Motors for Dusty & Extremely Cold Environments (MDECE) Project

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Motivation

- Rotational actuators for Space mechanisms require a mechanical gearbox to meet mass, volume requirements
- Mechanical gears require lubrication to achieve satisfactory performance & life
- SOA approaches for temperatures < -60 °C:

Current Approaches	Current Penalty
Heat gearbox/motor to ≥ -60 °C & use grease lubrication	Increased complexity & mass, less power for science
Use dry film lubricant on contacting surfaces	Reductions in life design constraints on load & speed *(often significant)*

- **This is a pervasive problem** – *potential for big impact*

Mechanisms Affected
Rover wheels
Solar arrays
Gimbals
ISRU (drills, buckets, etc)
Robot arms
…

Environments Affected
Lunar surface
Lunar Gateway
Mars
Europa
Titan
…

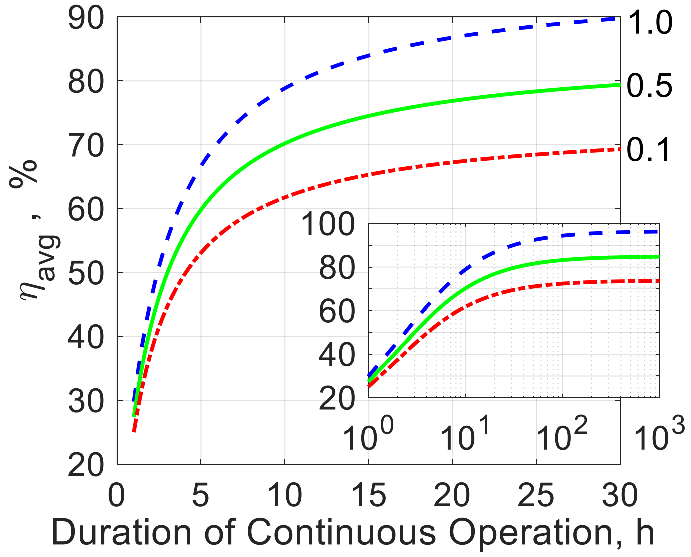
Motivation

Quantified the impact of heating conventional, grease-lubricated actuators in lunar permanently shadowed region (PSR) using *new, intrinsic metric*

- Average total efficiency = avg. of (mechanical power output) / (heater power + power input to produce torque)

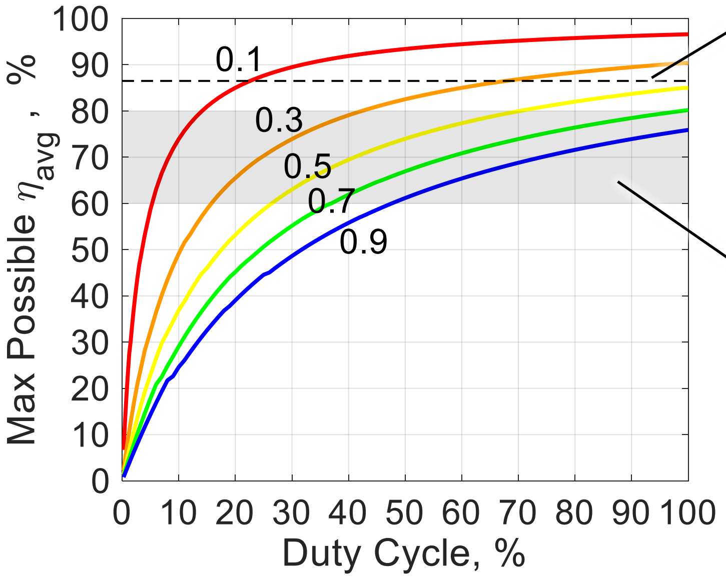
Con-ops case 1 – short duration (< about 100 hours) continuous operation after heating from survival

Change in average total efficiency over time for different emissivities



Con-ops case 2 – long duration (> about 100 hours) operation with constant duty cycle

Maximum possible average total efficiency for duty cycle operation & different emissivities



Dashed line – Current best estimate of MDECE magnetic actuator's efficiency

Gray region – MDECE magnetic actuator key performance parameters for efficiency

1. Scheidler, J.J. et al., The Impacts of Heating Actuators in Extremely Cold Space Environments, *Proc. IEEE Aerospace Conference*, Big Sky, MT, 2022.

