National Aeronautics and Space Administration

What We Do Not Know

And Probably Need to Know

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What Do We Know About Problems Identified During Apollo?

Dust Degrades Capabilities

- **Apollo astronauts cited multiple problems caused by lunar dust**
- **Dust degradation effects can be sorted into categories***
  - Vision obscuration
  - False instrument readings
  - Loss of foot traction
  - Dust coating and contamination
  - Seal failures
  - Clogging of mechanisms
  - Abrasion of materials
  - Thermal control problems
  - Inhalation and irritation risks *

J.R. Gaier, *"The Effects of Lunar Dust on EVA Systems During the Apollo Missions"*, NASA/TM-2005-213610/Rev1

Vision Obscuration Problems

- **First noted on Apollo 11 LM landing**
  - •Began noticing at altitude of 100 ft
  - •More severe as altitude decreased
- **Apollo 12 even more severe**
  - •Concerned LM foot could land on boulder, small crater
- **Landing profile changed, Apollo 14 had fewer problems**
  - •Had fewer dust problems of all types
  - •Intrinsically less dust site?
- **Apollo 15, 16 both reported problems seeing ground on landing**
  - •Both used higher landing profile
- **No mention in Apollo 17 debriefing**
  - •Also had fewer dust problems reported
- **Minor camera problems on Apollo 15**
  - •Fixed by brushing off lens

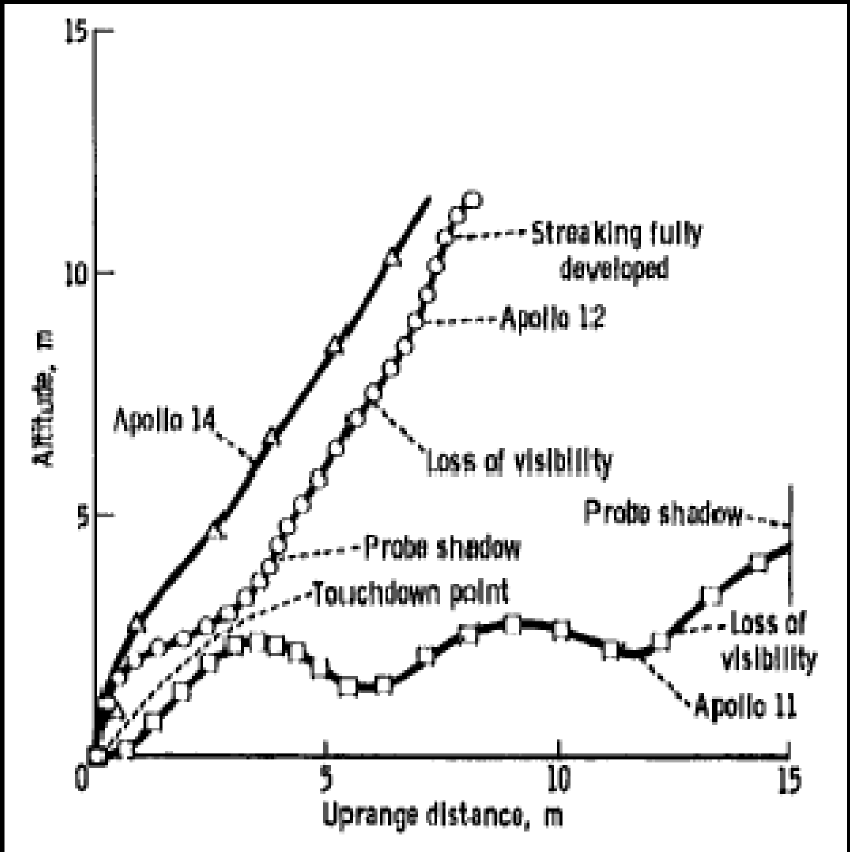
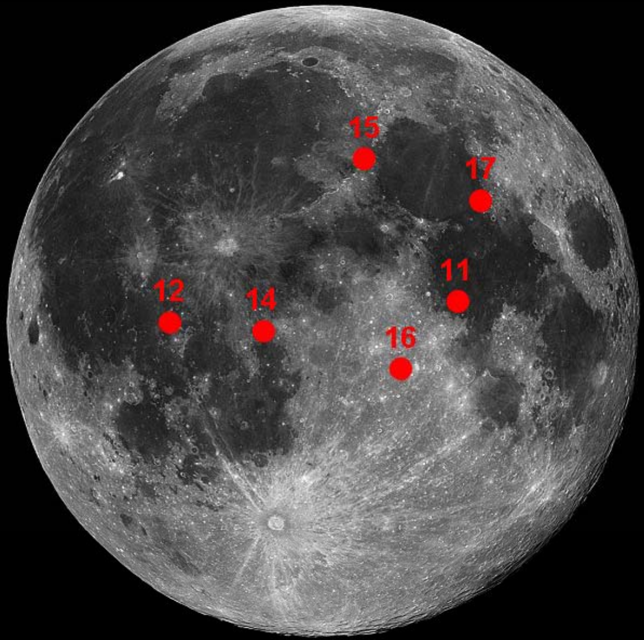


