The Need for High Fidelity Lunar Regolith Simulants

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Acknowledgements

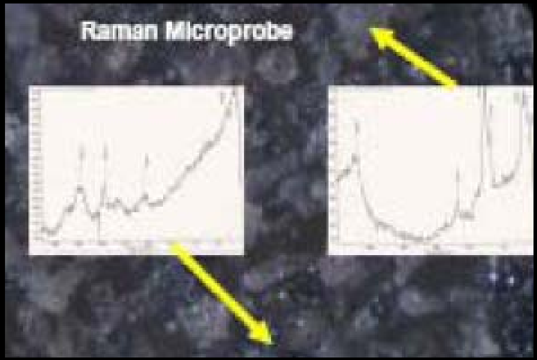
- Minor component additives
  - Aloysius F. Hepp
  - Jeremiah S. McNatt
  - Ching-Cheh Hung
- Activation
  - Randall L. Vander Wal (NCER)
  - Kenneth W. Street
  - Scott R. Panko (ARCO)
- Funding
  - GRC Internal Research and Development (FY07)

What Is High Fidelity?

- Answer dependent on application
  - ISRU oxygen production
    - Correct fraction of oxygen producing mineral
    - Correct fraction of interfering materials
  - Adhesion to spacecraft components
    - Correct size and shape distributions
    - Correct surface chemistry
    - Correct electrostatic properties
- Lunar environmental changes dust properties
  - No adsorbed water, carbon dioxide on surfaces
  - Lunar dust contains implanted solar wind
  - Lunar dust subjected to solar and galactic radiation
  - Lunar dust subjected to meteoroid bombardment
- *How high fidelity is high enough?*

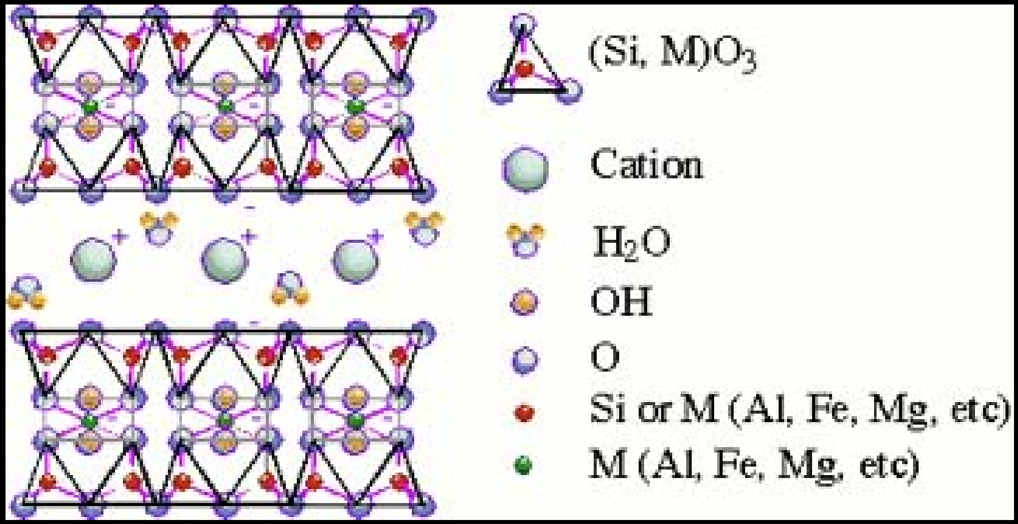
Lunar Minerals in High Fidelity Simulants

- Silicate minerals/glass make up to 90% regolith volume
  - Pyroxene - $(CaFeMg)_2Si_{12}O_6$
  - Plagioclase feldspar – $(CaNa)(AlSi)_4O_8$
  - Olivine - $(MgFe)_2SiO_4$
- Oxide minerals make up to 20% volume
  - Ilmenite – $(MgFe)TiO_3$
  - Spinel – $FeCr_2O_4$, Fe_2TiO_4, $FeAl_2O_4$, $MgTiO_4$
  - Armalcolite – $(MgFe)Ti_2O_5$
- Low abundance of native metals
  - Fe, Ni, Co
- Most sulfur contained in single mineral
  - Troilite – FeS
- Traces of many other minerals (~100)



