Lunar Dust Effects on Space Mechanism Ball Bearings for Sustained Human Lunar Operations

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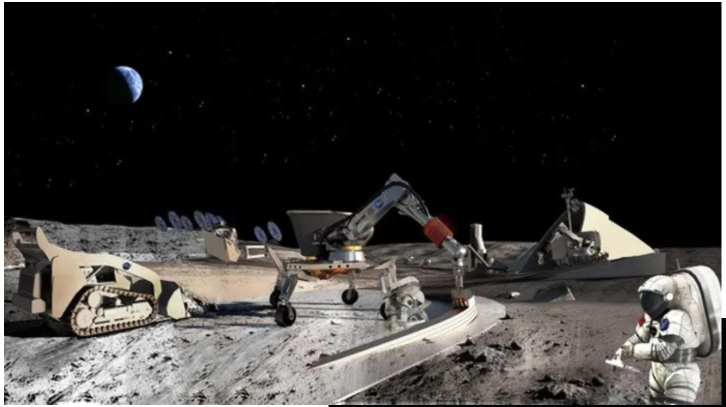
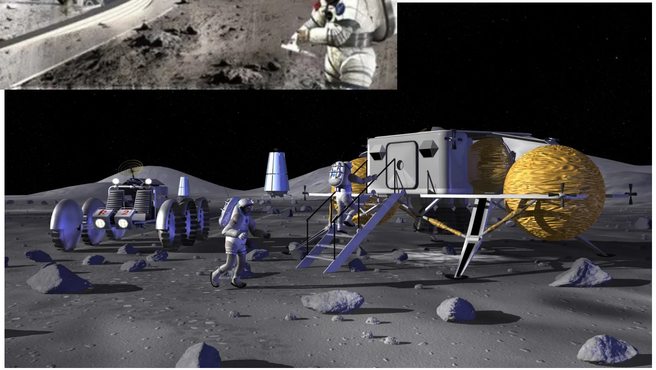
NASA Lunar Surface Operations - Background

- NASA's Artemis Program: Launched in 2017 - Human Spaceflight Program with goals to:
  - Land Humans on the Lunar Surface by 2025
  - Establish a Sustained Human Presence on the Lunar Surface
  - Enable Extraction of Lunar Resources
  - Lay the Foundation for Eventual Human Access to Mars





Artist Renderings of Conceptual Lunar Outposts. (NASA)

NASA Lunar Surface Operations - Background

- Apollo-Era Lunar Operations Lessons Learned:
  - Lunar ”dust” is pervasive – fine, hard, abrasive particles made of lunar regolith (soil)
  - Observations from Apollo astronauts:
    - “…you’re continually fighting the dust problem both outside and inside the spacecraft…it inhabits every nook and cranny in the spacecraft…” Gene Cernan, Apollo 17 Commander.
    - Sealing issues and sticky mechanisms took place on the Moon and return flights

Example sources of dust production, lofting,and distribution. (NASA)

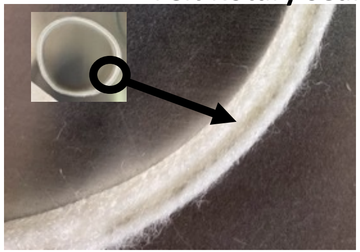
(Source: NASA/TM-2009-215821)

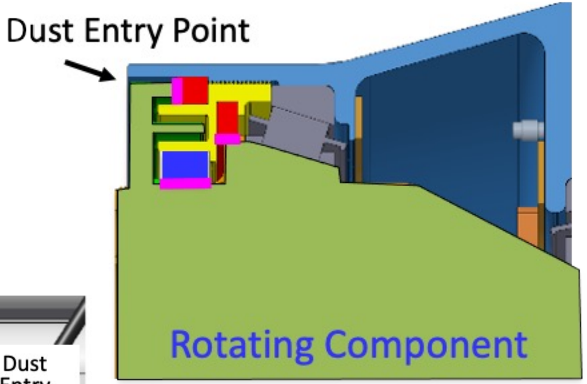
NASA Lunar Surface Operations - Motivation

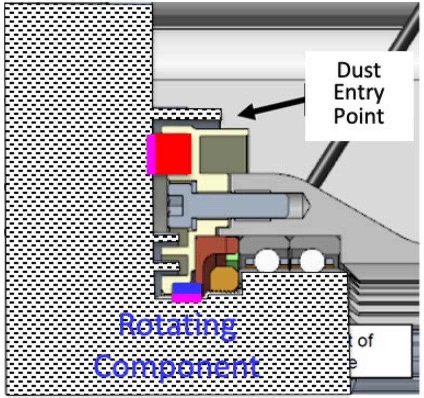
- Lunar Dust is Expected to Present a Significant Tribology Challenge for Space Mechanisms on the Lunar Surface:
  - Lubricant contamination
  - Bearing damage (focus of this work)
    - Increased torque
    - Reduced life
    - Degraded smoothness
    - Bearing jamming (rotation prevented)
  - Seal Damage
    - Rotary and non-rotary
    - Wear of sealing surfaces
    - Damage to coatings
    - Degraded seal performance

