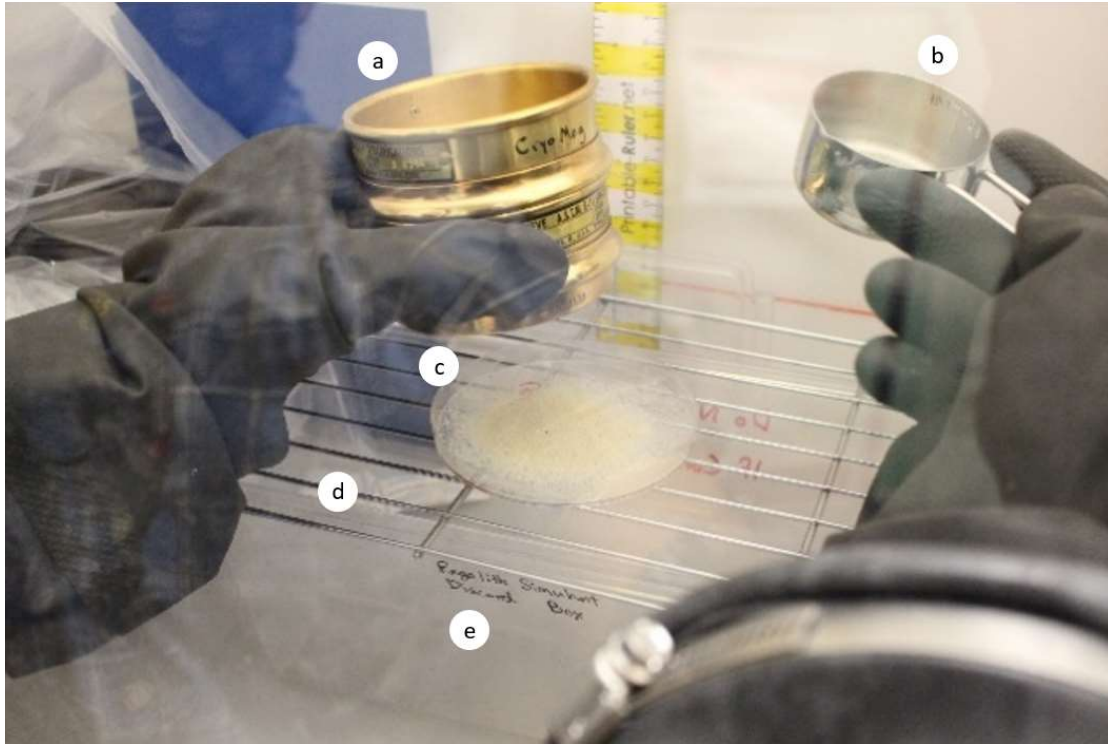


Fig. 4 Regolith simulant deposition process: (a) sieve stack, (b) measuring cup, (c) petri test surface, (d) wire rack, and (e) regolith simulant discard box.

Three sizes were obtained, shown in Fig. 5, and initial testing revealed that a number 35 (0.48 mm) sieve on top of a number 140 (0.10 mm) sieve provided an adequate PSD to test the iris and 4-inch cap mechanisms. The PSD required for testing is driven partly by the PSD of actual lunar regolith, and partly by the scale of potential dust intrusion gaps. The portion of the simulant PSD smaller than 0.10 mm was of most interest for this test of mechanism intrusion. Testing of the cap also included testing with only the #35 sieve to include the larger particle sizes as well.

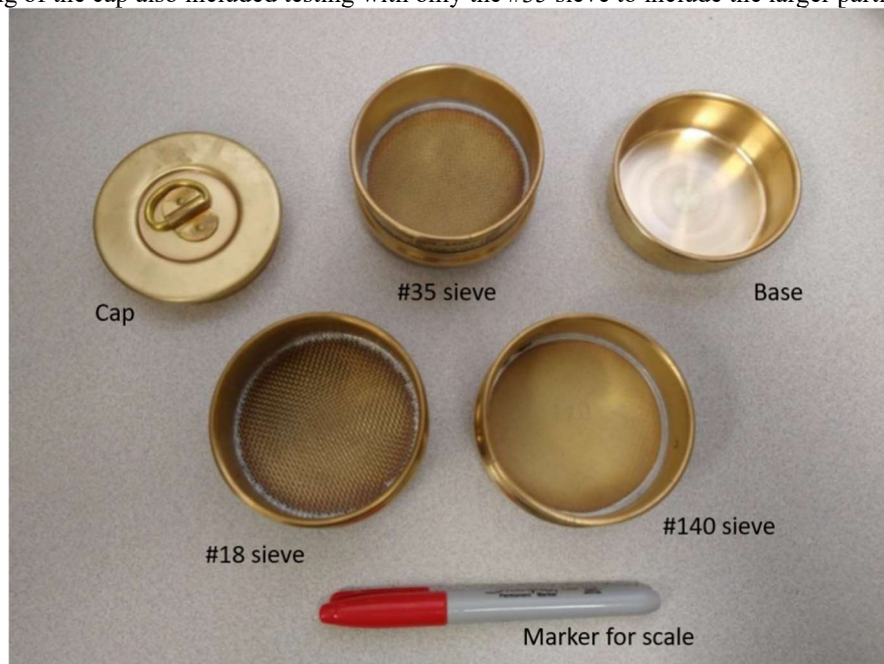


Fig. 5 Stackable sieves in three sizes with cap and base.

IV. Test Methods

Evaluation of dust intrusion into the test articles consisted of three phases: pre-test evaluation, dust application, and post-test evaluation. Once the test article was prepared (cleaned and attached to a collection dish if necessary), the test article assembly underwent a pre-test evaluation including qualitative assessment of the mechanism and measuring the mass of the test article assembly. After dust application in the DELTA glovebox, the test article assembly underwent a post-test evaluation to again assess the mechanisms and measure the mass. This weight differential was used to quantify total dust intrusion into the test article. The qualitative assessment of the mechanism was included to understand the impact of the dust intrusion. A method was developed for quantifying specifically the dust that intrudes into a fluid path of a test article.

