Dust Mitigation for the VIPER Mobility System

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NASA's Volatiles Investigating Polar Exploration Rover (VIPER) is built to prospect, provide ground truth measurements, and build regional maps of the volatiles at the lunar South Pole that were previously detected by Lunar Reconnaissance Orbiter (LRO), Lunar Crater Observation and Sensing Satellite (LCROSS), and Chandrayaan-1. The rover's mobility system, responsible for navigating the moon's partially defined terrain, is the part of VIPER that is most exposed to the lunar surface environment. To ensure it can survive the thermal extremes and lunar regolith, the VIPER project utilized resources across NASA centers to create and evaluate a multi-functional environmental protection strategy. The project's approach combined thermal insulation with dust protection in a flexible barrier across dynamic actuated joints to serve as the first defense between the hardware and the environment. Additionally, the VIPER project integrated a selection of seals (labyrinth, Nomex felt, and spring-energized PTFE) with individual mechanisms to further mitigate dust infiltration and abrasion risk to the bearings, motors, and sensors. In stages, the project performed extensive testing through a matrix of simulated environmental parameters to evaluate performance margins from the component level to the integrated mobility system. This paper addresses the project's lessons learned, with an emphasis on systems integration and how this work can affect future long-duration lunar surface systems, such as crewed unpressurized rovers and in-situ resource utilization robotics.

Acronyms and Nomenclature

BLDC = brushless direct current
COTS = commercial-off-the-shelf
ESD = electrostatic discharge
GSE = ground support equipment
ISRU = in-situ resource utilization
LRO = Lunar Reconnaissance Orbiter
LCROSS = Lunar Crater Observation and Sensing Satellite
MER = Mars Exploration Rovers
MGRU = Moon Gravity Representation Unit
MLI = multi-layer insulation
MSL = Mars Science Laboratory
NASA = National Aeronautics and Space Administration
PSR = Permanently Shadowed Region
PV = pressure-velocity
PTFE = Polytetrafluoroethylene
SLOPE = Simulated Lunar Operations Laboratory
VDA = Vacuum Deposited Aluminum
VIPER = Volatiles Investigating Polar Exploration Rover

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I. Introduction

The primary scientific objective of the Volatiles Investigating Polar Exploration Rover (VIPER) mission is to characterize the distribution and physical state of water ice and other volatiles on the lunar polar surface and subsurface. This goal follows in the footsteps of remote sensing missions such as Clementine, Lunar Prospector, Chandrayaan, and LRO/LCROSS[1]. Each of these previous missions have indicated the presence of hydrogen-bearing molecules at the lunar poles, with some signatures indicating potentially significant abundance within permanently shadowed regions in craters (PSRs). These PSRs are of particular interest as they may be environmental reservoirs for volatiles. Ultimately, VIPER aims to validate previous findings derived from remote sensing with direct surface measurements, thereby enabling a more accurate assessment of the feasibility and requirements for extracting and processing regolith into useable resources. The resulting data will be critical for advancing in-situ resource utilization (ISRU) strategies in support of sustained lunar exploration. The science payload suite hosted by the VIPER platform is uniquely postured to answer substantial questions about volatile distribution, density, and depth by surficial prospecting and sub-surface excavation[2].

Mobile exploration on the lunar surface comes with significant challenges. Based on lessons from the Apollo lunar landings[3], dust is a primary example. VIPER's mobility modules were identified early in the design phase as critically susceptible to the hazards of lunar dust and regolith, due to their dynamic range of motion, exposure to the lunar environment, and importance to the success of the mission. Thus, the VIPER project devised a layered approach to stack mitigation strategies into the design, followed by iterative testing to gain confidence in the mobility system's endurance on unknown lunar terrains. Each of VIPER's four mobility modules has a global dust barrier covering the components lying outside the vehicle's chassis, which serves as the main deterrent for particulates and obstacles, while local seals are designed into individual actuators. This combination of a global barrier, labyrinth, Nomex felt, and spring-energized PTFE seals assures the mobility system can weather the hazards of the moon for the duration of VIPER's mission.

A. Hazards of the Lunar Environment

The lunar environment is harsh, particularly at the lunar south pole where VIPER is intended to explore. Significant craters and mountains define the macro-landscape's slopes while smaller craters, boulders, and rocks are scattered between the mission waypoints. Mission planners design traverses that optimize for slopes and rock encounters, but are often limited by the available photo resolution of smaller surface features[4]. Exploration of the surface by mobile platforms will require traversing many of these smaller features or accepting operational constraints. These mid-scale features ultimately define the mobility system architecture.

The physical makeup of the regolith dust is of particular interest to the mobility component design, and these micro-scale features drive local mobility actuator designs. VIPER's design references indicated grain particle sizes 0.1 mm or smaller could constitute as much as 40-70% of the bulk regolith mass[5]. Additionally, the clast (broken-off rock fragments) distribution within regolith can be over 50% for 1 mm and smaller particulate. The regolith particles comprise minerals with varying hardness and wear properties. Several of these minerals, such as spinel, represent significant abrasive wear risk, demonstrating extreme toughness and hardness while failing in a way that creates very sharp edges on the new finer particulate[6]. This confluence of properties highlights how critical it is to seal fine particles from mechanism components.

The thermal environment near the lunar south pole is complex and directly tied to the availability of sunlight. Due to the sun's low angle of incidence at the high latitudes, mountains and hills cast massive shadows across the landscape. This phenomenon is what drives the existence of PSRs where the local geography shields craters from sunlight year-round. While roving, the VIPER platform is expected to encounter significant temperature differences between the sunlit and shadow sides of the vehicle. Therefore, while designing for dust mitigation, the thermal extremes of the sealing components must also be considered. Implementations such as springs (or compression of softgoods such as Nomex) provide accommodations for large temperature ranges.

II. VIPER Mobility Overview

The VIPER rover is a four-wheeled vehicle with a total roving mass of 450 kg. The mobility system allows for omnidirectional steering to traverse the lunar surface in any direction while sustaining a solar array position optimized for charging. The vehicle has four mobility modules, shown in Figure II-1, each with independent actuated suspension and steering. Environmental factors, and the functional requirements derived from them, such as slopes, rock sizes, crater depths, and their distributions, all needed to be accounted for in the mobility system architecture.