Minerals Absent from High Fidelity Simulants

- Rare on moon (though common on earth)
  - Potassium feldspar - $KAlSi_3O_8$
  - Silica – SiO_2
- Absent on moon (because they contain water)
  - Clays
  - Micas
  - Amphiboles



Clay structure from NASA SSC on www7430.nrlssc

Lunar Agglutinate Formation

- Meteoroid strikes on the surface
  - Hottest zone underneath impact melts rock together
    - Adsorbed H, He from solar wind escape
    - Oxygen from rock vaporizes and escapes
    - Iron is reduced, vaporizes and re-deposits
    - Mineral grains structure shocked
    - Minerals melted into glass
  - Glass flows down into regolith and glues grains together
    - Forms frothy agglutinates
  - Zone beneath hot zone feels pressure
    - Fractures rock into small, sharp particles
- More agglutinates in "mature" soils

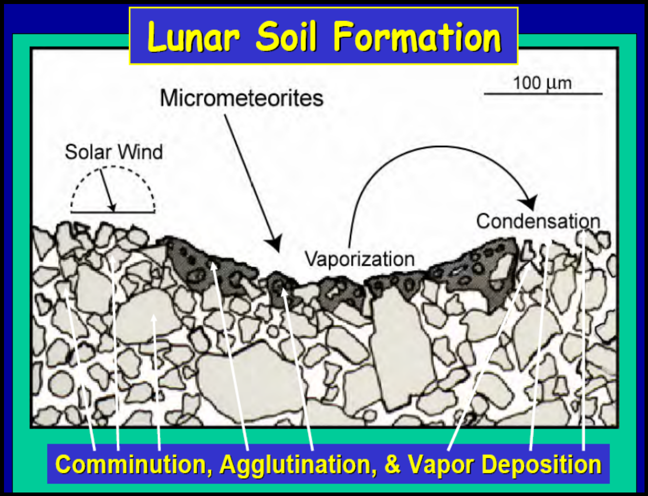
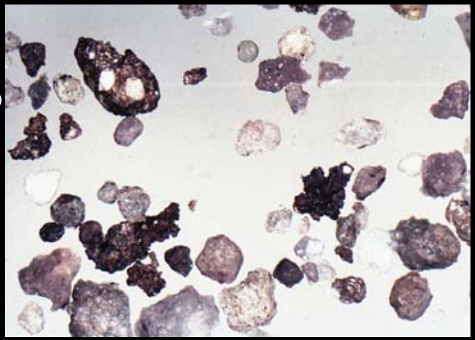


Figure from L. Taylor presentation at Lunar Simulant Materials Workshop, Jan 2005.

Properties of Agglutinates

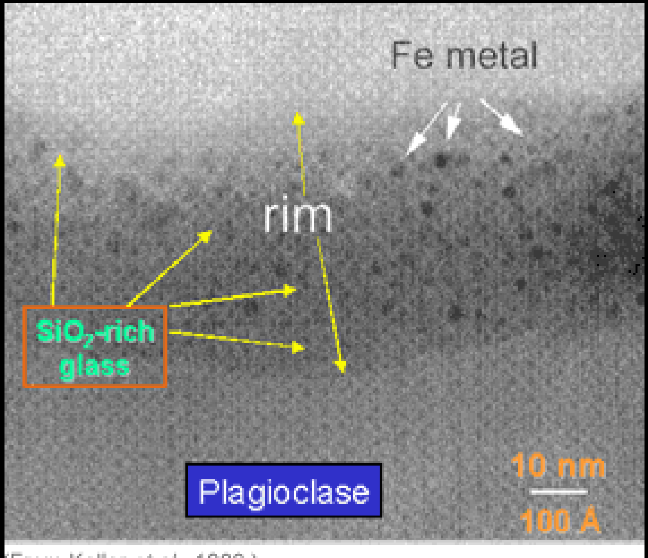
- Properties
  - Part mineral, part glass, nanophase Fe°
  - Very high surface area, low density
  - Mechanically fragile
  - Irregular surfaces
- Implications
  - Will break up when mechanically worked
    - May need to be replaced regularly in mechanical testing
  - Shape will effect adhesion
    - Few points of contact will lower van der Waals adhesion
    - Jagged edges may hook into fabrics
- Synthetic agglutinates being made
  - USGS, Orbitec, PPI