A. Pre-exposure Preparation and Assessment

The test article was prepared prior to insertion into the DELTA glovebox. The irises were attached to disposable petri “collection” dishes using 3D-printed adapters secured with clear cellophane tape to capture and quantify dust intrusion through the mechanism. Figure 6 shows the 3D-printed adapters attached to the irises. The mechanisms were actuated several times to establish a baseline operation and the assemblies were weighed.



Fig. 6 Iris mechanisms with 3D-printed adapters.

B. Dust Application

Dust application occurs inside of the sealed DELTA glovebox. The test article and all other necessary equipment were sealed inside of the DELTA glovebox, along with desiccant, a sufficient amount of time before the test began. One option was to prepare for the next test immediately after cleaning the glovebox from the previous test, by sealing it with the next test article to give the desiccants time to absorb moisture from the last cleaning. Typically, a minimum of 24 hours passed between sealing the DELTA glovebox and dust application. All the supplies, including various wet and dry wipes, sets of disposable bags for cleaning and storage, and simulant disposal boxes were restocked in the DELTA glovebox. During testing, the test articles were placed on a grating over a 11-inch by 5-inch by 5-inch clear plastic collection box for “used” dust. Collecting the used dust allows for potential reuse of the dust and minimizes the amount of post-test cleanup. The regolith simulant was stored in jars; a metal, ¼-cup measuring cup used for baking was used to transfer the regolith simulant to the sieve stack. The metal measuring cup was also used to tap on the brass sieve stack in order to dislodge any regolith simulant caught in the meshes.

After stocking the DELTA glovebox and letting the desiccants control the humidity to below 35 percent, the equipment in the DELTA glovebox was prepared for dust application. First, the used dust collection box with the wire rack were set up in the center of the DELTA glovebox. The sieves to be used were stacked, largest on top, and staged on the wire rack out of the way. This method of stacking the sieves serves to slow down the regolith simulant flow rate enough to achieve an even coating of the regolith simulant, rather than a pile. The selection of mesh sizes for the sieves should allow a maximum dust size related to the critical clearances of the test article, because these will be the most likely sizes to cause malfunctions. The test conductor should also perform a trial run on a test surface

(a disposable plastic petri dish works well) to ensure the desired effect. The metal measuring cup was used by hand to tap on the side of sieve stack to agitate the regolith simulant to travel through the sieves.

The NASA has estimated lunar regolith dust loadings based on deposition mechanisms (anthropogenic, rocket plume, et cetera) which are available in Ref. [7]. The cases that best matched the envisioned concept of operation for the CryoMag Coupler are human-caused loading and natural charged lofting cases, listed in Table 3. These cases cover surface loading from natural movement of the lunar dust caused by electrostatic forces as well as dust kicked up off the surface by human movement. Visual and mass-based surface loading was first done to a control surface (a plastic petri dish). Some iteration was required to achieve the desired results. For test articles of approximately 65 cm³, 15 ml of regolith simulant was found to be sufficient to obtain the desired loading.

Table 3 Excerpt of planetary external load cases [7].

Sources of dust	Particle size	Surface accumulated loading	Dust velocity	Charge to mass ratio
Human-generated surface transported dust	< 500 μm	< 40 g/m ²	< 10 m/s	0.1 – 10 nC/g
Natural charged dust transport	< 1000 μm	Combined loading case	Variable	~ 10,000 nC/g

C. Post-Test Cleaning and Evaluation

After dust was applied, photographs were taken without disturbing the deposited regolith simulant. The test article was then tilted to approximately vertical to allow excess dust to flow off the outer surface, and the grating was tapped on to dislodge the dust. This method is in accordance with the CryoMag Coupler concept of operations and is based on expected user action. The test article mechanisms were then actuated multiple times to assess the impact of dust intrusion. To safely open the DELTA glovebox and remove the test article for further evaluation, the exterior of the test article and the interior of the DELTA glovebox must be cleaned to minimize air contamination from the regolith simulant. This cleaning process took the most amount of time and effort. The basic order of operations was to dry-wipe, from top to bottom, the DELTA glovebox, the closed storage boxes, and the test article, ending with sweeping the piled dust onto a sheet of cardstock and depositing it into the collection box. This process was then followed with a wet wipe-down, again from top to bottom. After bagging the used wipes into a seal closure waste bag, the airborne regolith simulant was allowed to settle out for a minimum of 4 hours (based on the initial estimate for settling time), followed by a final wet-wipe cleaning. A handheld air quality monitor was used to determine when it would be safe to open the DELTA glovebox, generally after at least 3 hours.

To record and quantify the dispersion and migration of regolith simulant onto the test articles, two methods were used. The first method of quantification involved an Ohaus Scout™ SPX (Ohaus Corporation, Parsippany, New Jersey) laboratory scale, to weigh the test articles pre- and post-exposure. The difficulty in using a scale is that the mass of dust “caught” in the test articles is low compared with the test articles themselves, so the scale must have sufficient precision. The scale used for this testing has a precision of 0.01 g. The second method of quantification was visual, with photographs taken using a DSLR camera shooting through the glovebox window. Obscuration of the window by excess dust along with the limited window size made this method challenging. The functionality of the test articles was also evaluated pre- and post-exposure, indicating how much the function of the article had degraded due to dust intrusion.

D. Quantification of Internal Regolith Intrusion

One of the primary requirements of the CryoMag coupler is to limit dust intrusion into the fluid being transported. Evaluation of this requirement relies on the ability to quantify dust in the flow path specifically, as opposed to overall dust intrusion into the coupler in general. The mass-difference method discussed in the section above is limited to characterizing total dust accumulation for the entire test article, so an additional method was required. Purging the dust from the flow path and collecting it for measurement was the selected method, with consideration being given to what fluid would be used for the purge and how the dust would be collected for measurement. Liquid nitrogen being the fluid commodity used for preliminary evaluation of the CryoMag coupler, it was the first choice considered. Contamination levels of cryogenic fluids are not straightforward to assess, however, and collecting the contaminated fluid and allowing it to evaporate in order to directly measure the dust left behind risks an inaccurate result if smaller particles are carried away during the evaporation. As well, LN2 is a hazard, which makes it more difficult to work with than other, non-hazardous liquids such as water. Another option is to use isopropyl alcohol as the working fluid because it evaporates slower and less violently than does LN2, but it is also considered a hazardous material subject to restrictions when being worked with.