FIGURE 4-1.—A comparison of the final-approach profiles of the Apollo 11, 12, and 14 LM's.

Mitchell, et al., NASA SP-272 (1971)

False Instrument Readings

- **Apollo 12 velocity trackers gave false readings**
  - Locked onto moving dust and debris during descent
- **Apollo 15 landing radar outputs affected**
  - Altitudes less than 30 feet
- **Apollo 17 reported minimal problems of this sort**
  - Less loose dust at landing site(?)
  - ***Each landing site will be different!***

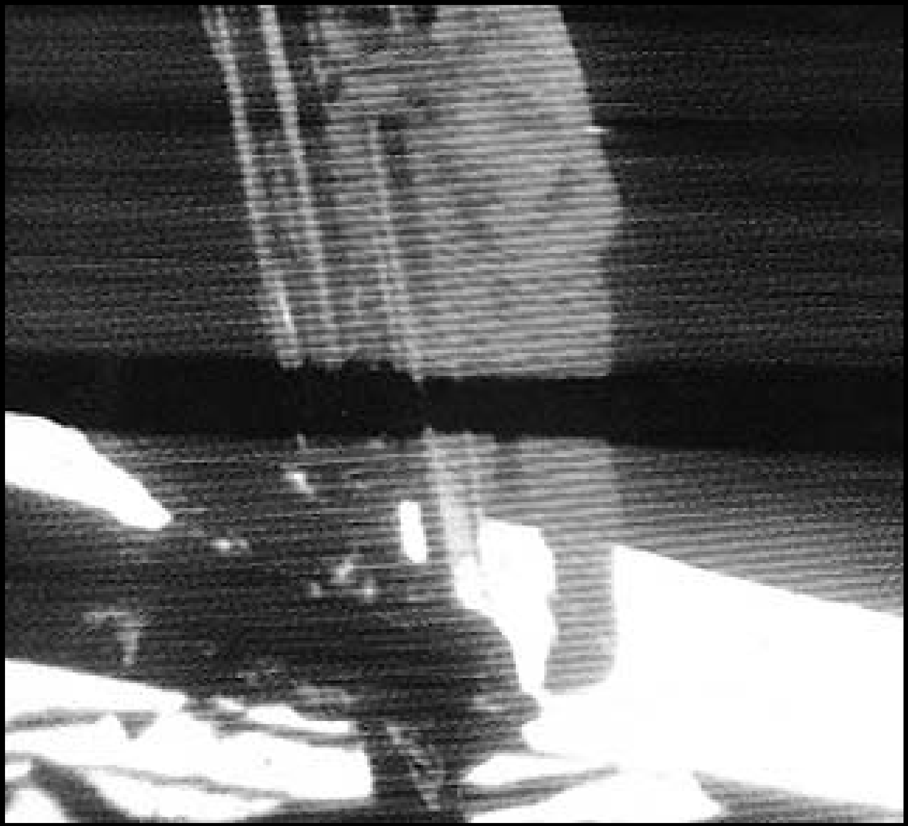


What we need to know about
Vision Obscuration/False Instrument Readings

- **Need to understand dust transport**
  - Under day/night terminator passing
  - Under landing conditions
  - Under launch conditions
- **Need to understand light scattering properties**
  - Visible
  - Radar