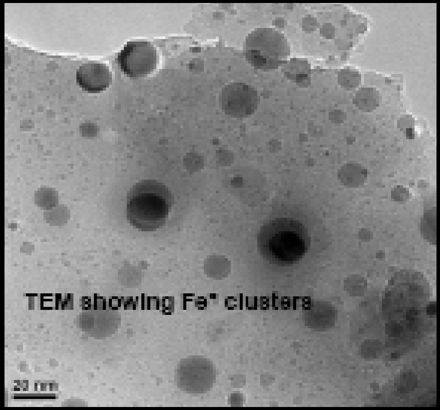
Lunar agglutinate image from Union College on www.Union.edu

Properties of Nanophase Iron

- Fe° deposited during agglutination
  - Much in glassy rinds covering surface
  - Some deposited as metal on surfaces
- Implications
  - Fe° affects magnetic properties
    - Nanophase superparamagnetic
    - Larger particles ferromagnetic
    - Good microwave absorber
  - Surface Fe° on nanoparticles toxic?
    - Enter bloodstream through lungs
- Synthetic nanophase Fe° being fabricated
  - GRC, Orbitec, USGS

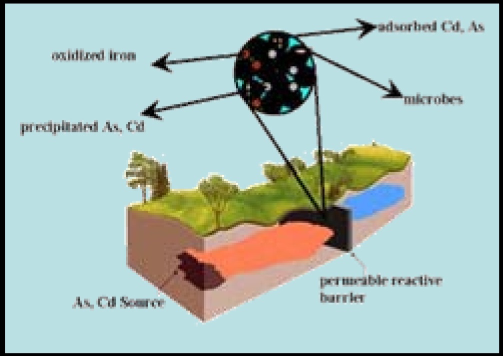


(From Keller et al., 1999.)



Properties of Lunar Sulfur

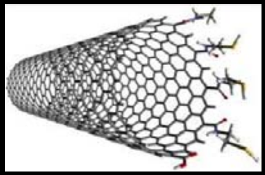
- Troilite (FeS) reactive mineral ~ 1% all lunar regolith
  - FeS rare in terrestrial surface rock
  - Must be added to simulants
- FeS can react with ISRU processes
  - H_2S and SO_2 production likely
  - Must be removed from breathable O_2
- FeS can poison catalytic surfaces
  - Fisher-Tropsch catalysts for reforming CH_4
  - Sulfur compounds may poison fuel cell catalysts
  - Nobel metals poisoned
- FeS may be a resource
  - Hayes (UM) has proposed nanophase FeS to filter toxic metals (As, Cd) from water
  - NiS or other metal sulfides in regolith?

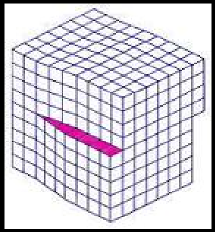


Activation Definitions

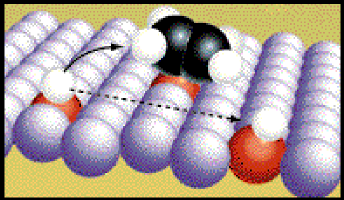
- Activated Surfaces defined:
  - A relatively large number of highly reactive surface aton

- Types of reactive surface sites
  - Free radicals – atoms with unpaired electrons
  - Dangling bonds – unsatisfied valence shell bonding
  - Crystal defects – create highly unstable, strained bonds





- Activation energy
  - Energy difference between ground state and excited state
  - Energy to remove electrons
  - Energy to displace atoms from equilibrium lattice positions
- Passivation
  - The relaxation of excited states into ground states
  - Includes reactions with foreign bodies



Space Radiation at the Lunar Surface

- About 5.8 eV will eject an e⁻ from a mineral surface
- Mineral bonds are broken by the input of 3-9 eV
- Minerals have about 10^{15} surface atoms/cm² (*)