Air and water, each with its own set of advantages and disadvantages, were considered next because the laboratory has supply lines for both readily available. As with the design of the DELTA glovebox, a low-cost solution made with COTS parts was desired. Multiple filter options exist that are compatible with air or water and are capable of filtering most or all of the relevant particle sizes; two were selected for each fluid for evaluation. The components for filtering air were lighter - making it easier to measure differences in mass due to captured dust - and less expensive, but there was a concern that the air would not be able to clear all of the dust particles from the serpentine flow path of the LFD, leaving some trapped and providing inaccurate results. Using the weight-difference method to measure the amount of dust filtered from the water is complicated by the need to either soak the filter before taking the pre-test measurement (to account for the weight of the water) or allow the filter to fully dry before taking the post-test measurement. Additionally, the water that flows through the filter has to be captured, adding to the test setup; the same is not true of air. Based on the advantages and disadvantages, air was selected for use, with water as a backup option.

Testing the feasibility of this approach with the LFD itself risked contaminating the LFD and affecting the results of future tests if not all of the dust could be removed by the fluid. The LFD has a serpentine flow path with nearly 90-deg turns where dust could get stuck. Substituting for the LFD during the feasibility assessment required finding a readily-available mechanism with a similarly convoluted flow path. A globe valve was determined to have a suitable flow path, compatibility with the fluids, and the appropriate sizes available to match the filters selected for evaluation. A comparison of the flow paths of the LFD and globe valve are provided in Fig. 7.

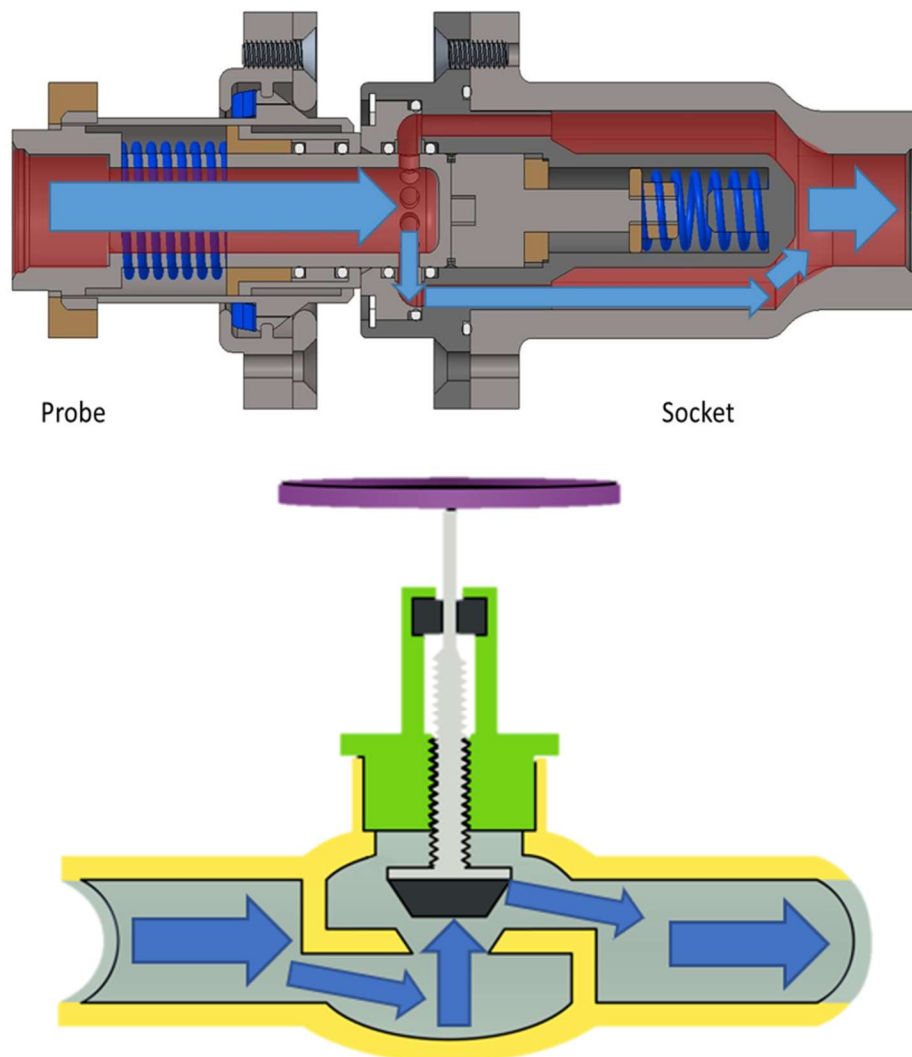


Fig. 7 The flow path of the Low Force Disconnect (top) versus a typical globe valve flow path (bottom) [13].

Hoses were used to connect all of the components together and to the supply source, as shown in Fig. 8. An on/off valve was added to better control the flow and a filter was placed upstream of the globe valve to ensure potential contaminants in the supply source would not affect the results. A ¼-inch inner diameter was used for all components for the initial feasibility evaluation.