Example/notional components vulnerable to dust contamination

Felt Rotary Seal







Lunar Dust Effects - Objective

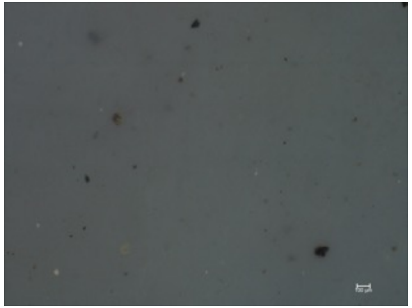
Two Primary Goals: Characterize and Mitigate the Effects of lunar Dust on Bearings

- Characterize the extent and nature of lunar dust damage on Commercial Off-The-Shelf (COTS) bearings
  - Test bearings with known lunar dust contamination in lubricant
  - Test bearings with clean lubricant in dust exposure conditions
  - Visually inspect bearings for damage
  - Test exposed/damaged bearings to torque measurements
  - Life test bearings after exposure/damage
- Develop/identify strategies to reduce/mitigate lunar dust damage
  - Test potential concepts for dust resistance or tolerance improvements over COTS bearings
    - Seals
    - Bearing materials
    - Coatings
    - Barriers/Traps
    - Other
  - Disseminate results to aid in development of best practices for the dust community

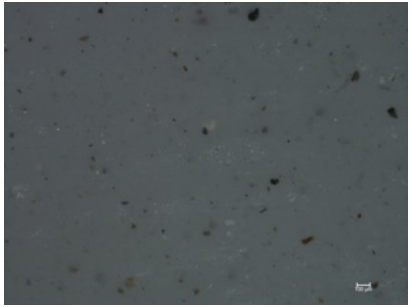
Lunar Dust Effects – Characterization Testing

- The current phase of lunar dust testing is focused on characterizing damage from dust-laden grease –to represent bearings that have suffered dust infiltration
- R8 size bearings (0.500" bore) are utilized
- Earth-based simulant is used to represent lunar regolith dust as lunar material is not readily available
    - Simulant is manufactured by Off Planet Research (type OPRN4W30)
    - Simulant is engineered to replicate the chemical and physical make-up of lunar highlands regolith
        - Chemical make up of 90% anorthosite and 10% basaltic cinder
        - Physical make up of 70% powder and 30% agglutinates (a hard glassy form resulting from micrometeorite impacts).

Rheolube 2000 with 2% OPRN4W30 Simulant by Mass

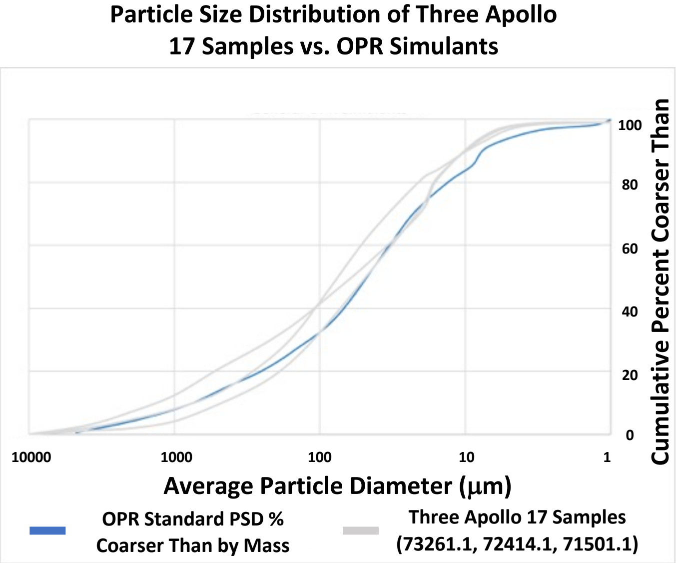


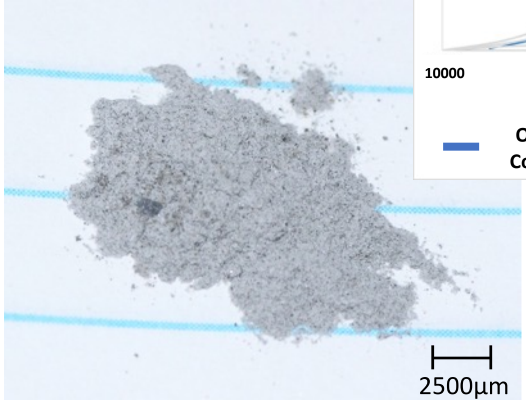
Rheolube 2000 with 6% OPRN4W30 Simulant by Mass