MDECE Overview

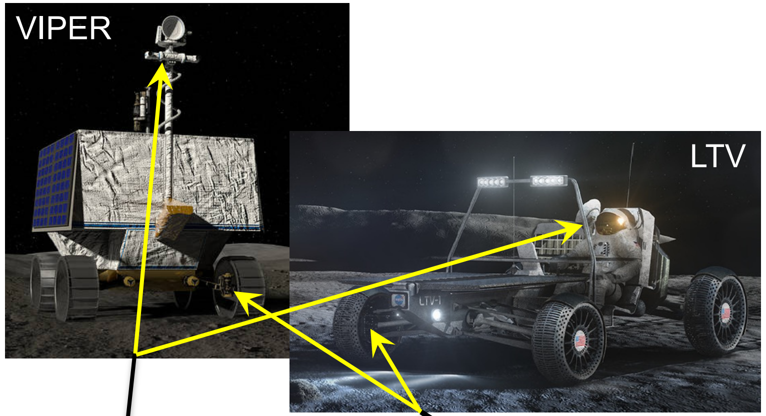
- **R&D & ground test project, Oct 2021 – Sep 2024**
- **Goal:** Develop 2 unheated rotational actuators that can operate for a long duration in extreme cold (ambient temperature of -243 ºC (30 K))
  - Evaluate life in controlled, representative lunar dust environment
- **Approach:** Eliminate gear lubrication – 1 actuator with non-contact gearing, 1 actuator with no gears
- **Scope:**

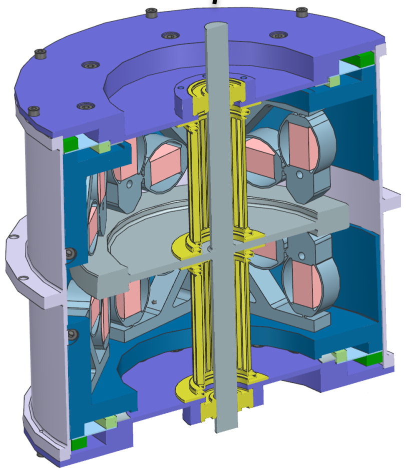
In scope
- Compatibility with drive/controller
- Relevant environment testing
- Lunar dust impact on life
- Testing COTS actuator components

Out of scope
- Bearings
- Dust seals
- Dust mitigation tech

- **Key Performance Parameters:** Min. operating temperature ▪ dust-free life ▪ efficiency of magnetic actuator ▪ output resolution of piezoelectric actuator
- **Relevant environment:** Broadly applicable; focusing on lunar PSR
- **Promising applications:**
  - Magnetic actuator: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - Piezoelectric actuator: precision pointing (e.g., laser communication) ▪ low power robotic arm joints

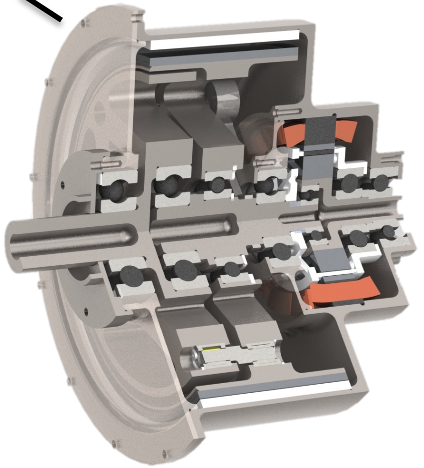
Example mechanisms for demonstrating prototypes (NASA KSC)





Piezoelectric actuator preliminary design (JPL)

[graphic courtesy of NDEAA team / JPL / Caltech / NASA (Patent pending)]



Magnetically-geared actuator preliminary design (NASA GRC & GSFC)