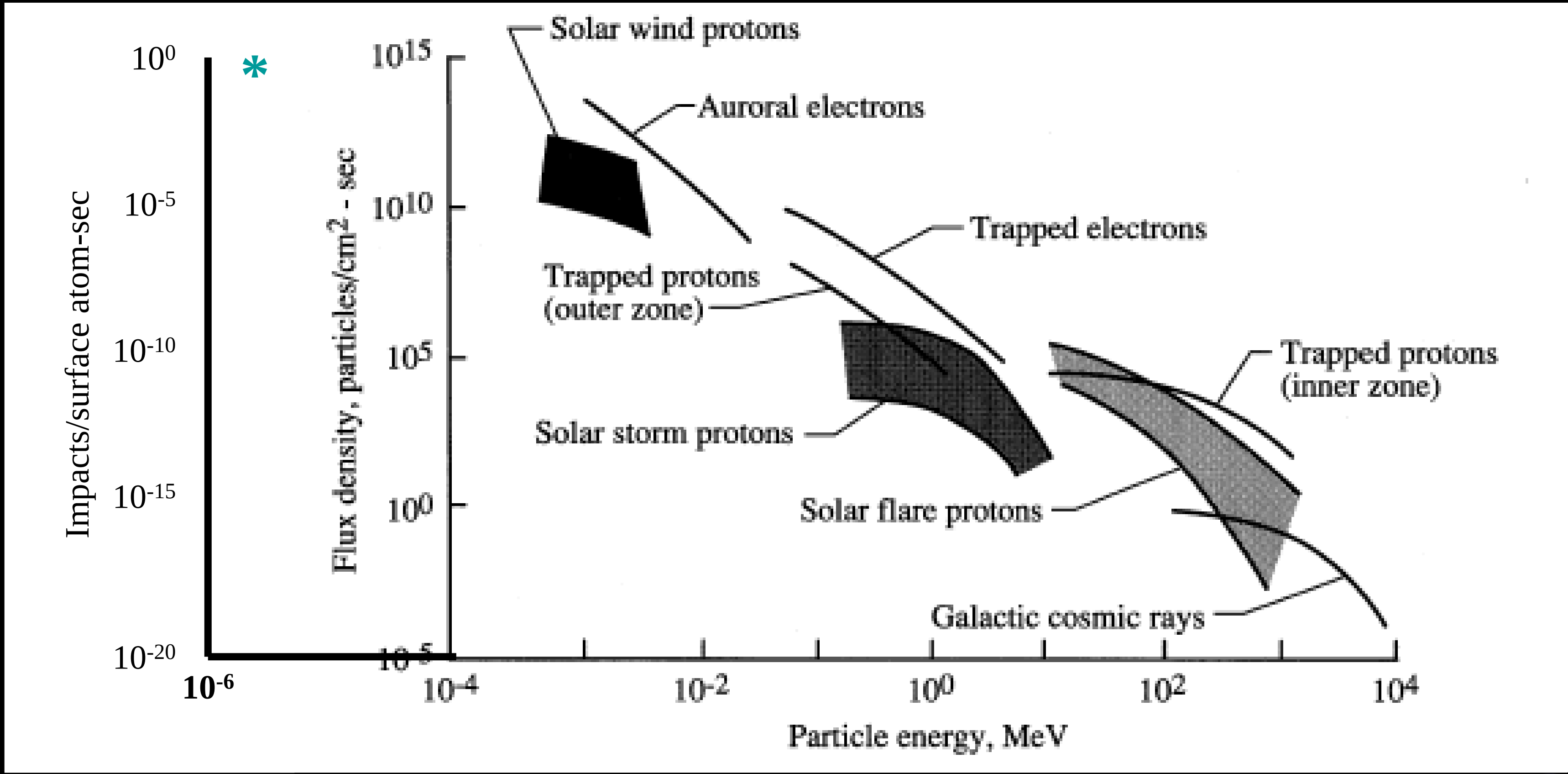


Figure derived from J.W. Wilson, et al., NASA Ref Pub 1257 (1991).