Lunar Dust Effects – Characterization Testing

- Lunar Dust Simulant is Mixed into a Vacuum/Space Grease (Nye Lubricants Rheolube 2000)
- Various mixtures tested:
  - 2% simulant by mass
    - As-received (i.e. not sieved)
    - Sieved to ≤ 125 micron (number 120 sieve)
    - Sieved to ≤ 20 micron (number 635 sieve)
  - 6% simulant by mass
    - As-received (i.e. not sieved)
    - Sieved to ≤ 125 micron
    - Sieved to ≤ 20 micron



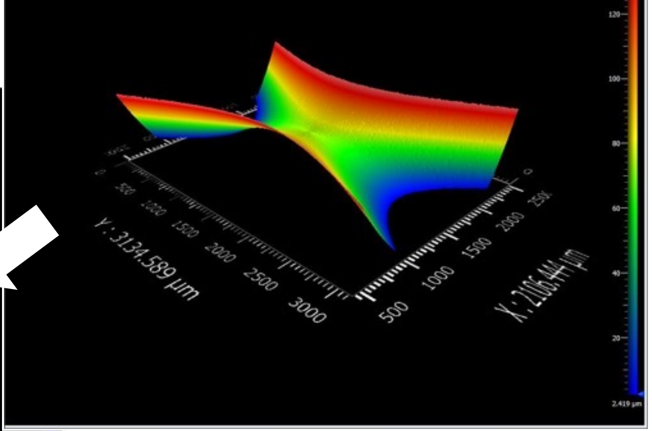


Lunar Dust Effects – Characterization Testing

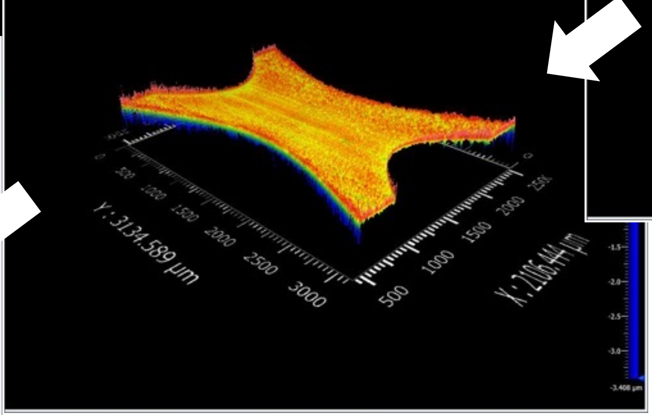
- Bearings filled to approx. 30% fill by volume (0.30g lube plus simulant)
- Bearings installed in belt-driven spindle with two bearings spring-preloaded against one another
  - Axial preload wave spring generates ~35 N (8.0 lb) of axial preload
  - Belt drive applies ~44 N (10 lb) of radial load to drive-end bearing
    - Drive-end bearing is under test, opposite end is slave bearing
- Operating speed = 1000 RPM
- Run time = 5 hours (300,000 revs total)

Lunar Dust Effects – Characterization Testing

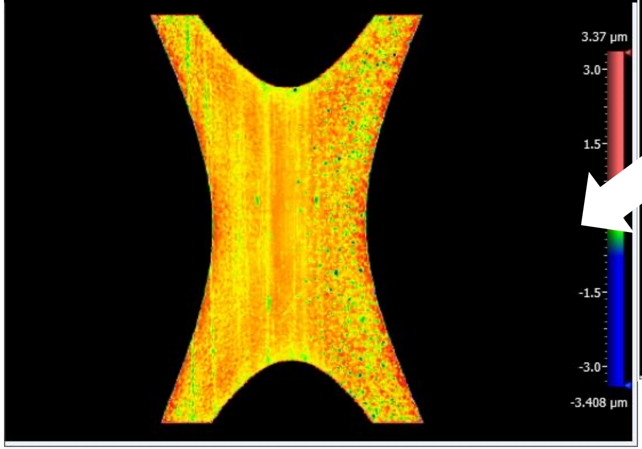
- Bearings disassembled and inspected after 300,000 revs
- Inspection included:
  - General Visual Inspection
  - Optical Microscopy
  - 3-D Optical Profilometry