Loss of Foot Traction

- **Neil Armstrong reported material on boot sole made ladder slippery**
- **No other similar reports**
  - •Apollo 12 astronauts report specifically there were no problems
- **Astronauts started kicking ladder before ingress**
  - •Kept some of the dust out of the LM
  - •May have shaken enough dust off to prevent slipping
  - •Limited number of egress-ingress cycles
- ***Not thought to be a major concern***



Dust Coating and Contamination

- **Dust quickly and effectively coated surfaces**
  - •Boots, gloves, suits, and hand tools affected
  - •Dust on Apollo 11 TV cord concealed it and created tripping hazard
  - •Dropped Apollo 12 contrast chart became unusable
  - •LRV fender extensions knocked off, resulting in astronauts and equipment being covered with dust

- ***Coating problems developed into other problems***
  - •Clogging of mechanisms
  - •Seal failures
  - •Abrasion
  - •Thermal control
- **Dust created housekeeping problems**
  - •Much astronaut time devoted to ineffective brushing and wiping down equipment

Clogging of Mechanisms

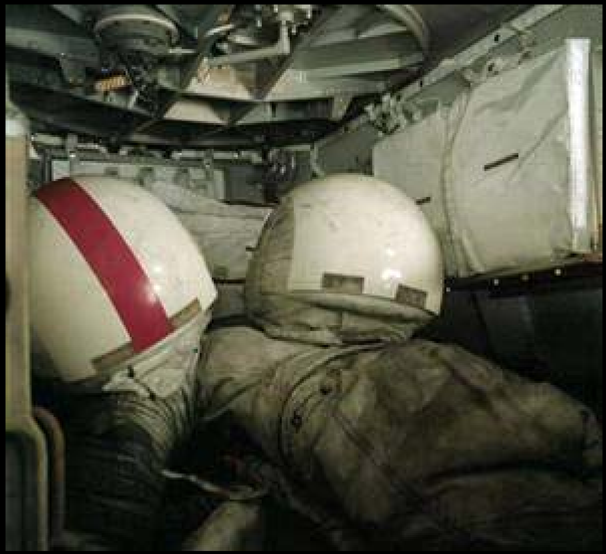
- **Equipment clogged and mechanisms jammed on every mission**
  - •Equipment conveyor to LM
  - •Lock buttons
  - •Camera equipment
  - •Velcro® fasteners
  - •Zippers
  - •Wrist locks
  - •Hose locks
  - •Faceplates
  - •Sunshades
  - •Vacuum cleaner

Apollo 17 Fender Fix

- **Particularly problem when fender extensions were knocked off LRV**
- ***Several crew remarked could not have sustained more surface activity***

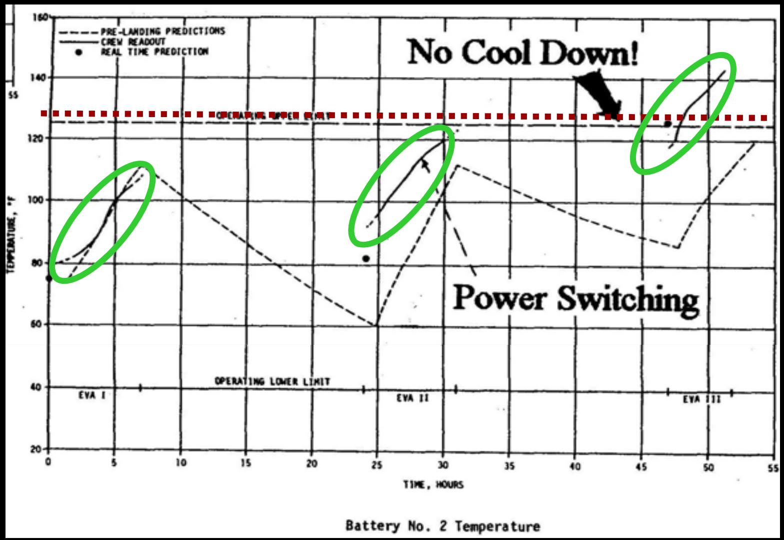
What we need to know about
Dust Coating, Contamination, Clogging and Loss of Traction