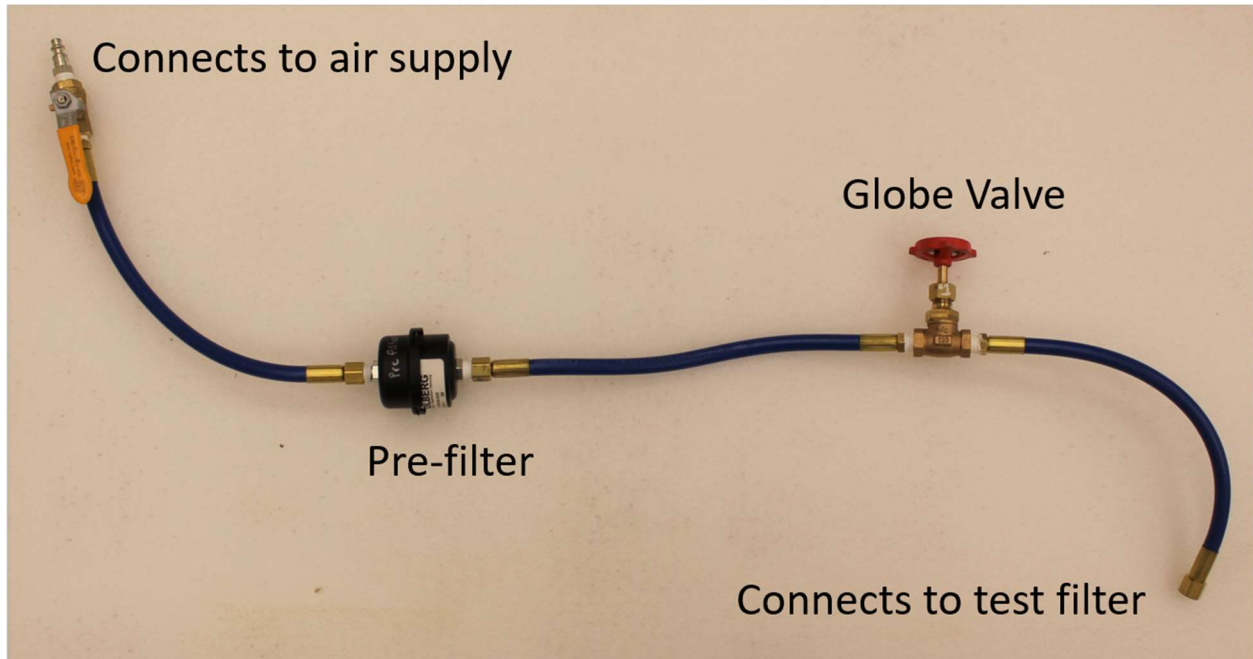
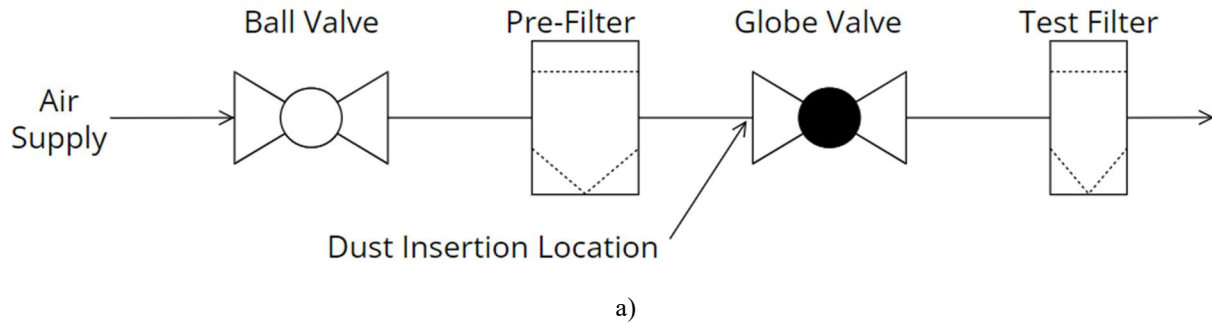


Fig. 8 Filtration evaluation test system layout, (a) diagram, and (b) actual.

The DELTA glovebox has the necessary ports to allow air (or water with some modifications) to be passed in from an outside source; however, attaching the DELTA glovebox to the laboratory sources and ensuring proper disposal of the potentially contaminated water (if used) would not be trivial. The evaluation, therefore, of the feasibility of the methodology and the filters used had to be conducted outside of the DELTA glovebox, preventing the use of the lunar regolith simulants. An alternate, less hazardous, simulant was required. Particle size distributions for common, non-hazardous powders (for example, talcum powder, baking soda, and cornstarch) were assessed; baking soda was selected for the initial evaluation. The particle size distribution for talcum powder is more similar to simulants GRC-3 and JSC-1A but talcum powder could not be sourced. Many commercial products that used talcum powder appear to have replaced it with cornstarch due to cancer concerns; cornstarch was used for the second round of testing because it has a smaller particle sizes than baking soda.

Evaluation of the methodology, fluid type, and specific filter was conducted simultaneously. The test filter mass was measured and then connected to the test system. A known mass of powder was added to the globe valve on the upstream side which was then connected to the rest of the system, with care to avoid spilling. The test system was

attached to the air supply and the on/off valve was opened in multiple short bursts. After detaching from the air supply, the test filter was removed and weighed again. The difference in the mass of the filter was compared to the mass of powder added to the system to determine the effectiveness of the filter. The globe valve was then carefully removed from the system and was both visually inspected and tapped on the table to dislodge any remaining dust to assess the effectiveness of the fluid type and method. The first filter tested captured 87 percent of the baking soda; the second filter captured 93 percent of the baking soda. The second filter was then cleaned and tested again with a smaller quantity of cornstarch, of which only 74 percent was captured. The lack of dust remaining in the globe valve indicates that air works as a purge fluid. The second filter showed better performance than the first, but only when the amount of dust intrusion was high, such as in preliminary testing and evaluation of dust intrusion without any kind of dust protection. The methodology was further limited by the precision of the scale. The scale used for these measurements had a reported accuracy of 0.001 g; however, a measurement drift of 0.004 g was observed with the lid of the scale closed and a drift of 0.006 g was observed with the lid open. Measurement of the second filter was monitored over a few minutes and scale drift on the order of a few milligrams was observed. As the requirement for the CryoMag is less than 2.5 mg of dust per liter, that scale drift is problematic. For this method to be fully effective with smaller amounts of dust, a higher-precision scale would be required. The second filter had a removable housing, allowing the paper filter to be weighed separately, using the scale to its greatest advantage. Unfortunately, a significant amount of dust clung to the housing, as shown in Fig. 9. A coating of some kind might address this problem and may be explored further in the future if desired.



Fig. 9 Dust adhered to filter housing.