3D Optical Profile of Bearing Top Dead Center



3D Optical Profile with Form (Curvatures) Removed



Top Down View with Form Removed

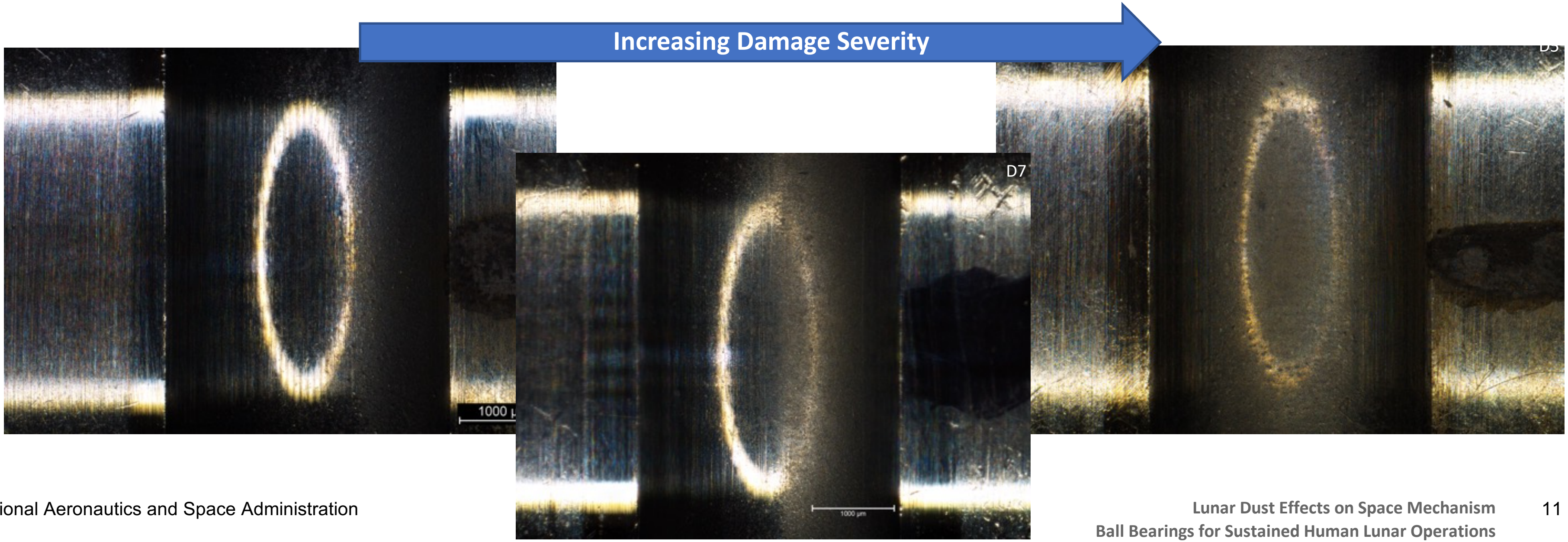
Lunar Dust Effects – Characterization Testing

- Visual Inspection Results:
  - In general, all bearings tested with simulant-contaminated grease exhibited damage easily visible with the naked eye
  - Relative degrees of damage were somewhat distinguishable, ex: minor vs severe, but only qualitative
  - Visual inspection is not extremely useful aside from verification that damage did occur

Inner Race showing visual appearance of wear

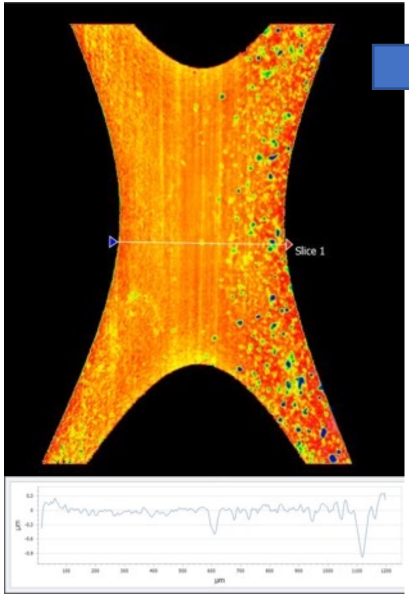
Lunar Dust Effects – Characterization Testing

- Optical Microscopy Results:
  - Microscopy was found to be useful for determining the extent of damage
  - Under low magnification (~4x), width and density of damage is easily determined
  - Quantitative assessments not readily possible

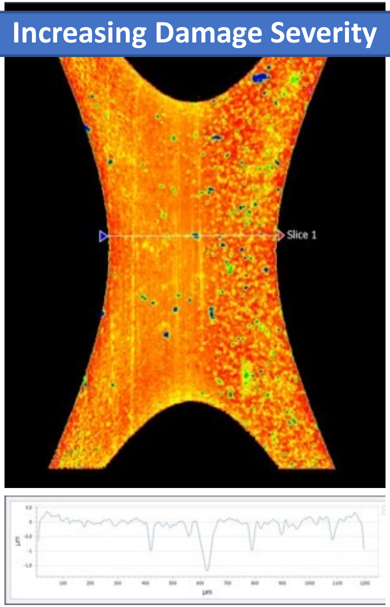


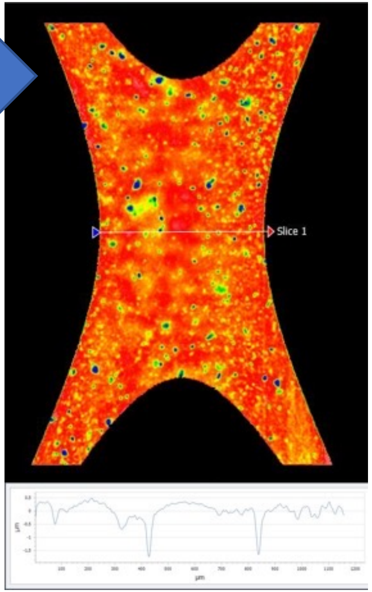
Lunar Dust Effects – Characterization Testing