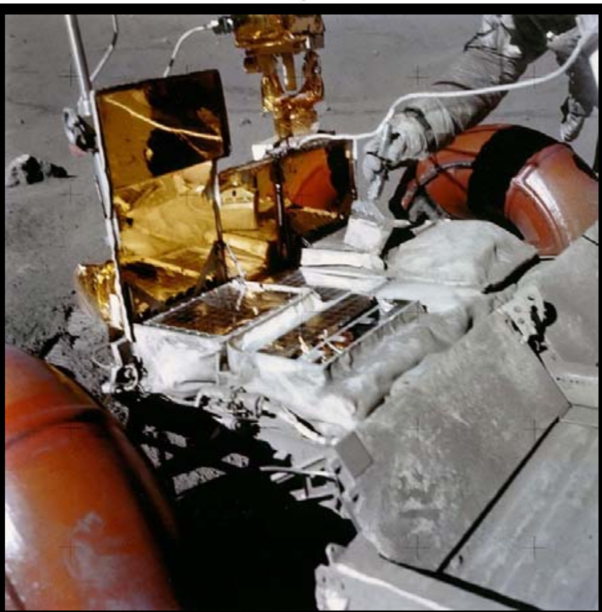
- **Dust transport by human activities**
  - Walking
  - Roving
- **Dust adhesion to spacecraft materials**
- **Dust cohesion**



Thermal Control Problems

- **LRV batteries exceeded temperature limits**
  - Losing fender extensions increased dust exposure for dust covers and radiators
  - Power switching required on Apollo 16
- **Communications, TV camera, experiment radiators also adversely affected**
- **Surface Electrical Properties (SEP) experiment failed**
- **Valuable EVA time spent trying to clean radiators**
  - Limited effectiveness
- ***Ground-based tests for dust removal by brushing were inadequate and misleading***
  - Need high quality thermal/vacuum test facility
  - Need “believable” testing of prevention and mitigation methods, correlated with actual system models