Overall, this method is a useful capability for preliminary testing. Incorporating this method into the DELTA glovebox is possible through the use of the ports on the rear of the DELTA glovebox, although some modifications may be required.

V. Results

The DELTA glovebox capabilities were developed to enable rapid testing of dust mitigation prototypes for the CryoMag Coupler. Testing of these early prototypes provided verification of the capability. The first set of dust mitigation prototypes were mechanical irises, intended for use in optical systems. The second prototype was a cap-and-sleeve concept mounted to a prototype of the coupler design. The results for the initial evaluation of the dust dispersion method are included in this section along with the results of the various prototypes.

A. Dust Dispersion Evaluation

Before the test articles themselves could be tested, experimentation was required to develop and evaluate an appropriate method of dust dispersion, detailed above. Different combinations of sieves were tried, and it was found that two sieves worked best. Using only one sieve did not provide enough control over the distribution; a three-sieve stack was too tall to be used easily in the confines of the DELTA glovebox. Intrusion of the dust into mechanisms being of primary interest, the very fine particle distribution of the #35 (top) and #140 (bottom) sieves achieved desirable dust dispersion, shown in Fig. 10.



Fig. 10 Dust dispersion evaluation initial attempt (left), and more evenly dispersed (right).

Dispersion of the dust was concentrated at the center of the sieves; to cover the whole test article, the sieves must be moved around as the dust is poured through. Tapping on the sieve stack during dispersal helped move the particles through the stack. These findings were implemented in the procedure for subsequent tests.

B. Irises

Irises are primarily used for optical applications and are optimized for the control of light passing through the iris. Types of irises can be categorized by the actuation method (ring or lever) and amount of potential light blockage (blackout versus non-blackout). To maximize evaluation of the different categories, the two irises tested first were a lever-actuated blackout iris and a ring-actuated non-blackout iris. The irises were evaluated on two criteria: the amount of regolith simulant that intruded into the enclosed volume, and the robustness of the opening and closure movements after regolith exposure. The optimal approach for direct comparison would be to test irises of the same maximum diameter; unfortunately, commercially available irises of the different types were not available in the same diameter. Table 4 provides details of the irises tested and the measured regolith dust intrusion.

Table 4 Iris mechanisms tested.

Test article	Aperture type	Actuation type	Intruded regolith	Normalized
50-mm aperture	2mm min	ring	0.2 grams	101.8 g/m ²
75-mm aperture	blackout	lever	0.7 grams	158.4 g/m ²

The first iris tested was the 50mm ring-actuated non-blackout iris. The leaves of this iris are actuated (opened and closed) using a thin ring on the outer edge which proved difficult to grasp with the DELTA glovebox gloves and made it difficult to actuate even before dust exposure. Figure 11 shows the ring-actuated iris before testing, after dust exposure, being actuated, and after having been actuated a few times. Worst-case dust loading was simulated by situating the test article with the mechanism facing upwards, thereby in position to receive full dust loading. The dust dispersion method used achieved a suitable dust loading over the leaves of the iris; although the outer ring was not uniformly coated, as seen in Fig. 11(b), the surfaces of primary interest were covered adequately.