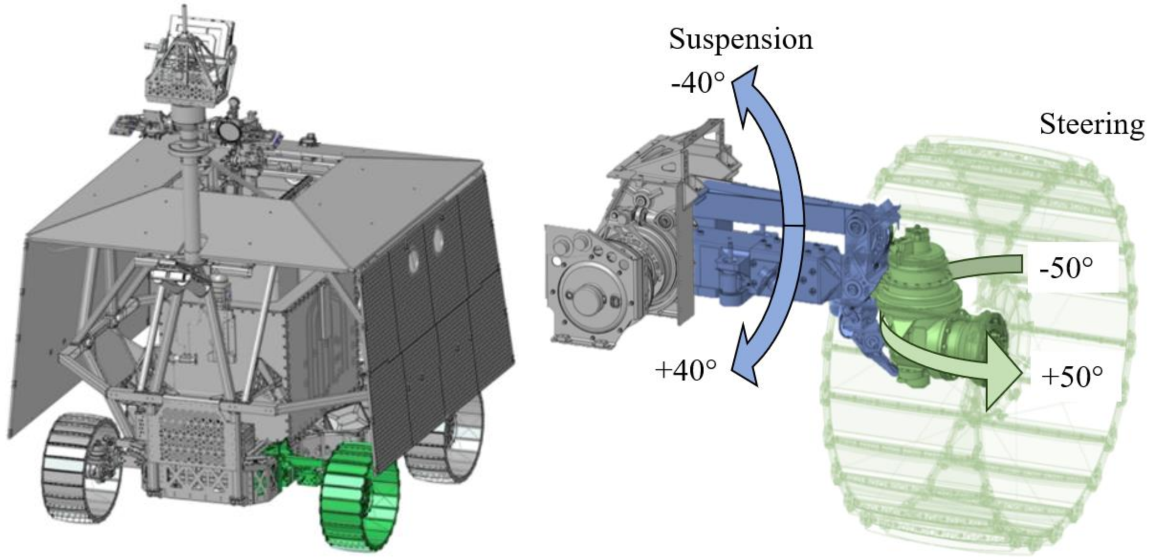

Figure II-1: VIPER model with highlighted mobility module (left), Range of motion for suspension and steering (right)

VIPER's wheels are rigid, with large grousers (paddles) designed to improve tractive performance in the loose lunar regolith. However, these grousers introduce new challenges by directly exposing the actuators to regolith. Each grouser typically carries excavated fines up and over the wheel's diameter as it rotates. Debris often gets trapped within the wheel rim, allowing particles to fall onto the drive and steer actuator assembly. The volume of regolith transported by each grouser is dictated by the sinkage experienced by the wheel on terrain, but this relationship is not well defined at this time.

All actuators, driven by brushless direct current (BLDC) motors, were developed at NASA's Johnson Space Center. Commercial-off-the-shelf (COTS) hardware for motors, resolvers, and gearboxes were utilized in each design, often with slight or major modifications. The drive actuator is a continuous rotation output device driven by a 3-stage planetary gearbox. The steering actuator consists of a harmonic gearbox, with limited rotation output within a range of +/- 50 degrees. The suspension assembly is more complex, including a single-stage planetary gearbox driving a fully mechanical unidirectional brake. The brake serves to significantly reduce the holding power drawn by the suspension actuator at idle conditions. The brake feeds an additional harmonic gearbox reduction. The suspension assembly output is the lower arm of a four-bar linkage that provides near linear translation of the drive/steering assembly and wheel. The suspension linkage has a range of motion of +/- 40 degrees. The actuators are required to operate between -45 and +110°C and include thermal management components (e.g. heaters, temperature sensors) for operational periods. The hardware is also capable of surviving at least 80 hours of shadow survival conditions with no power.

III. Global Dust Mitigation: Sock Design

Each mobility module is fitted with a global barrier (see Figure III-1) that covers it from the rover's chassis to the drive actuator's interface with the wheel. The global mobility barrier, referred to as the "Sock", is a softgoods product made up of layered fabrics and films that flexes with the range of motion of the mobility module (drivetrain, steering, & suspension). The purpose of the Sock is to protect the mobility mechanisms from lofted dust particulates and direct ground interactions caused by steep slopes, fluffy soil conditions, and rock interactions. The Sock incorporates 20 layers of multi-layer insulation (MLI) to thermally insulate the mobility system from the temperature extremes over the course of the lunar summer cycle near the south pole. The Sock design included a phased approach with a focus on the material selection for the outermost layer exposed to the environment, the patterning of the Sock itself, and the Sock's interfaces with the mobility system. The VIPER project undertook iterative testing at predetermined milestones to gauge success on the path to system integration.

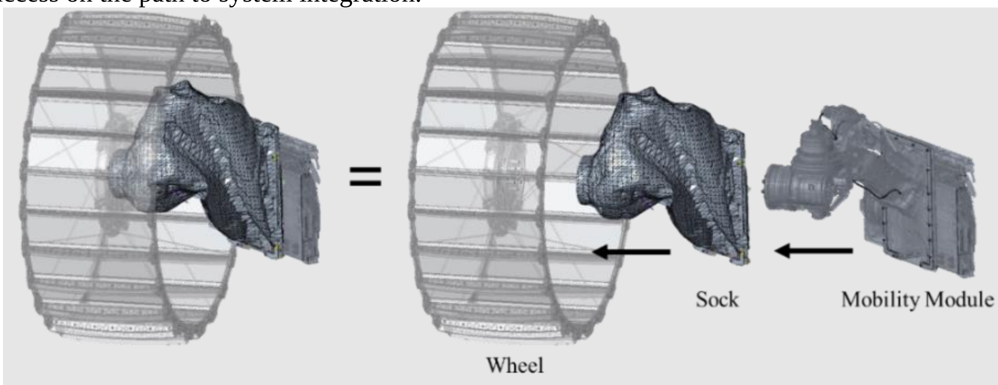

Figure III-1: Assembly process of the wheel, Sock, and mobility module for VIPER

A. Sock Fabrication and Layup

There are four types of material in the layup of the Socks, with a total of 42 layers. The outward facing layer exposed to the lunar environment is constructed of a combination of Black Kapton XC reinforced with Kevlar weave. The outer face is either uncoated or coated with Germanium for improved thermal optical properties. Dunmore RK40311 (with Germanium) and RK40312 (without Germanium) refer to the custom material part numbers developed for the external layer and are the result of extensive material testing and development described in subsequent sections of this publication. The interior face of the outer fabric contains a layer of Vacuum Deposited Aluminum (VDA). To maintain the thermal insulation of the mobility system, 20 layers of alternating B4A netting and perforated VDA2 Kapton make up the multi-layer insulation (MLI). The internal layer facing the mobility hardware is Chemstat 919, a Nomex woven textile with a 0.5-inch (1.2 cm) woven grid of graphite to meet surface resistivity requirements. Because the Chemstat 919 interfaces directly with the moving hardware and harnesses, it was important to choose a textile that would stand up against snags, rips, and tears, and remain flexible to protect the Sock's MLI from the movement of the mobility system. The full stack up is illustrated in Figure III-2.