- 3-D Optical Profilometer Results:
  - Optical Profilometry can provide quantitative measurements of damage on bearing inner races
  - Magnification (2.75x), focal length scan (145 µm, depth of field)



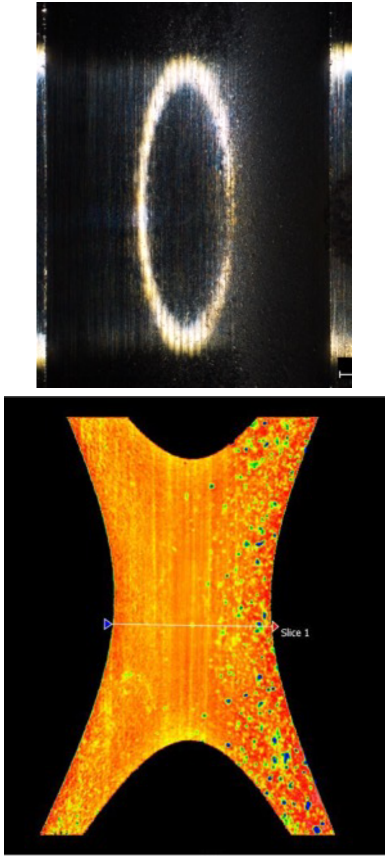
Increasing Damage Severity

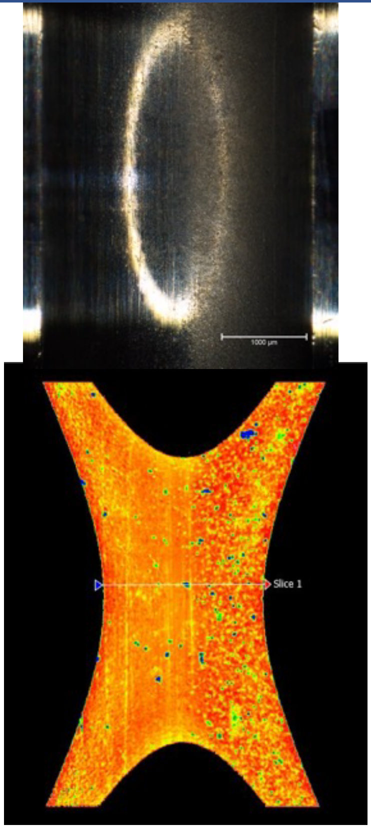


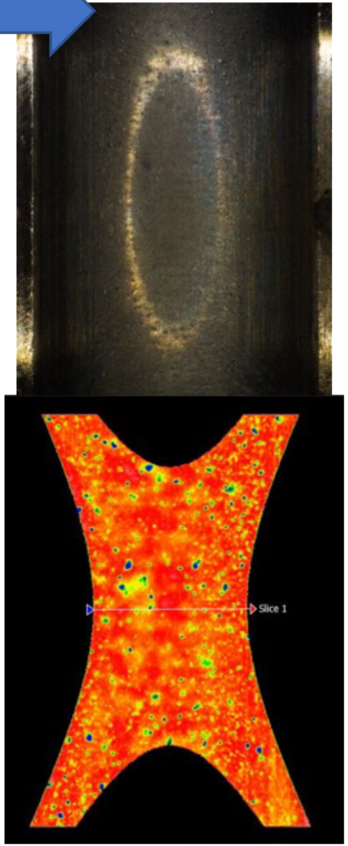


Lunar Dust Effects – Characterization Testing

Increasing Damage Severity



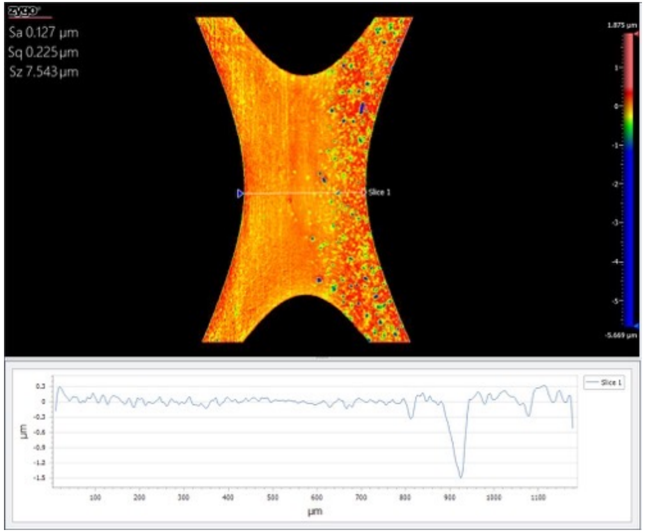




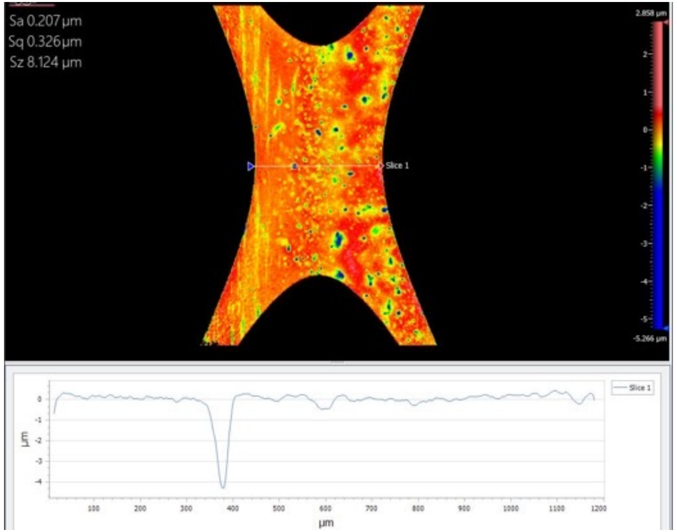
Lunar Dust Effects – Preliminary Results

- Effect of Contamination Level ("Dirtiness") with raw simulant (unsieved):