Environment Activates Lunar Regolith

- Energetic solar particles and galactic cosmic rays
  - Hard UV, x-rays, and γ-rays
  - Implantation of H^+, He^{2+},…
  - Sputtering of atoms off of surface
- Micrometeoroid strike surface
  - Fractures regolith, shocking structures
- Large thermal cycles
  - Equatorial regions range 100 – 400 K (-280 to 260 °F)
  - Polar range 210 – 230 K (permanently shadowed craters 40 K?)
- Ultra-high vacuum (10^{-12} – 10^{-14} Torr)
  - Each surface atom hit once a day by a gaseous atom
    - On earth each surface atom hit 10^8 times per second
  - Passivation of dangling bonds and defects is *very* slow

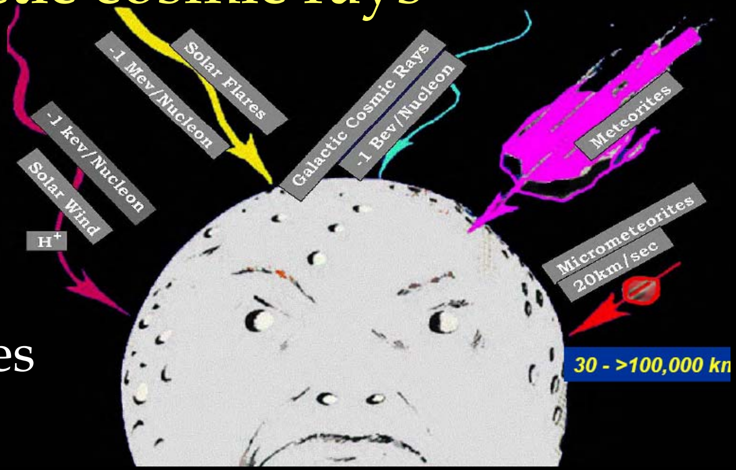


Figure from L. Taylor presentation at Lunar Simulant Materials Workshop, Jan 2005.

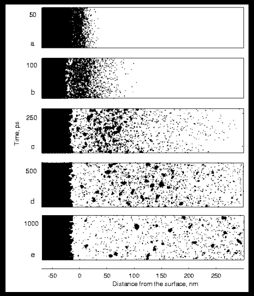
Evidence for Activated Dust

- Grossman (1970) measured cohesion in sample 10065-33
  - Porous and friable micro-breccia
  - Fractured in 7×10^{-10} Torr vacuum
  - Initial cohesion **800 dynes**
    - 4 min → **200 dynes**
    - 15 min → **~ 0**

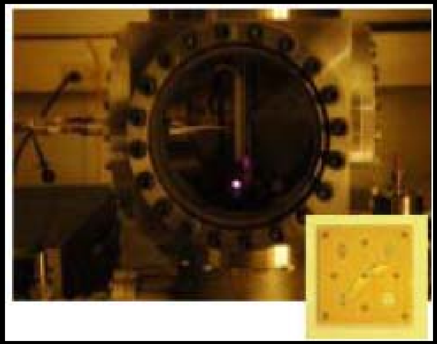
- Pungent odor given off of lunar dust consistent with reactions with odorant receptors in nose
  - From David Scott in the Apollo 15 Technical Debriefing
    - *"When you took the helmet off, you could smell the lunar dirt. It smelled like – the nearest analogy I can think of is gunpowder."*
- Odor dissipated in a short time, consistent with passivation of by oxygen or water vapor
  - *Carlton Allen*, Biological Effects of Lunar Dust Workshop (2005)
    - *"The gunpowder smell went away in a few hours."*

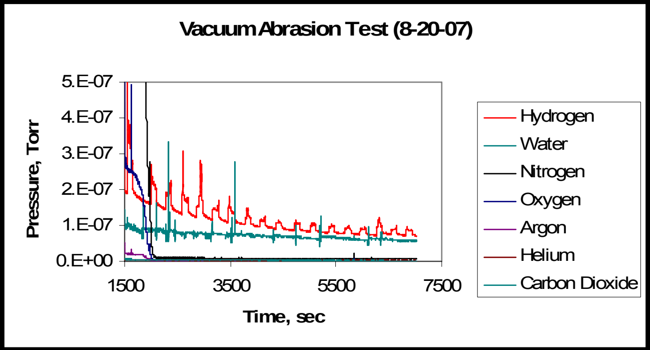
Investigations into Simulant Activation

- Subject lunar simulants to surface activation processes:
  - Fracture using high impact milling
  - High energy RF plasma
  - High energy ablation