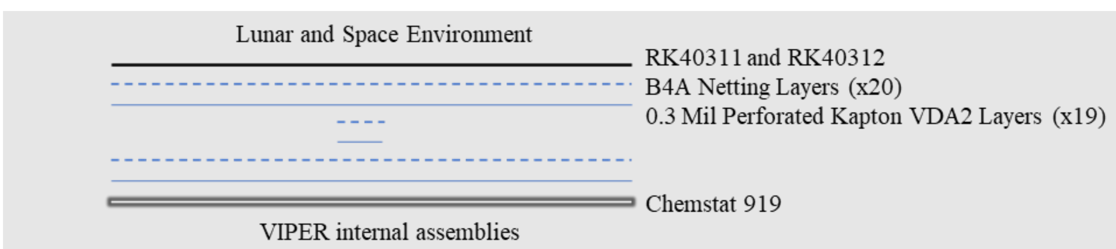

Figure III-2: Cross section material layup of the mobility module Sock

B. Outer Material Selection

The outermost layer of the Sock is the first line of defense protecting the mobility module from the moon's environmental hazards. Design requirements for the outermost material include being:

- Durable against sharp rocks and wheel interactions
- Resistant to fatigue under thousands of motion cycles
- Flexible/low parasitic load to mechanisms
- Impenetrable to micro-sized dust particles
- Tolerant to thermal range (-45 to +110°C)
- Preventative to electrostatic discharge to underlying hardware (surface resistivity < 10^9 Ohms)
- Composed of optical properties with low emissivity
- Radiation resistant to lunar surface conditions for a single lunar summer

The project evaluated commercially available substrates, with a focus on woven textiles and films, for abrasion resistance in a Martindale Abrasion Test. The evaluation parameters of each sample included: air permeation testing, thickness after wear cycles, weight after wear cycles, flexibility, and visual wear.

Table 1: Material Evaluation list for Dust Mitigation

Type	Part Name	Material Composition
Woven	Ortho Fabric	Nomex + Kevlar / PTFE weave
	Chemstat 919	99% filament Nomex +1% carbon
	Tenara 4T40HF	PTFE with ePTFE coating
	EH-35-T2	PTFE with ePTFE coating
	RF801 Beta	Beta cloth fiberglass No Etch
Films	MO01503	VDA / 0.001-inch (0.0254 mm) Kapton reinforced with lightweight Kevlar / VDA
	DE355	VDA / 0.005-inch (0.127 mm) Kapton / VDA
	101287-1	Fiber glass reinforced 0.0005-inch (0.0127 mm) Kapton / VDA
	DM056	0.001-inch (0.0254 mm) Kapton reinforced with Fiberglass
	TR01447	VDA / 0.0005-inch (0.0127 mm) Kapton reinforced with heavyweight Kevlar / VDA

Table 2: Dust Mitigation Material Evaluation Results

Part Name	Martindale Completion	Air Permeation Increase	Thickness Degradation	Weight Degradation	Status
Ortho Fabric	100%	-	-	-	Failed*
Chemstat 919	<20%	-	-	-	Failed
Tenara 4T40HF	100%	0%	-	-	Failed†
EH-35-T2	100%	5.9%	11.3%	1.0%	Failed‡
RF801 Beta	<10%	-	-	-	Failed
MO01503	200%	0%	23.1%	3.9%	Passed
DE355	100%	0%	49.5%	21.7%	Failed§
101287-1	<10%	-	-	-	Failed
DM056	<10%	-	-	-	Failed
TR01447	100%	0%	7.8%	1.2%	Passed

* While Ortho Fabric performs well on areas of strength, durability, and flexibility, it fails for small particulate infiltration with the baseline air permeation test of 22.5 cfm (38.23 m^3/h), allowing all sizes of JSC-1A to freely pass through the substrate and was thus eliminated from consideration.

† Tenara 4T40HF is very rigid, and while it passes all the quantitative aspects of the abrasion test, it is not flexible enough to be fabricated into the initial Sock pattern, let alone flex under the range of motion of the mobility module without inducing resistance on the actuators. It was therefore eliminated.

‡ EH-35-T2 does not meet the surface resistivity requirements to dissipate electrostatic charges due to its Teflon material and is more susceptible to electrostatic build up. Temperate ranges are also not specified by the manufacturer.

§ DE355 is a 0.005-inch (0.127 mm) Kapton film, lacking durability under cyclic flexing and is prone to tear propagations as well as kinking during fabrication. Lack of manufacturability eliminated this material.

The Martindale Test subjects each sample to a moving abradant in a repeated Lissajous pattern (see Figure III-3) over three-square inch (19.35 cm^2) area with a 1-psi (6.89 KPa) load and a 1-inch (2.54 cm) diameter plate for 10,500 cycles. Failure results in the formation of visibly large holes. The abradant, a 150-grit garnet sandpaper matches several properties of JSC-1A lunar simulant, is replaced at every 10% increment of the test. The 150-grit was chosen because it aligns with the upper end of JSC-1A particulate sizes, providing the most damage from an abrading source. Sandpaper compositions considered included: emery, garnet, aluminum oxide, and silicon carbide abradants. Garnet was selected due to its superior composition and conchoidal fracture pattern related to the JSC-1A. In addition, the Mohr hardness scale of Garnet at 6.5-7.5[7] matches the upper range of JSC-1A 4-5[8].

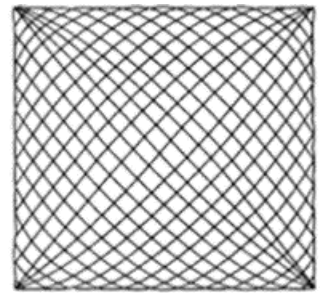

Figure III-3: Lissajous abrasion pattern containing 16 passes

Results indicated that out of the tested materials, TR01147 Kapton reinforced with Kevlar performs the best overall, and after a few customizations, it was selected for the baseline flight Sock design and to cover all areas of the rover with high exposure to lunar dust, rocks, and ground impacts. The final material can be found as part numbers RK40311 and RK40312, with and without germanium outer coating respectively. The woven Kevlar textile provides the benefits of strength and flexibility while the Kapton film affords conductive properties and seals the weave against particulate infiltration. While light and heavyweight Kevlar fill percentages are available options, the KM2+ heavyweight was selected due to the higher strength. The originally tested HN Kapton was replaced with XC Black Kapton to meet surface resistivity requirements for electrostatic discharge (ESD) and grounding. The interior surface has a Vacuum Deposited Aluminum (VDA) layer to reduce radiative heat loss. Finally, this material has several options for top coatings to optimize optical absorptivity and emissivity. Stamet and germanium top coatings are available from the vendor, as well as white conductive coating options from NASA Goddard Space Flight Center's Thermal Coating Lab. Ultimately, the VIPER project chose a combination of Germanium and uncoated Black Kapton surfaces (as shown in Figure III-4) for the flight socks. Section V-C on wheel interference further discusses coating selection.