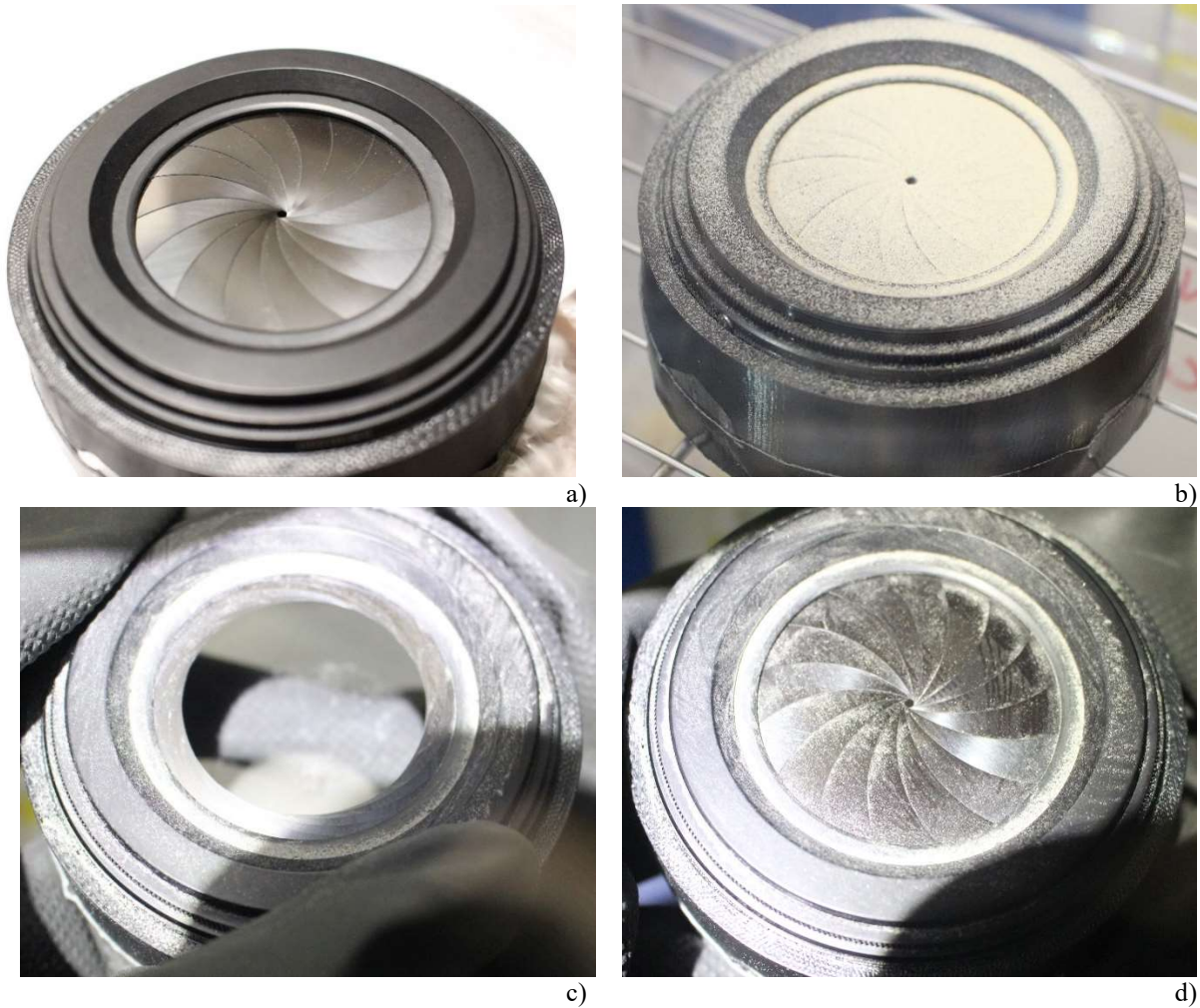


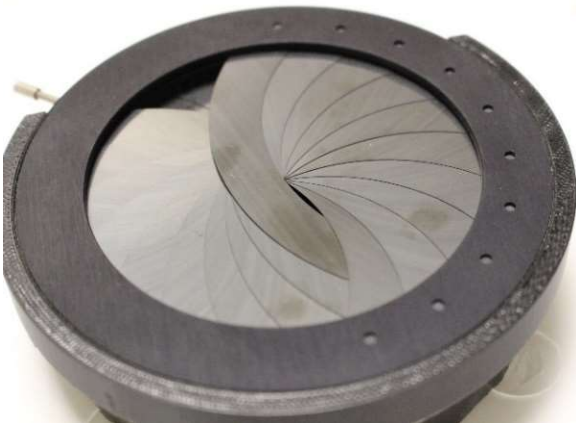
Fig. 11 Ring-actuated iris: a) before testing, b) after dust exposure, c) being actuated, and d) after multiple actuations.

During dust dispersal, a small amount of dust entered the collection dish through the center 2-mm gap, as expected. The actual amount of dust intrusion was actually less than expected given the size of the hole relative to the distribution of particle sizes. After tilting the test article up to approximately vertical and tapping on it to remove excess dust, some amount of dust was still present on the leaves and other surfaces. During multiple subsequent actuations of the iris fully open and fully closed, the dust remained on the leaves rather than falling into the collection dish. No increase in difficulty was encountered actuating the iris after dust exposure as had been experienced prior to testing, suggesting any dust intrusion into the mechanism did not cause immediate degradation. Further study with repeated dust exposure would be desired to assess potential degradation over a representative lifespan. After visual and functional assessment of dust intrusion was complete, the outer surface was cleaned of almost all of the dust, as described above. As shown in Fig. 12, only a very light scattering of dust remained post-cleaning.

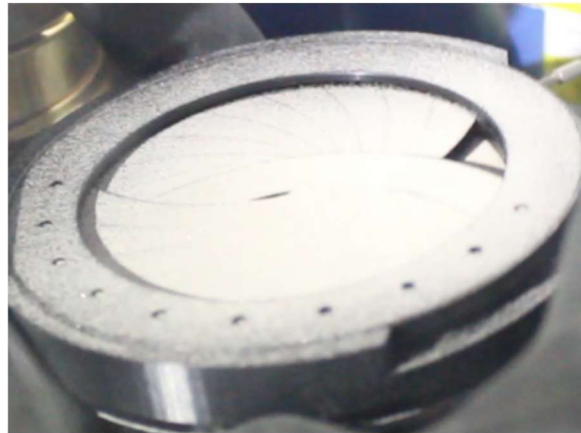


Fig. 12 Ring-actuated iris, post-cleaning.

The 75-mm lever-actuated blackout iris was tested next. Unlike the ring on the ring-actuated iris, the lever was very easy to actuate during the pre-test evaluation. Figure 13 shows the lever-actuated iris before testing, after dust exposure, after dust was tapped off, and being actuated.



a)



b)



c)



d)

Fig. 13 Lever-actuated iris: a) before testing, b) after dust exposure, c) after dust tapped off, and d) being actuated.

The blackout iris differs from the non-blackout iris in that it has two sets of leaves that overlap to prevent the intrusion of light. During dust deposition while the iris was held flat, this design also prevented dust intrusion into the collection dish. There is, however, a gap in each set of leaves and in between the sets of leaves that allowed for dust intrusion when the iris was tilted up to tap the excess dust off. Additionally, more dust remained on the leaves after tapping than with the ring-actuated iris. During subsequent actuations, most of this dust fell into the collection dish, as shown in Fig. 14.



Fig. 14 Dust intrusion through blackout iris after multiple actuations.

Actuation of the lever mechanism was rough, gritty, and audibly “crunchy,” indicating dust intrusion had caused degradation of the mechanism. Additionally, there was some difficulty actuating the iris fully closed on each actuation after dust exposure. The blackout type of iris was determined by the team to be unsuitable for dust mitigation because of the amount of dust that intruded into both the interior and the mechanism. Evaluation of a non-blackout lever-actuated iris was planned to determine if the lever mechanism or the double set of leaves was a greater contributor to the degradation of the mechanism, but this evaluation was not pursued for want of team availability.

Although the ring-actuated iris showed some promise as a dust mitigation method, integrating an iris mechanism into the CryoMag Coupler posed challenges. Commercially available irises were not available in the necessary size, and there was concern that the ferrous material of the thin iris leaves would be impacted by the magnetic fields or impact the magnet performance. All of the irises had a gap or path for the regolith simulant dust to reach the interior. The project team thus decided to pursue a cap-and-sleeve type DMS instead.

C. Cap and Sleeve

Preliminary testing of the cap-and-sleeve concept focused on dust intrusion into the hinge and latch mechanisms rather than intrusion into the inner part of the cap itself. The primary reason for not also assessing dust intrusion is that the cap, being 3D printed out of acrylonitrile butadiene styrene (ABS) for this test, deflected significantly in the closed configuration, and did not seal correctly around the perimeter, as shown in Fig. 15.