- Multiple characterization techniques:
  - SEM, TEM, HRTEM, SAED for <u>physical</u> structure
  - Fluorescence and Raman (*in situ*) for <u>chemical</u> structure
  - Quartz crystal microbalance, resistivity for *in situ* <u>reactivity</u> determination
  - RGA analysis of implanted solar wind volatiles

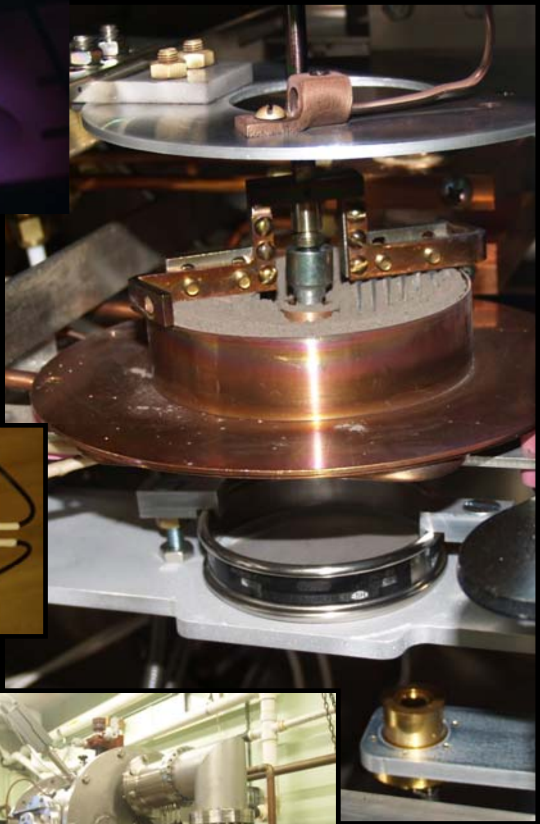


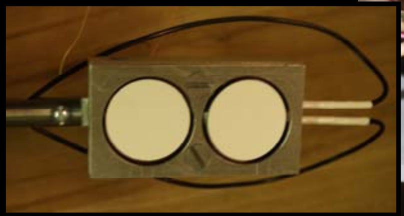


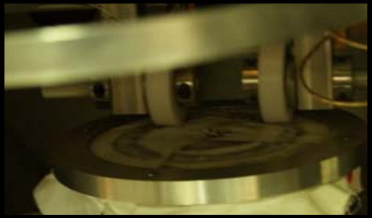
- Physical and Chemical Reactivity Testing
  - Adhesion studies upon materials and coatings
  - Abrasion characterization upon simple cleaning

Lunar Dust Adhesion Belljar Capabilities

- High vacuum (10^{-8} Torr)
  - Quantify residual gases
- *In situ* activation of dust
  - Stirring/heating to drive off terrestrial volatiles
  - Activation in oxidizing/reducing RF plasmas
  - Sieving dust onto samples
  - UV-Vis-IR irradiation
- Characterization of samples
  - Absorptance
  - Emittance to cold wall as low as 25 K
  - Steady state temperatures vs/applied power
  - Particle sizes/concentrations/mass on surface
  - Adhesion to surfaces
  - Abrasion testing (Taber test)







Conclusions

- No high fidelity simulants widely available
  - Not JSC-1, MLS-1, FJS-1…
- "High fidelity" definition application dependent
  - ISRU requirements may differ from dust mitigation
- Minor constituents may have major effects
  - Catalyst poisoning by traces of sulfur?
  - Enhanced toxicity by surface iron?
- Lunar environment changes properties
  - Activated surfaces affect adhesion, cohesion…
  - Must test properties in the right environment