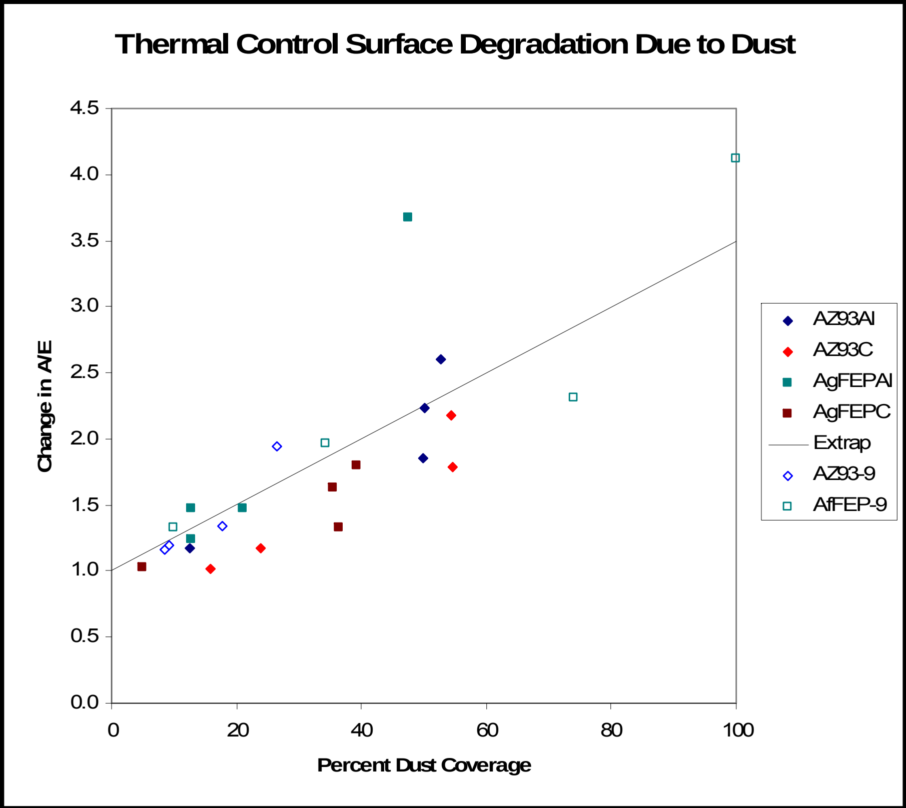




Astronaut Brushing Radiator

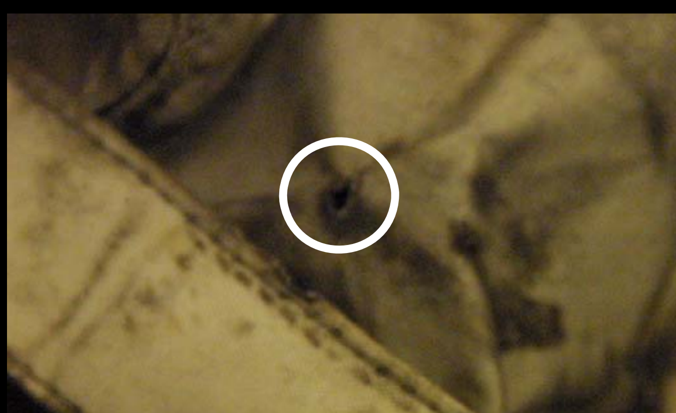
What we need to know about Thermal Control Problems

- Adhesion to thermal control surfaces
- Emissivity of dust covered thermal control surfaces
- Absorptivity of dust covered thermal control surfaces
- Bulk thermal conductivity of the lunar regolith



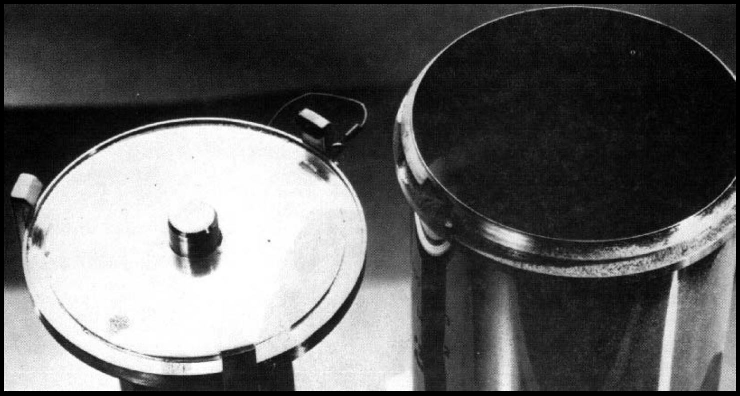
Abrasion of Materials

- **Conrad and Bean's suits worn through above boot**
  - Micrometeoroid protection layer breached
  - Several layers of Kapton® multi-layer thermal insulation breached
- **Brushing dust off scratched indicator dial faceplates**
  - Made some LRV indicators unreadable on Apollo 16
- **Obscured vision**
  - Harrison Schmitt's visor sun shade so scratched he could not see in certain directions
- **Abrasion caused serious problems**



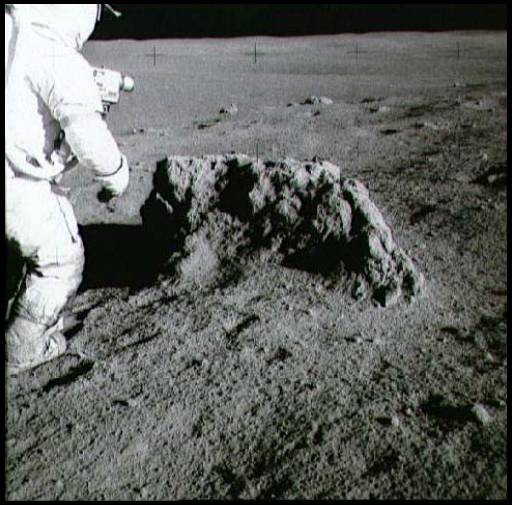
Seal Failures

- **Ability to seal suits for EVA's compromised**
- **Apollo 12 higher than normal suit pressure decay**
  - Pete Conrad's suit was tight before first EVA
  - After first EVA 0.15 psi/min
  - After second EVA 0.25 psi/min
    - Safety limit was 0.30 psi/min
  - Dust could not be completely cleared off of fittings
- **<u>All</u> Apollo environmental, gas, and regolith sample seals compromised**
  - Samples contaminated before reached earth



What we need to know about
Abrasion of Materials and Seal Failures

- **Adhesion as it affects abrasion**
- **Cohesion as it affects abrasion**
- **Abrasion of spacecraft materials**