Figure III-4: Flight unit mobility module Sock

C. Template Design and Build

The pattern of the Sock consists of 11 different pieces that are sewn together with relatively tight tolerances and seam allowances to keep bulk to a minimum. The edges of the Kevlar seams are sealed with Gentil 101 to prevent fraying, protect from moisture absorbance by the raw fibers, and seal excessive hydrocarbons from off-gassing and contaminating the science instruments. Two grounding wire assemblies electrically connect all 42 layers of the Sock with a rivet and ground the Sock to the chassis. A 1.75 square-inch (11.29 cm^2), 35-micron spectra-mesh filter is located near the chassis interface to vent the internal volume of the Sock and its layers during vehicle depressurization. The filter (top-right) and one of the two grounding wire rivets (lower-center) are shown in Figure III-4. Both grounding wire assemblies and their terminal lugs can be seen on the right side of the image, exiting beneath the Sock and bolted to the chassis through the Sock clamp in two locations. The template design required multiple iterations, by mobility testing on engineering units to inform the fit and function of the Sock. The final design required enough material to allow for full range of motion, but not too much as to interfere with the internal mechanisms and harnesses or externally with the wheel. Planform views and templates are shown in Figure III-5 below.

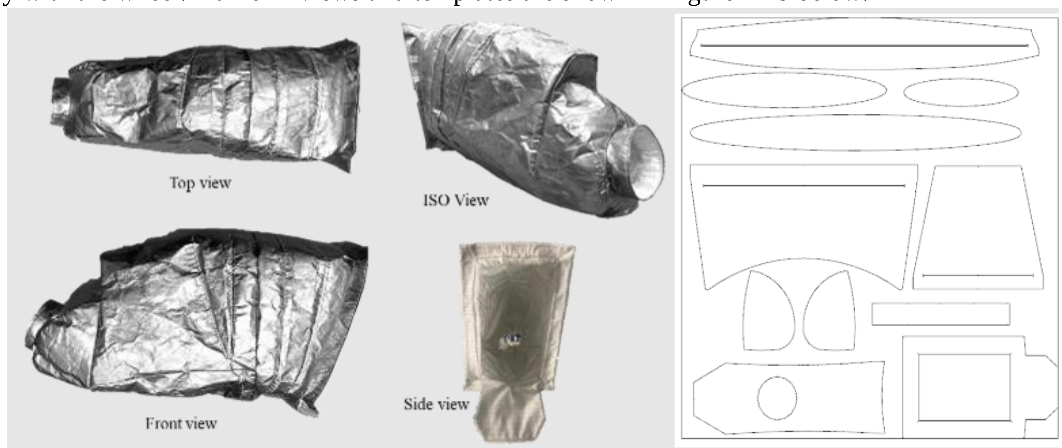

Figure III-5: Flight Sock planforms (left), and flat patterns (right).

IV. Local Dust Mitigation for Mobility Mechanisms

Beneath the global barrier discussed in Section III, individual mobility actuators applied a local sealing solution for redundancy to the sock. Generally, bolted joint connections are considered adequately dust-proof, provided they have sufficient faying surface area and even clamping around the joint perimeter. This section focuses on how the VIPER mission sealed the interior mechanisms, most notably the bearing elements, which are prone to failure from dust intrusion. These local sealing strategies fall into three distinct types: labyrinth seals (i.e. torturous path), Nomex felt seals, and spring-energized PTFE seals. Each method is implemented in a specific series, listed below, in order to gradually shield against smaller particles at each progressive barrier interface**.** For example, because a spring-energized PTFE seal can degrade faster in the presence of larger dust particles, they are more likely to damage the PTFE material. Therefore, they are most effective as the final seal in the series to exclude the finest particles**.** This method draws from historical dust mitigation approaches utilized on the Mars Exploration Rover (MER) and Mars Science Laboratory (MSL) missions, NASA research on spring-energized seals[9], and discussions with industry experts.

The labyrinth designs on VIPER's mechanisms vary in geometry across each actuator and do not exhibit a significant number of teeth. Since the general effectiveness and gap sizes of the labyrinth seal have yet to be evaluated, further testing is recommended to understand the efficacy of labyrinth seals in isolation. In general approach, the labyrinths are intended to be coarse barriers for rejecting gravel-sized regolith debris (e.g. clasts). Prioritizing manufacturability with loose tolerances drove labyrinth gaps on the order of 0.76 mm radially, and 1.00-1.27mm axially.

Fine debris are further mitigated with Nomex-based radial or face felt seals. The choice of face or radial sealing is primarily driven by available design geometry (often restricted due to volume constraints); however, face seals are generally easier to retain and control compression. For face seals, the VIPER project used 20% compression of the seal thickness, based on historical experience from the MER and MSL missions. Other NASA programs such as Tri-ATHLETE Lunar Vehicle Prototype have suggested as little as 5-10% felt seal compression[10]. Because variances in the felt weight will affect the performance, each seal should be tested to meet programs requirements.

Radial seals are sized with early attention to parasitic torques imparted into the actuators. A radial seal test was performed with varying interferences while taking torque measurements at ambient conditions and then at the actuator's min/max temperatures using an oven/chiller at ambient pressure. It is good design practice to carefully track drag torques induced on a mechanism at every seal interface and ensure sufficient torque margin exists in its application[11]. Additionally, an important design detail is the ratio of the Nomex seal's thickness to its radial face width (face seal) or axial width (radial seal). Given Nomex's low stiffness, the installation and retention of thin aspect ratio seals is difficult. Thin ratio seals are more prone to extruding out of their gland, particularly during installation. The seal geometry chosen on VIPER was not optimal—in many cases, the seals are very thin. The project learned to in the future prioritize the volume necessary to utilize a more robust seal cross-section. Ultimately, because replaceable seals were not a design criterion, Nomex seals were epoxied into position, an implementation technique that has pros and cons.

As noted, the third barrier in VIPER's mitigation scheme are spring-energized PTFE seals. Based on the design constraints of each actuator, both radial and face configuration were utilized for the spring-energized seals as well. Previous work on the Resource Prospector project largely informed the drivetrain actuator's custom wiper seal, allowing the VIPER project to continue collaborating with the supplier to update the radial seal to the new larger actuator geometry. Meanwhile, the suspension actuator design called for a face seal with significantly different pressure-velocity (PV) operating conditions. PV conditions are a primary driver of seal and bushing design. VIPER procured a spring-energized face seal from BalSeal Engineering for that application. Both designs call for more controlled tolerances of the seal gland and sliding interface to provide the fine debris sealing.