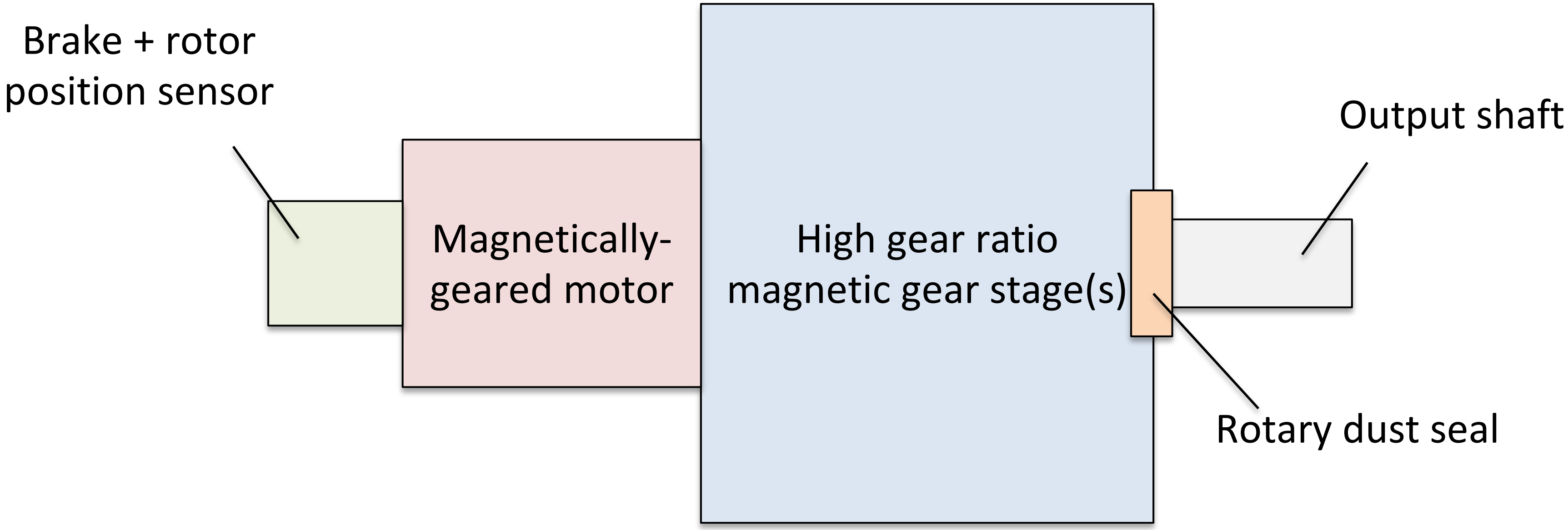
Why Can't We Design Away the Importance of Dust Testing?

- Multiple applications of current interest will exceed or far exceed flight proven life of lunar dust seals

Lunar rover	Wheel drive actuator life in output revolutions	
	Design life	Achieved life before end of mission
Lunar Roving Vehicle (US)	~46,700	~13,900
Lunokhod 1 (USSR)	?	~6,600
Lunokhod 2 (USSR)	?	~24,500
YuTu-1 (China)	Roughly 1,100 to 15,900	~120
YuTu-2 (China)	Roughly 1,100 to 15,900	~550 (as of Aug 2020)

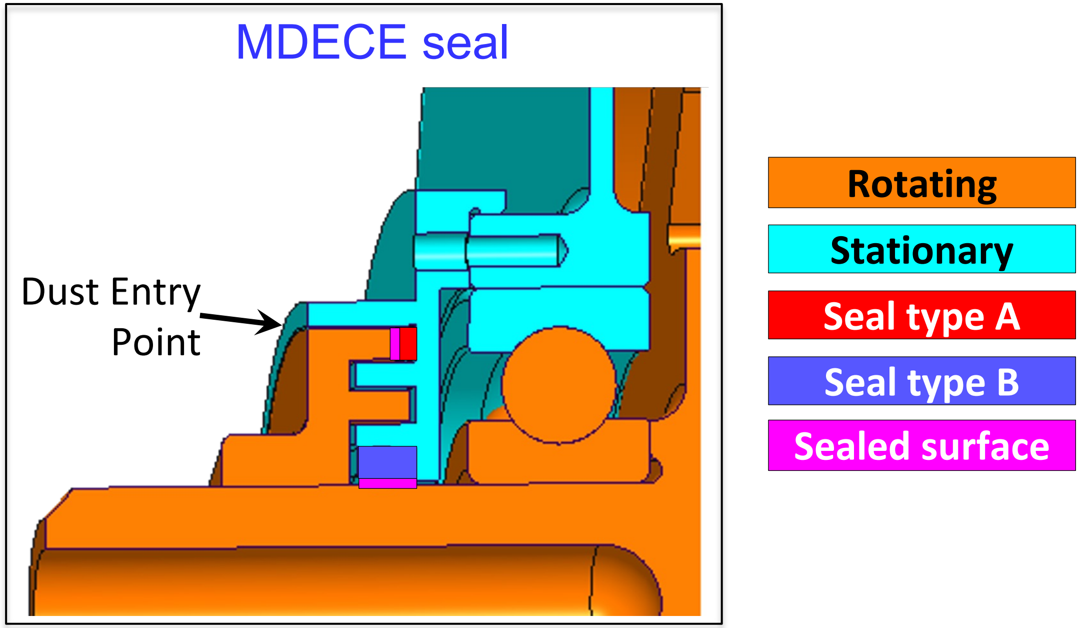
- Sealing effectiveness will improve if number of seals increased or preload on seal increased, but…
  - Seal wear rate expected to increase (life expected to decrease)
  - Seal drag torque and heat generation will increase
  - Although mass and volume increase may be acceptable, must also consider impact on reaction loads applied to mechanism or actuator
- Lower torque actuators more susceptible to increases in drag torque, although somewhat mitigated by reduced dust ingestion area
  - Current best estimates for baseline seal design of MDECE actuator:
    - Drag torque of *each* contact seal is 0.11% / 0.05% of continuous / peak output torque
    - Heat generation of *each* contact seal is 0.6% / 0.3% of continuous / peak heat load