Inhalation and Irritation Risks

- *Dust could compromise astronaut health*
- **Apollo 11 reported dust gave off distinctive, pungent odor**
  - Suggests small particle sizes were suspended in spacecraft
  - May have reactive volatiles on the surface of the dust
  - Dust irritated eyes, but was easily removed
  - Dust under fingernails was persistent
- **Apollo 12 reported eye and lung irritation on return trip**
  - Contaminated the CM after docking with LM
- **Apollo 12 crew reported dust got in everywhere**
  - Conrad and Bean covered with dust when they removed space suits
- **Harrison Schmitt reported hay fever-like symptoms from dust**
  - Lasted much of the return trip
- **No astronaut has had recurring problems attributed to dust exposure**

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Lunar Particle Surfaces in Excited States

- **Constantly streaming solar wind impact lunar surface**
  - H^+, He^{2+}, e^-, small number of heavier ions
  - Solar particle events greatly increase number and energy
  - Constant output of hard UV, x-rays, and γ-rays
- **Galactic cosmic rays**
  - H^+, He^{2+}, e^-, small number of heavier ions
  - Very high energies
  - Come from all directions
- **Constant bombardment from meteoroids**
  - Most smaller than 1 mm in size
  - High kinetic energy (11-72 km/s velocity)
- **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

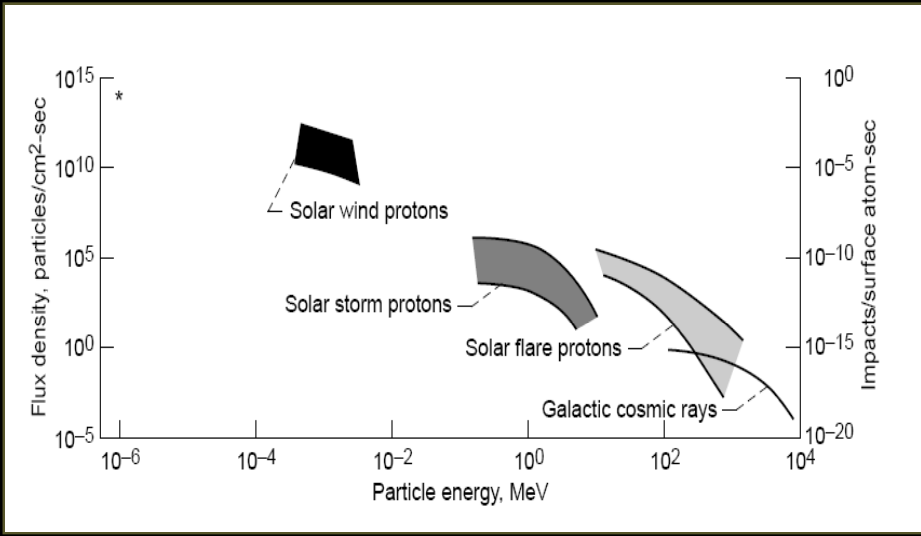

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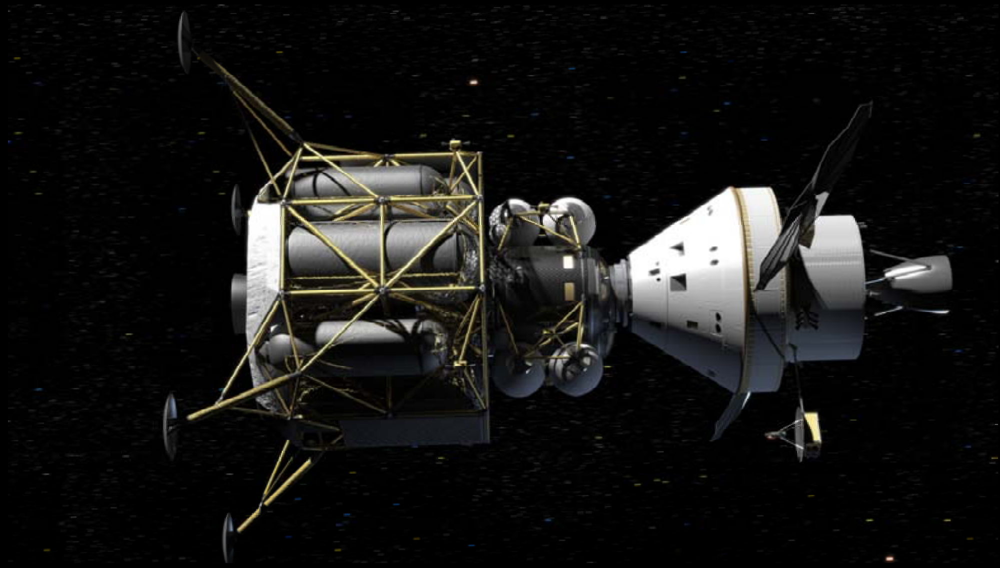
Figure derived from Wilson, et al., NASA Ref. Pub 1257 (1991).