The following sections review in detail the application of each seal type within the mobility module actuators. Each of four mobility modules has three independent actuators providing actuated suspension, steering, and drive to each of the vehicle's wheels. Each actuator utilizes a similar design layout to seal against dust, with minor variations given application-specific constraints. Every exposed rotating joint received a dust sealing strategy tailored to the speeds, loads, and bearing type at each location. Figure IV-1 provides overall context, while later figures offer further detail.

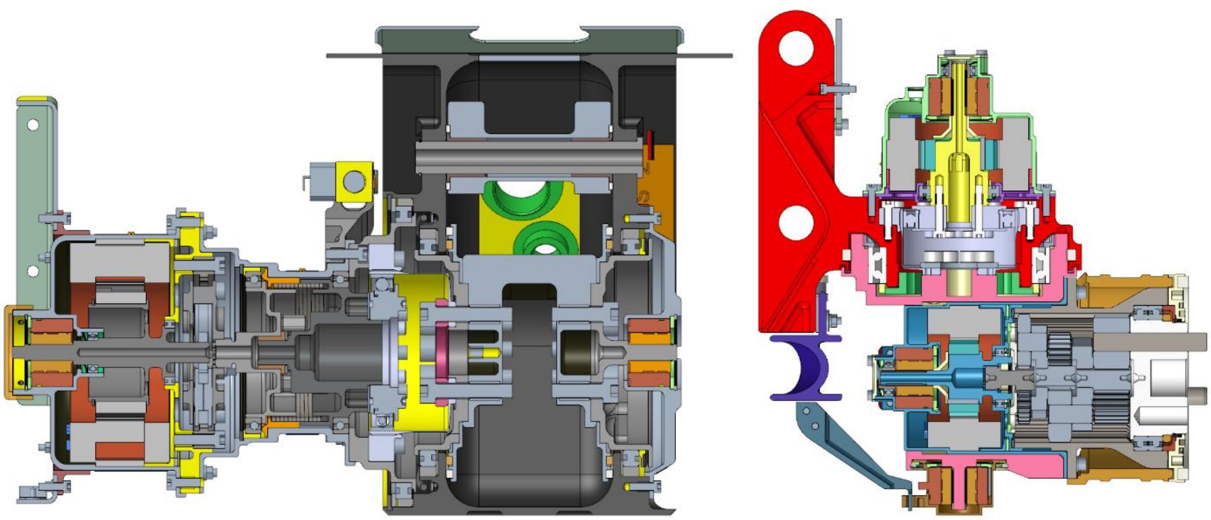

Figure IV-1: Cross-section of suspension actuator (left), and cross-section of drive/steering actuators (right).

A. Drive Actuator

The drive actuator dust mitigation is focused on the wheel-to-actuator interface. This is the most concerning location for dust ingress, as it cannot rely on the global sock barrier. In Figure: IV-2, the wheel hub (shown on the left) is bolted to and rotates with the white planetary gear output, both of which are supported by a back-to-back pair of angular contact bearings. The bearings also represent the initial and most likely point of failure due to dust ingress. All other components in the figure remain static.

The dust entry point is shown where the sock ends at the rotating wheel hub surface. A slight tortuous path is provided by the wheel hubs' overhang before the earliest true seal, a Nomex felt face seal. A more traditional labyrinth seal follows, providing a second torturous path, before reaching the radial stainless-steel spring-energized scraper-style PTFE seal (shown in dark purple). The PTFE seal rides along the white planetary gear output with a tightly controlled surface roughness (Ra 0.8μm). Braycote 600 grease is used to lubricate the interface.

In addition to the previously mentioned seals, a buildup of grease applied at the very tight clearance of the white planetary gear output can create a dam in which dust particles may become trapped. This is an effective method of additional dust mitigation that can be used at tight shaft clearances and bearings.

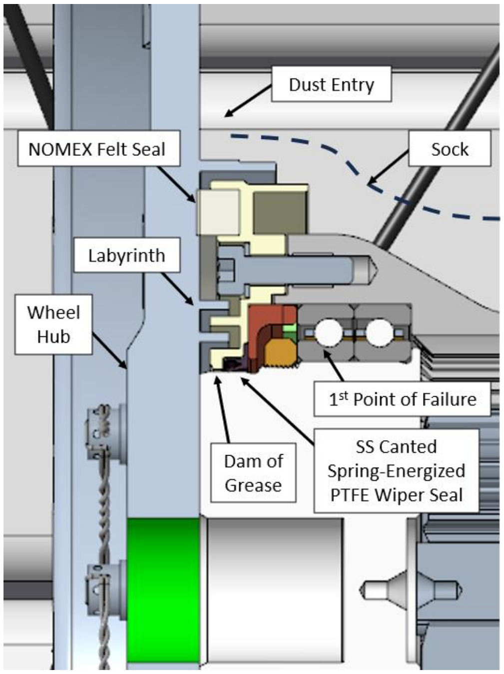

Figure: IV-2 Drivetrain to wheel interface

B. Steering Actuator

The steering actuator assembly provides the primary structural interface to the suspension linkage arms and carries the drive actuator assembly via the steering output. A labyrinth and radial Nomex seal protect this actuator from debris (see Figure IV-3). A spring-energized seal was included in preliminary designs but removed due to geometry challenges and a desire to lean into the reduced risk provided by the steering axis' gravity-aligned orientation. The labyrinth in this application is likely the most robust across the mobility actuators, including an appropriate entrance and exit direction with respect to gravity and 3 full teeth. The Nomex seal is situated just above the labyrinth's exit to provide additional protection. Furthermore, an additional vertical distance in the anti-gravity direction and another pair of 90 degrees turns must be traversed before debris can reach the actuator's output bearings.

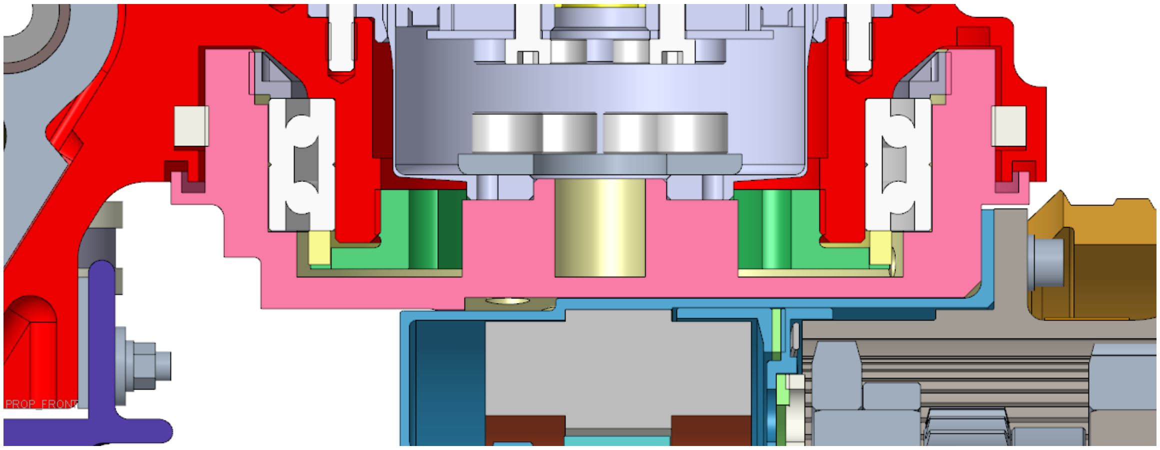

Figure IV-3: Steering actuator with labyrinth and radial Nomex seal (white)

C. Suspension Actuator

The suspension assembly comprises a motor and gear train assembly, a chassis structural interface, a load cell link, and a four-bar linkage providing linear output motion of the drive and steering assembly. The suspension output bearings and the associated four-bar linkage pin joints present numerous locations for dust ingress and exposure to detrimental wear.