Fig. 15 The 3D printed cap-and-sleeve DMS prototype (left), and a close-up of the deficient gap when closed (right).

The 3D-printed material was much less stiff than the material used for later prototypes, causing a significant gap between the cap and the sleeve when closed; however, this is not anticipated to occur with the 316 stainless steel used for the later system-level testing, which will be machined to much tighter tolerances. It is expected that with the cap fully closed, dust intrusion will be completely blocked. Even with the gaps in the 3D-printed cap, very little dust intrusion was observed, shown in Fig. 16.

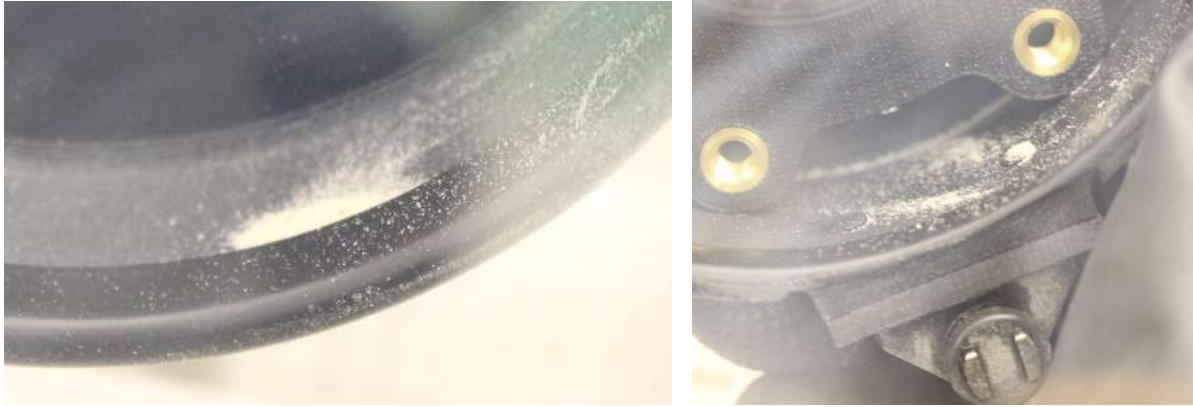
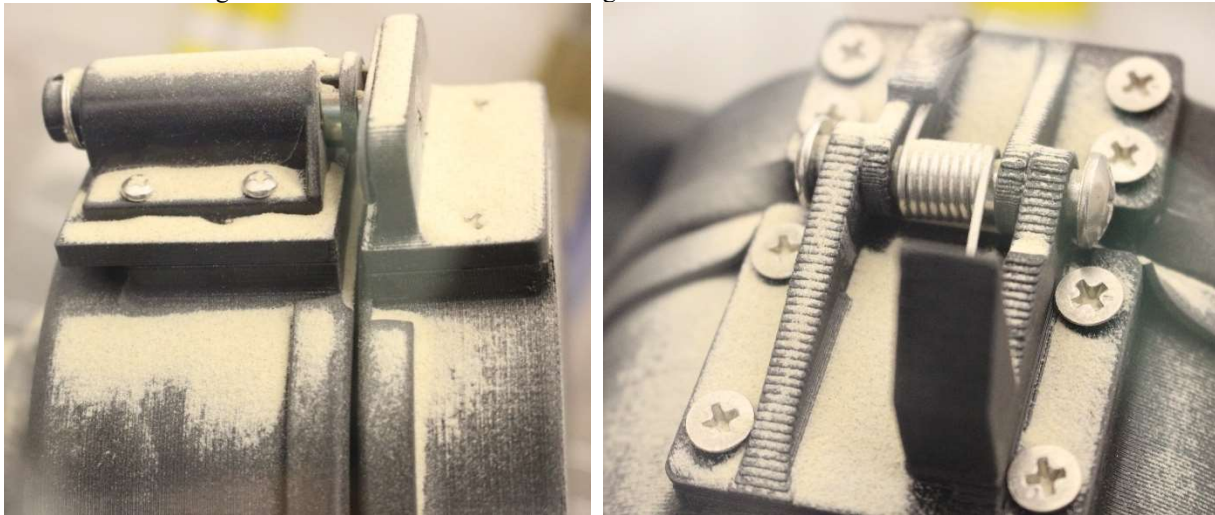


Fig. 16 Dust intrusion into the 3D-printed cap prototype.

The prototype cap-and-sleeve concept was tested to evaluate the robustness of the mechanism after regolith exposure, and was found to be quite resilient. The hinge and latch mechanisms, of primary interest for this test article, were tested separately because they are on opposite sides and only one could be exposed to the dust dispersion at a time. Full dust loading on each mechanism is shown in Fig. 17.



a)

b)

Fig. 17 Dust exposure on (a) the latch, and (b) the hinge.

After dust exposure, both the hinge and the latch functioned normally. The large features did not seem detrimentally affected by the small particle sizes. Dust dispersion over the hinge was repeated using only the larger sieve size to evaluate if larger particle sizes had greater impact. Although dust intrusion into the mechanism was indicated by an audible “crunchy” sound when the hinge was actuated, the effectivity of the mechanism was not noticeably affected. Figure 18 shows the dust remaining on the hinge after multiple actuations.