- 2% simulant vs 6% simulant by mass:

2% Simulant



6% Simulant

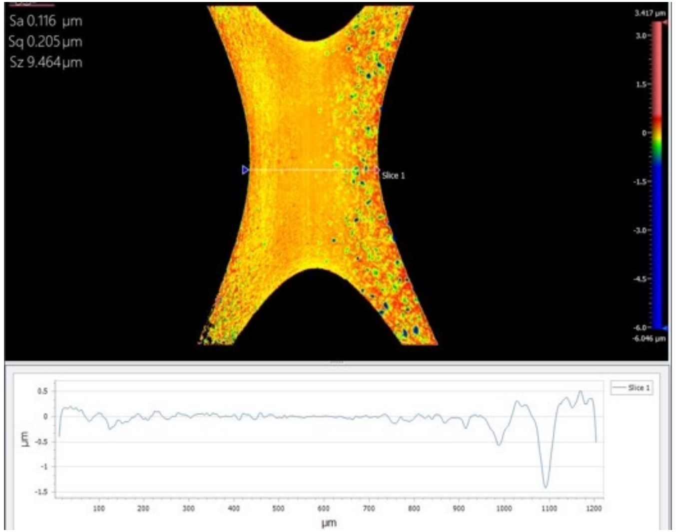


- Lower level of contamination results in more localized damage – biased toward the axial load direction
- Higher level of contamination results in more global damage –

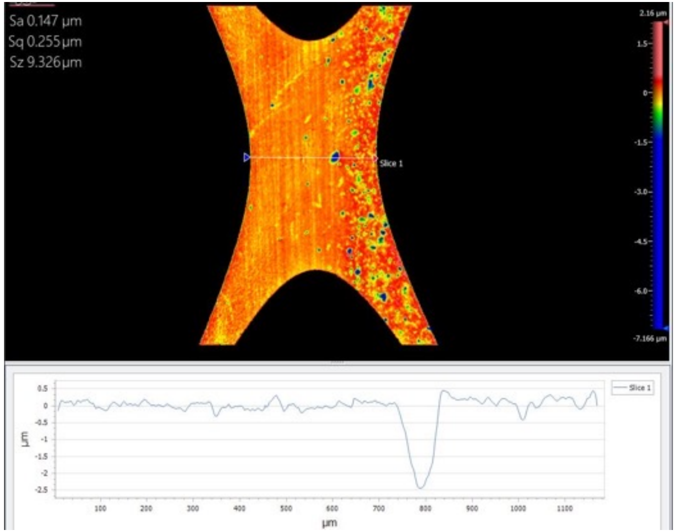
Lunar Dust Effects – Preliminary Results

- Effect of Ball Material – Steel vs. Ceramic (440C vs. Si3N4):

440C Balls



Si3N4 Balls

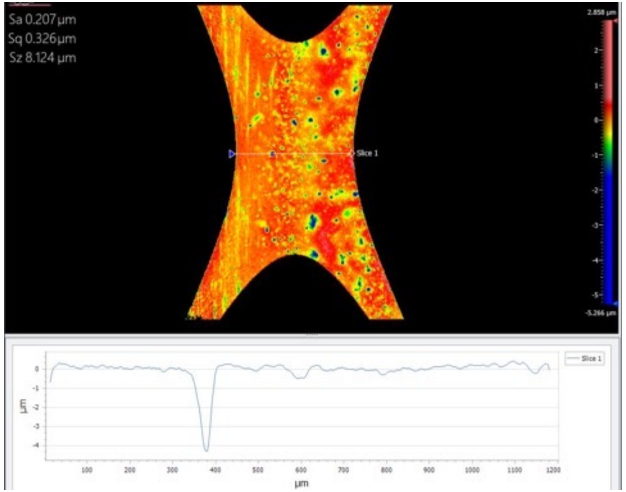


- Bearing with ceramic balls has slightly more severe damage – pattern is similar, but density and depth of dents are increased
- Higher contact stress - possible cause?