Uniquely, the suspension actuator is housed within the VIPER chassis; this space is generally regarded as sealed to dust due to the static dust/thermal softgoods barrier installed upon its exterior. The suspension motor therefore took a different approach to the sealed motor compartments of the steering and drivetrain and omitted dust mitigation at the rear in order to expose a ground support equipment (GSE) tool interface for manual suspension actuation. The load cell link is loaded through a released degree of freedom provided by a large diameter ball bearing (see Figure IV-4). While this bearing only rotates relative to the minute displacement of the load cell, keeping it free of large particles is key to consistent load measurement. The unique location in the sealed chassis allowed for the application of grease damming, a more modest mitigation strategy. Since there is little motion in the bearing, viscous drag torques are of little concern and significantly more grease lubricant can be applied than is typical. This thick barrier of grease sufficiently prevents particulates from impeding the load cell measurement.

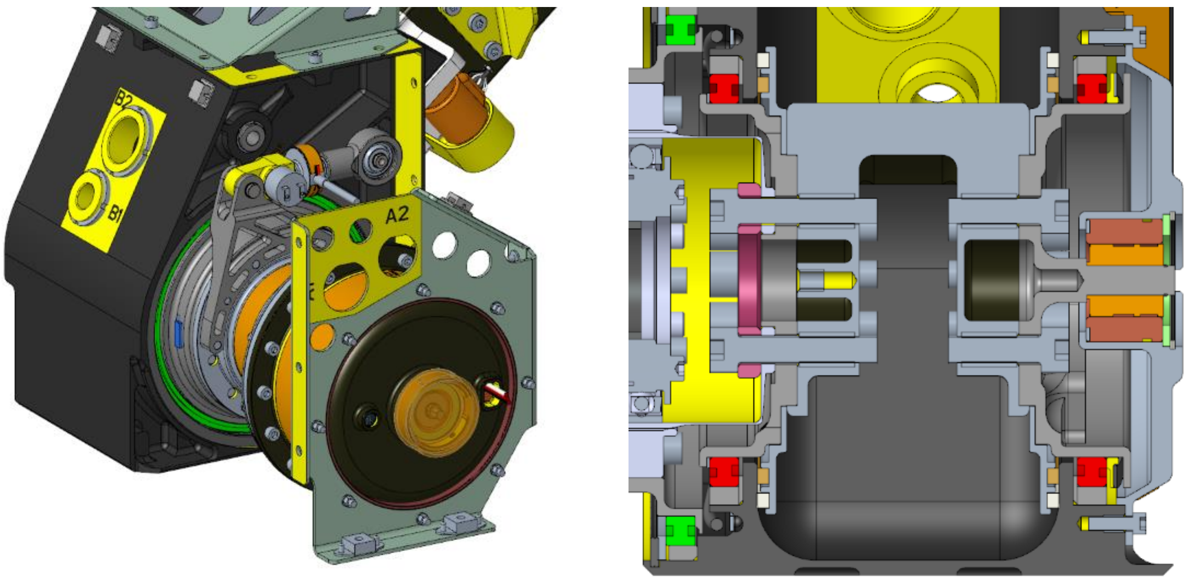

Figure IV-4: View of load cell bearing (highlighted in green) within VIPER chassis volume (left), and cross-section of suspension output bearings (red) with Nomex (white) and PTFE seals (brown) (right)

The output bearing pair situated on either side of the lower linkage (shown in Figure IV-4) is the only suspension ball bearing set with seals for dust mitigation, as they are the initial exposure point to the global softgoods barrier volume (or the external environment in the event of a softgoods failure). This bearing set employs a Nomex face seal with a PTFE spring-energized face seal just behind. Regrettably, a labyrinth was not included due to the manufacturing complexities of the structural interface component. However, the dual-seal design was deemed robust in combination with the suspension's location and significant torque margin. The component stack-up in the suspension's design requires shimming in order to guarantee appropriate seal compression.

Each pin joint (shown in Figure IV-5) was designed with a pair of Vespel SP-3 bushings. These bushings are self-lubricating, thus reducing the attraction of particulate into the rotating joint were it wet lubricated. A Nomex face seal was applied outside the bushing's shoulder diameter, preventing direct exposure. In other locations, where no structure existed to install a similar face seal, the pin head and a purpose-built end cap were designed with a labyrinth. Bushings in general carry a significantly lower risk of failure due to dust intrusion than bearing.

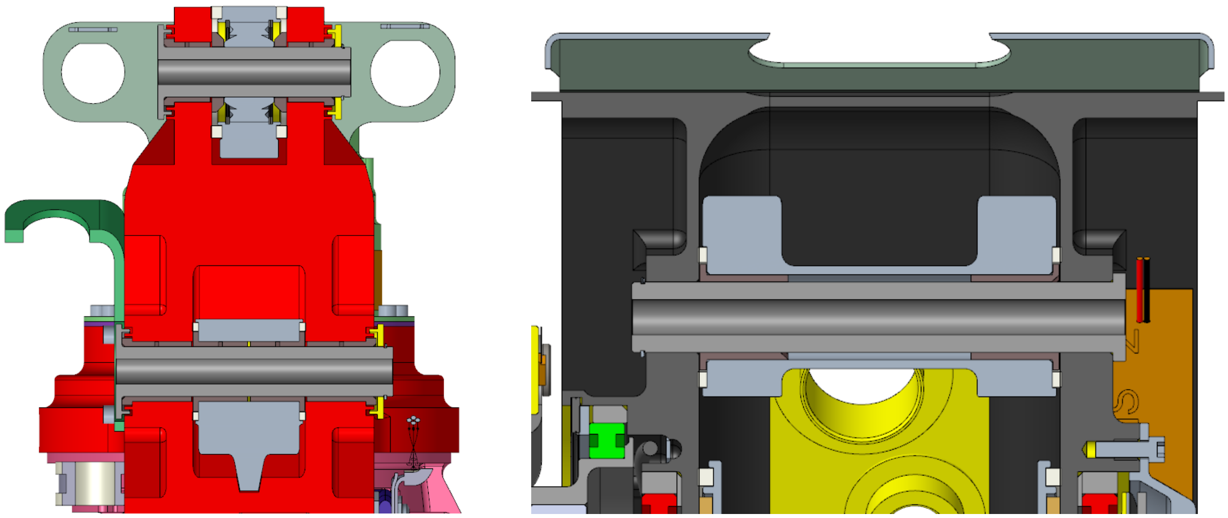

Figure IV-5: Cross-section of linkage pins at drive/steering assembly with labyrinth caps and Nomex seals (white) (left), and cross-section of upper linkage pin at suspension with Nomex seals (white) (right)