MDECE Magnetic Actuator Configuration

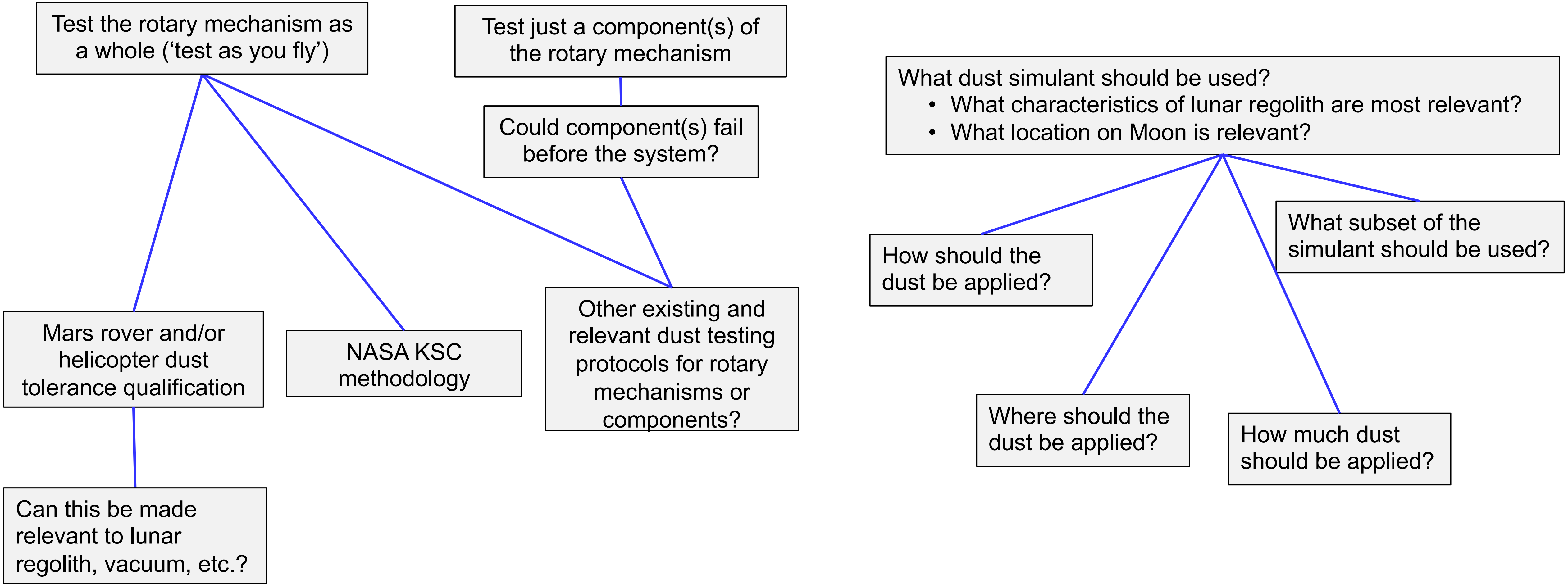


MDECE Magnetic Actuator – Dust Seal Design

- <u>Design objective</u>: meet life goal with minimal mass & loss
- Rotary seal effectiveness not well-quantified, but promising preliminary results from NASA testing by others in similar conditions (vacuum, cold, dust exposure)
  - Seals intended to be readily replaced if needed for actuator life test – seal not in critical path.
  - Design considerations for cryogenic operation in work – expected to impact interference fit specifications due to wide operating temperature range requirement.
- Shaft surface roughness & hardness requirements manageable
- Expected that internal pressure can escape through seals upon reaching vacuum environment to balance pressure