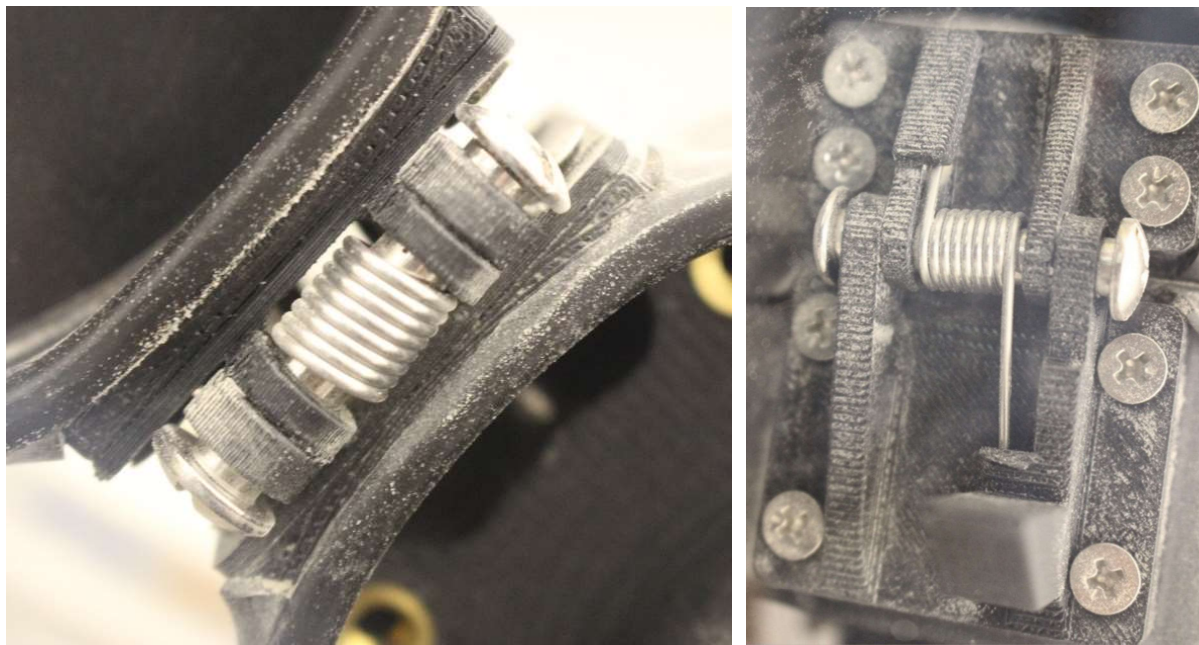


Fig. 18 The hinge mechanism, post-actuation.

VI. Lessons Learned and Conclusions

Overall, the Dust Environment Low-fidelity Test Apparatus (DELTA) glovebox worked well for preliminary testing of the dust mitigation concept prototypes. An even dust dispersal was achieved using sieves which were moved over the test article while being tapped to cause vibrations that helped drive the dust through the sieve stack. The preliminary testing allowed the team to rapidly test several concepts to choose the best concept to integrate and identify potential design needs for future prototype designs. The total budget for setting up a similar apparatus is quite low, at \$3,300, and the technical expertise required puts it within the realm of usefulness for a small college, university, or business.

It was initially assumed that the low-humidity environment of the Mojave Desert would make internal humidity of the DELTA glovebox easy to control; however, the small volume, close contact with engineers, and cleaning chemicals easily raised the internal relative humidity of the glovebox to above 50 percent. Ideally, the relative humidity inside DELTA would be as close to 0 percent as possible, to allow static electricity to play a dominant role in adhesion to the test article. Humidity can also cause the regolith to clump, altering the deposition physics. Several desiccants were used to control the humidity inside the DELTA glovebox. Standard silica gel desiccants, in both packet and bulk form were used, giving modest results of approximately 30 percent relative humidity (RH). Silica gel has trouble absorbing water vapor at RHs below 40 percent. Molecular sieve desiccants can absorb more water vapor at 10 percent RH than can silica gels. Even in the dry desert environment, the humidity was difficult to control in the glovebox, so the value of desiccant use cannot be overstated. Other options for drying the air could also be pursued.

Several iterations were required before a satisfactory cleaning procedure was finalized, because internal space was limited. Self-adhesive plastic hooks were used to mount items on the interior side and back walls of the DELTA glovebox to maximize the effective use of the limited internal space. Future users of similar apparatuses will need to establish dispersion and cleaning operations suited to their requirements. A practice run (without simulant) is recommended to test the layout of all necessary items during dispersion and cleaning operations.

Photography through the sometimes dust-spattered window of the DELTA glovebox was a significant challenge. The use of a digital single-lens reflex camera and manual focus provided the clearest photos. Battery-powered light emitting diode (LED) lighting, mounted to the upper inside surfaces of a DELTA glovebox, may improve photographs taken through the window.

An alternate method for a mass-based measurement of intruded regolith simulant that might be better for different projects would be to include the mass of the simulant, a clean discard box, and the sieves in the pre- and post-test mass measurements. This method works well for assessing total dust accumulation on the test article, but requires either a scale placed in the DELTA glovebox, or the ability to safely remove the relevant items for measurement before cleaning. Since the focus of the testing for CryoMag was on dust intrusion (instead of total accumulation), the dust on

the outside of the test article was not relevant and was cleaned off; the mass of this dust would not be captured by this alternate method.

Toward the end of the project, it was desired to conduct a “pre-verification” run on the final (or near-final) configuration of the entire CryoMag Coupler in the DELTA glovebox, to give the design team time to correct any glaring deficiencies. Given the ordinarily tight space in the DELTA glovebox, the need for additional fixturing to mount the coupler, and finally the need for extra space to demate the coupler, the original procedures could not be used. Instead, the team explored removing the window from the DELTA glovebox temporarily to install the additional fixture and remove the test article assembly after the test was concluded. This procedure was explored as both one-time (assuming that the seal could not be assured after window removal) and repeatable. Given the tight working space in smaller gloveboxes, considerable thought should be given to testing, operations, and cleaning inside a glovebox-based regolith simulant test environment.

VII. Future Work

The capabilities of the DELTA glovebox can be expanded in the following ways, which would not substantially increase cost. Dry “shop air” could be blown into the glovebox using one of the rear gas ports, to force internal humidity lower. A commercial air-drying system could be connected into the glovebox in the same way. Alternatively, using a combination of desiccants, and a small battery-powered fan for forced-air circulation, would lower the internal humidity level, and possibly lower the turnaround time between test iterations.

Several open-source image processing libraries exist, and it may be possible to automatically estimate the surface density of dispersed regolith simulant on a test surface, giving feedback to the dispersion mechanism. The SLOPE Laboratory at the GRC has such a system in the Uniform Dust Deposition System (UDDS) [14].

The CryoMag project team will test the fully integrated CryoMag Coupler at the UDDS at the GRC, for further verification of operation in lunar regolith environments.

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