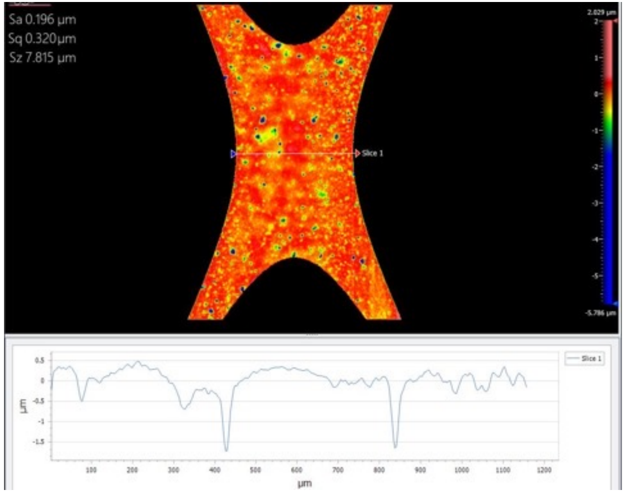
Lunar Dust Effects – Preliminary Results

- Effect of contamination particle size: (6% contamination)

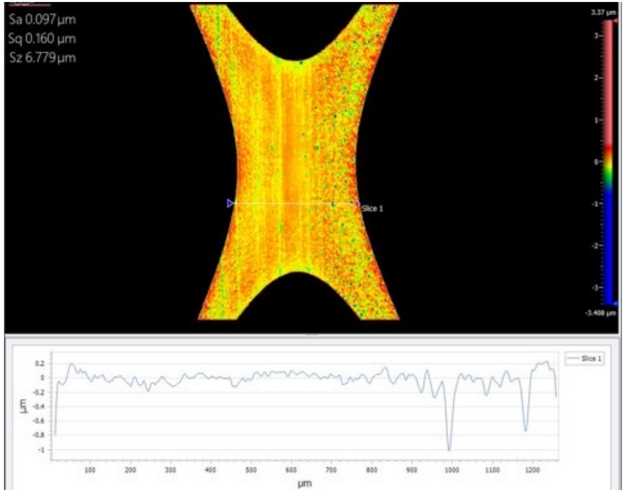
Un-sieved Simulant



Sieved to ≤ 125 µm



Sieved to ≤ 20 µm

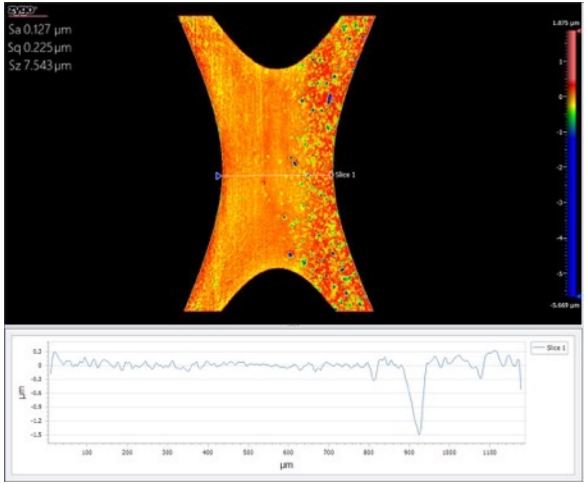


- For heavy contamination, particle size seems to track with damage – larger particles cause more damage compared to smaller particles.
- Smaller particles result in a larger quantity when contamination mass is constant – more smaller dents vs. fewer larger dents.

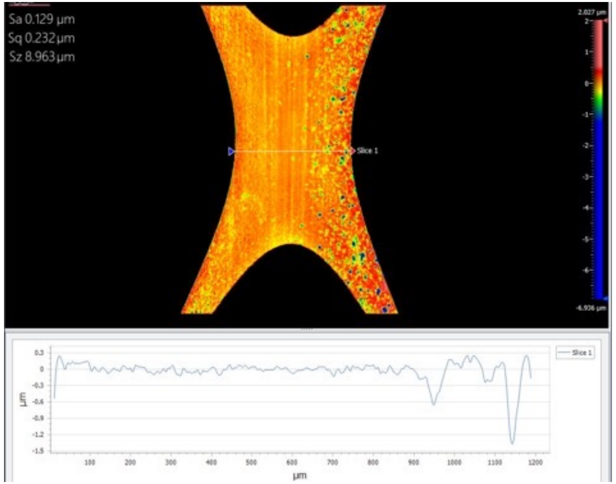
Lunar Dust Effects – Preliminary Results

- Effect of contamination particle size: (2% contamination)