V. System and Component Testing

A. Dynamic Dust Environment Test

Early in VIPER's design process, the project highlighted dust as a primary environmental hazard and risk to the mobility system equipment. A test was rapidly developed to evaluate the mechanical aspects of dust abrasion and infiltration into the system under a controlled dusty, but ambient, environment. The test facility's dust box (shown in Figure V-1) contained an initial iteration of the VIPER mobility module (inherited from the Resource Prospector mission) with a global seal and 1419 grams of JSC-1A simulant disturbed by fans every hour to keep dust in circulation around the test article. The test configuration is imaged in Figure V-2. This provided a baseline performance indicator of the proposed plan for a global barrier with localized seals.

The preliminary mobility unit was run with the drive, steering, and suspension actuators sweeping constantly for 56 hours to represent the 10km of early mission traverse expectations. Temperature and power draw were monitored to track possible trends indicating decreased performance. The function of the global barrier was evaluated at the end with a pass/fail criterion and a measurement of any dust intrusion into the system at key locations, including:

- Softgoods interface attachments on round geometry such as on the drive actuator
- Softgoods interface attachments to flat geometry such as on the chassis
- General softgood interfaces of seams, stress points under flexion, pleats, etc.
- Damage to internal MLI layers

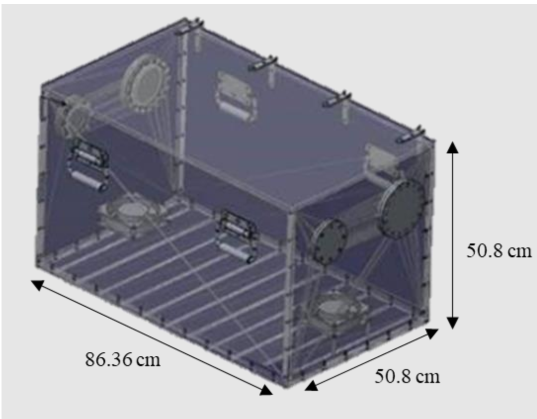

Figure V-1: Dust box with mechanical and electrical feed throughs and two fans to circulate lunar dust simulant

Figure V-2: Dust box test article before dust agitation (right) and after dust agitation (left)

After running for 57 hours and 35 minutes with the current draw and temperature ranges of internal hardware remaining within nominal ranges, the test article was removed, cleaned, and disassembled to look for damage and dust intrusions. No measurable amount of dust simulant was observed on the interior of the global barrier or on the internal hardware components. The softgoods barrier, once turned inside out, was pristine. Further dissecting intermediate layers at locations of high flexion revealed no damage to the interior mylar. While the materials and underlying hardware changed from this initial test to the flight design of VIPER, the fabrication procedures were kept consistent with the lessons gained from this dust box test, and were later retested for validation.

B. Mobility System Testing

The VIPER program developed four Moon Gravity Representation Units (MGRUs), each an iteration of the mobility units but on a platform 1/6th the weight of the expected flight VIPER unit. The test article is typically configured with a simulated center of gravity, in order to test the lunar mobility performance in a 1g environment. The MGRUs evolved several times as the design of VIPER matured, serving as a critical testing platform for all mobility operations, including Sock performance evaluations. MGRU frequently utilized the NASA Glenn Research Center's Simulated Lunar Operations Laboratory (SLOPE) for many of its tests in GRC-1 lunar simulant as well as the fillite bead sink tank[12]. Both test bins proved useful for testing VIPER's dust mitigation strategies for global and local protection. Images of testing are provided in Figure V-3.

MGRU ran through cycles of mobility tests and load evaluations with and without the global barrier of the Sock to expose local seals directly to a relevant dusty environment while the team monitored actuator performance of the drive, steering, and suspension units.

When evaluating the Sock's fit and function on the MGRU hardware, it became difficult to track pinch points or other interferences with the mechanisms and harnesses. To address this, transparent Socks were fabricated so movement of internal hardware could be observed with the Sock on, as depicted in Figure V-3. The main disadvantage of the transparent Socks is that they did not represent the same thickness or stiffness of the flight design Socks, lacking internal MLI layers. Despite this, they allowed the project to identify internal interferences and are recommended for similar flexible softgood designs.

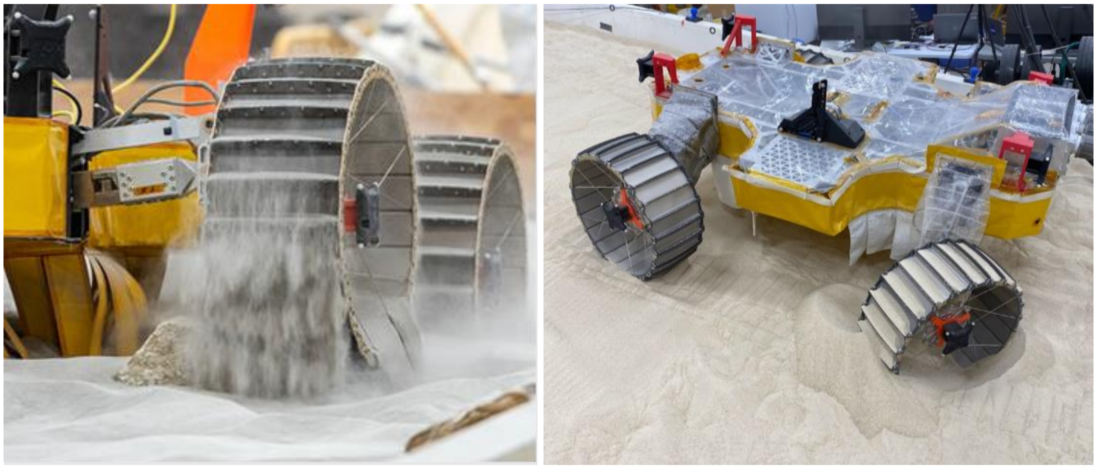

Figure V-3: MGRU in fillite beads testing the local actuator seals with no Socks (left), and at SLOPE Lab testing mobility performance in GRC-1 simulant (RK40312 Sock on left/transparent Sock on right) (right).