Open Questions for Actuator & Mechanism Developers



Rotary Actuator Testing in Lunar Simulant

NASA-STD-1008: Classifications and requirements for testing systems and hardware to be exposed to dust in planetary environments (9-21-2021)

- **Does** provide thorough overview of sources of dust, simulant preparation and storage
- **Does** recommend minimum set of dust simulant characteristics to consider for mechanism testing
- **Does** provide guidance on how much dust to apply on external surfaces (i.e., for system testing)
- **Does** suggest 2 methods for applying dust to an exposed surface
- Component testing guidance focused on friction and wear testing of dust-loaded grease or lubricant

Additional testing guidance required in the future (perhaps a future standard) to cover Rotary Actuator Testing in more detail, must include:

- **Notional Indication** of how much dust may infiltrate past certain types of seals
- **Recommendation** on where to apply dust
- **Recommendation** on how to apply dust on dry film lubricated contact surfaces that are internal to a mechanism
- **Recommendation** on how to consider unlubricated areas of concern (e.g., gap between rotating and stationary components)

MDECE Magnetic Actuator – Dust Simulant Selection

Specific dust requirements must be determined based on the actuators' operating regime and the location on the lunar surface.

Basis for Primary Important Lunar Simulant Requirements:

Particle Shape/Composition: Lunar dust abrasion is expected to be a potentially critical life-limiting factor for bearings and seals.

Particle Size: Dust infiltration is also a potential life-factor, simulant particle size distribution is critical for seal effectiveness and bearing life.

Magnetic Properties: The presence of strong magnetic fields in the gearbox dictate that simulant magnetic properties are important.

Electrical Charge: The presence of strong electrical fields in the motor dictate that simulant electrostatic properties are important.

MDECE's magnetic actuator's intended application and location are a water ice prospecting mission on the Moon's south pole.

Magnetic constituents in south pole dust

Magnetic component	Concern	Rationale	
		Abundance	Magnetic properties
Metallic iron (Fe)	High	0.4-0.8 wt% [CBE]	μ_r 1e4 [CBE] (size ≤ 30 nm) 1e4+ (size > 30 nm) M_s 100% of iron
Magnetite (Fe_3O_4)	Mid	[TBD]	μ_r ≈ 650 (size ≤ 20 nm) 2.5-6.5 (size > 20 nm) M_s 2.4% of iron
Hematite (αFe_2O_3)	Low	1-10 wt% not typ. at ≥ 85 °S rare on far side rare on crater floor	μ_r ≤ 1.2 M_s 0.05-0.12% of iron
Ilmenite ($FeTiO_3$)	Low	≤ 1 wt% [CBE]	μ_r 1.3-4.5 [CBE]

μ_r = relative magnetic permeability = 1 + susceptibility

M_s = saturation magnetization

MDECE Magnetic Actuator – Dust Simulant Selection

Dust Impact Assessment**

Dust Class ID **PE-L:1-500-36-2,5,6,8**

Working Dust Environment: PE = Planetary External

Planetary Body: L = Lunar

Dust Loading Vector: 1 = Surface Accumulated

Particle Size Range: 500 = Max particle size (micron)

Dust Loading: 36 (mg/m^2) (assumed over 10 years)

Test Categories:
2 = Abrasion/Wear
5 = Mechanism
6 = Seals
8 = Electrostatic

Preliminary selection of lunar dust simulants

Test	Simulant	Rationale
Abrasion	lunar polar simulant with ~30% agglutinates (Off Planet Research (OPR) OPRH4NW30)	• Highlands more relevant than Mare • Highlands minerals all have similar hardness • Higher fidelity & more relevant to south pole than typical recommendation for abrasion testing (BP-1)
Piezoelectric actuator		• Abrasion test rationale • Can develop realistic electric charge
Magnetic actuator	OPR simulant OPRH4NW30 + magnetic agglutinate additive	• Abrasion test rationale • State of the art for capturing magnetic properties

** Per NASA technical standard NASA-STD-1008

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THANK YOU


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Concept Description – Magnetically-Geared Motor

(GRC/Justin Scheidler)