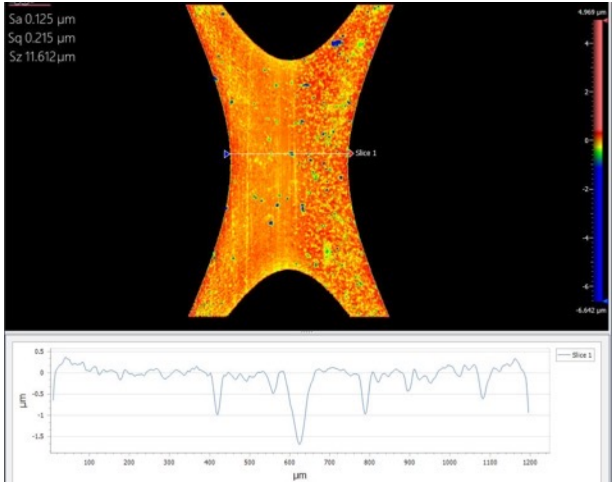
Un-sieved Simulant



Sieved to ≤ 125 µm



Sieved to ≤ 20 µm



- For lighter contamination, particle size does not seem to track with damage – damage appears very similar regardless of particle size.

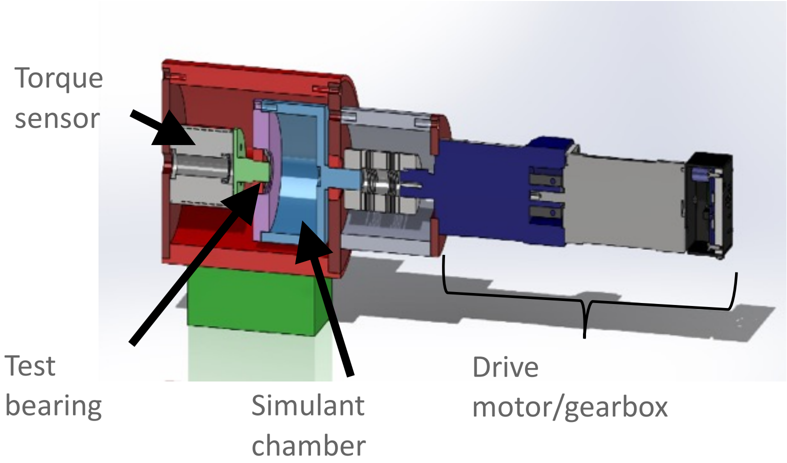
Lunar Dust Effects – Summary

- Optical Microscopy and visual inspection can give quick indications of relative damage
- 3-D Optical Profilometry gives the most quantitative insight into bearing damage due to lunar simulant contamination.
- Contamination level has a strong effect on bearing damage, and is observable with all three techniques.
- Rolling element material (steel vs. ceramic) did not appear to have a strong effect on bearing damage.
- Particle size had a proportional effect on damage (larger size = more damage) for heavy contamination, but less obvious effect for lighter contamination.

Lunar Dust Effects – Future Work

- Conduct additional replicates of previous tests – investigate repeatability/variability from test to test
- Run life tests with contaminated grease
- Run bearing tests with clean grease in dirty environment chamber to assess how much contamination is possible in a lunar simulated environment

New test Rig for Exposing Bearings to Lunar Simulant Currently in Build-up

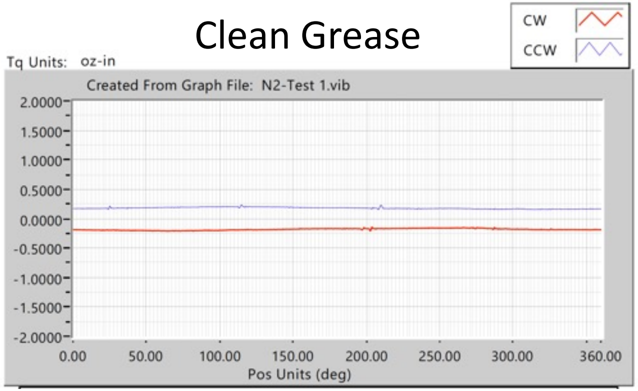


Lunar Dust Effects – Future Work

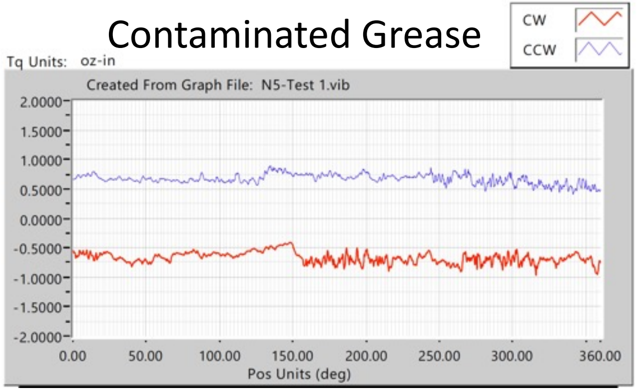
- Measure running torque with various contamination levels
- Track torque vs. time

Example Torque Data

Clean Grease



Contaminated Grease



Bearing Inspector – Measures start up and running torque

Data provided by Robert Searle, Vibrac, Inc. with bearings supplied by NASA GRC

Thank You

Questions?

NASA