C. Wheel-Sock Interference

The final design of the Sock could not be too tightly form-fitting to the mobility assembly, as it needed to maintain sufficient slack to allow for full range of motion. Unfortunately, this slack can interfere with the wheel at the combined suspension and steering range of motion limits. The interference subjects the Sock to abrasion from the rotating wheel spokes and rim (example interference locations shown in Figure V-4). While the mobility modules are not often expected to be in this configuration, some amount of wear is expected. The engineering development unit for the mobility and Socks were subjected to ambient testing to simulate 40 km of equivalent travel. The 40 km of tested run time is on the order of 2X expected full mission life traversed and represents significant margin against an unlikely but possible prolonged wear condition. This was executed with the greatest possible induced interference by running cycles of the mobility mechanisms through their full range of motion continuously. After 40 km in this worst-case scenario, there was visible wear on the outer germanium coating of the Sock's external material, including at panel seams that likely did not experience wheel abrasion. The Kevlar did not show signs of damage beyond minor stretches due to high tension near some of the seams, most notably at the base of the Sock. Because any outer thermal coating is expected to wear off, the flight units do not have the Germanium thermal coating in these areas of interference. This adjustment was supported with a thermal analysis showing minimal impact given the assumption of dust eventually covering the exterior of the Sock. Overall, the Kevlar withstood the abrasion of the wheel and prevented rips and damage from spreading to internal layers. Importantly, the thermal insulative layers were deemed to not be at risk of damage from prolonged exposure to the wheel. This interference is noted, well understood, and part of the baseline flight design. For each design iteration leading up to the final flight build, the same 40 km equivalent test was performed to evaluate the Sock's performance. In each case, similar wear was noted.

Figure V-4: Wheel-Sock interference region (left), and engineering development unit of Sock after wheel interference life testing.

VI. Lessons Learned

The VIPER mission was focused on low-cost and rapid execution, resulting in significant limitations in design and testing resources. The authors believe a robust design has been developed for VIPER's mission profile and risk tolerance but want to highlight deficiencies that will need to be addressed for longer duration lunar missions.

- The materials chosen for the space-rated softgoods likely do not have elasticity to them, making the design of the softgoods challenging around moving mechanisms. Load paths are difficult to identify and evaluate through the flexible substrates.
- When evaluating the integration of softgoods on hardware, a set of transparent softgoods can lend insight to how internal equipment is operating over the course of testing.
- Thermal insulation performs best in static applications. The integration of a thermal blanket in an inherently dynamic product required increased margins to maintain thermal performance.
- Across the mechanism designs, gaps where dust ingress is possible were not assessed for any specific debris size. These gaps were instead left generously large for manufacturing purposes. (This comment applies to all labyrinth designs as well.) Future work may include the evaluation of gap size in the effectiveness of labyrinth seals.
- The application of labyrinth seals on the steering pins are 1) poorly oriented and allow debris falling in the gravity direction to enter the sealed volume, and 2) likely would have performed better if replaced as compressed Nomex face seals (including simpler manufacturing geometry).
- The design of lug and clevis connections have proven difficult to integrate with labyrinths due to installation geometry.
- The Nomex seal designs were suboptimal in terms of aspect ratio. Several issues had to be resolved during integration due to the difficulty in retaining them in position.
- Harnesses also need to flex across the dynamic joints of the mobility module. And while harnesses and the softgoods are both soft and flexible articles, they do not flex due to the same mechanics and have different physical anchors. As such, during development the harnesses and softgoods often strained against each other, requiring additional slack in the softgoods and stiffening of the harnesses at specific locations.
- Expect and test for impact of the hardware to the softgoods but also the softgoods to the hardware for added resistance and range of motion restrictions. Just like in software, include margins for range of motion, such as the difference between a softstop and a hardstop, into the softgoods design requirements.
- Interferences are best to be avoided but, in some cases, the trade space does not allow it. Test for worst case as was done here in the wheel interference testing.
- Test and qualify assemblies as one. Do the best to identify gaps in the test matrix and try to avoid areas where an incomplete part of an assembly is tested. Note, it can be impossible to identify all gaps within a test matrix, so default to testing all components in the assembly as the test allows to cover uncertainties.
- It is very difficult to quantitatively define expected dust exposure to a mechanism. VIPER's approach was to overdesign for dust mitigation and perform very conservative tests with regard to dust exposure.

Significant future testing should be performed to understand the functional differences between each sealing strategy (labyrinth, felt, spring energized PTFE, grease damming, etc..) as well as understanding the design variables of each seal (e.g. the effects of compression and width of a felt seal).

VII. Conclusion

VIPER's multi-pronged approach to dust mitigation leveraged a defense-in-depth strategy to limit the risk of lunar regolith and dust to mission-critical components. Combining the benefits of stacked local seals throughout the actuators' design allowed the utilization of each seal's best attributes while minimizing their limitations. The global barrier, or Sock, is the first layer of defense against the hazards of the lunar environment's regolith and rocks. The Sock includes protection against temperature extremes as it fully integrates a thermal insulation blanket on the mobility appendages. Use of softgoods did require more iterations of the design and due to the complexity of the templates, required a hands-on approach with experts from NASA Johnson Space Center's Softgoods Lab. New material substrates were developed for the Socks based on heritage thermal materials combined with the experiences of making softgoods for on-board the International Space Station (space suits, tools, and storage).

VIPER's required mission life is only one lunar summer on the south pole, and while it is exposed to a great deal of environmental extremes, it is not expected to survive beyond the sun setting on the pole. Its short mission duration and higher risk posture of a mission without a human crew gave wider allowances of contested trade spaces. The

Artemis program currently plans to utilize several more mobility systems with faster drive speeds and heavier roving masses. These scaling of functions all pose significant challenges to dust mitigation, as wear on mechanisms will be accelerated if sufficient sealing cannot be achieved. Therefore, dedicated thoughtful dust mitigation designs must be carried out with appropriate verification testing. Should materials and design be considered from VIPER to components of the Artemis missions, a more thorough campaign is needed to show its ability to survive beyond VIPER's limited testing.

Acknowledgments

To the VIPER team: Throughout the years of development and integration many hardships were met and overcome. The amount of creativity and dedication this team showed time and time again is nothing less than an amazing inspiration. It's been a dream to work alongside you all. VIPER's future is still not clear, but per aspera ad lunam!

The wider NASA community is full of committed civil servants and contractors who contribute happily to any project in need of their expertise. The authors thank the many subject matter experts for their contributions to the VIPER project and its dust mitigation efforts.

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