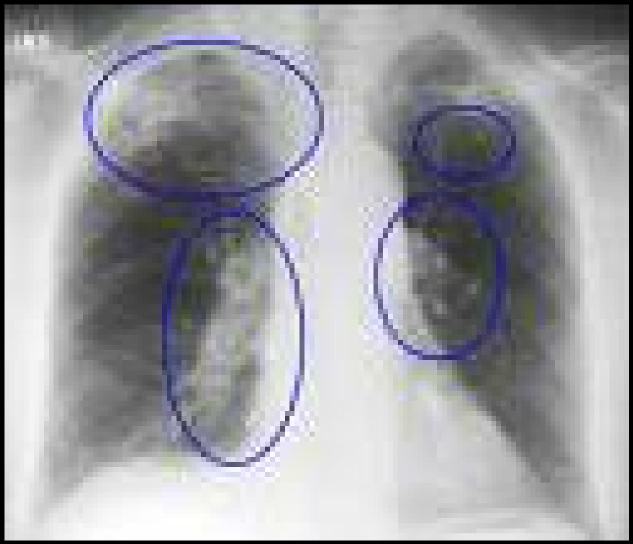
Activated Dust and Human Health

- **Conclusions of Biological Effects of Lunar Dust Workshop (2005)**
- **“Lunar dust has some striking similarities to terrestrial silica, which has cause the deaths of thousands of people (respirable size, metals, chemically reactive). But lunar dust has unique properties that we don’t understand from a toxicological perspective (ultrafines, shape, unique reactive surfaces).”**
- **“Initial toxicological studies can be conducted with existing lunar samples. These finding needs to be validated via in situ lunar measurements because the *lunar samples have changed during transport and storage*.”**

What We Need to Know About Inhalation Risk

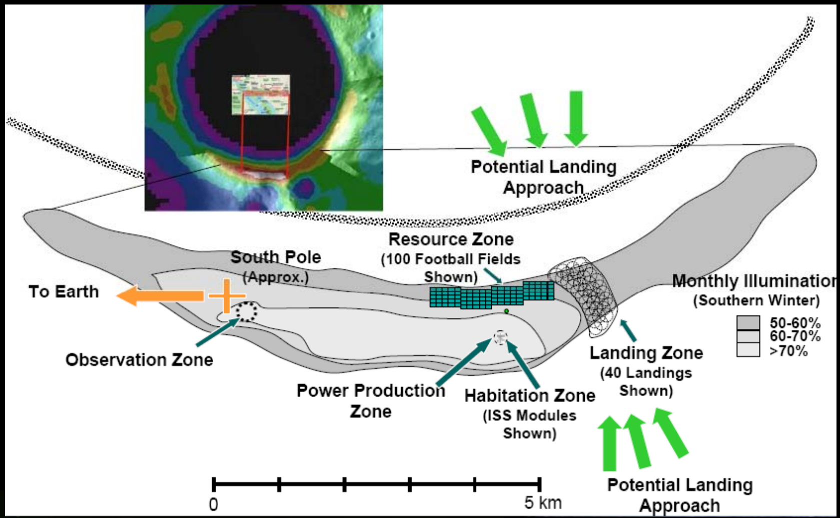
- **Reactivity of the fine fraction in moist air**
- **Reactivity in water and aqueous solutions**
- **Toxicological response**
  - Particularly of the fine fraction





What Do We Know About Building an Outpost

- Landing and Launching
- Construction Activities
- Power Generation

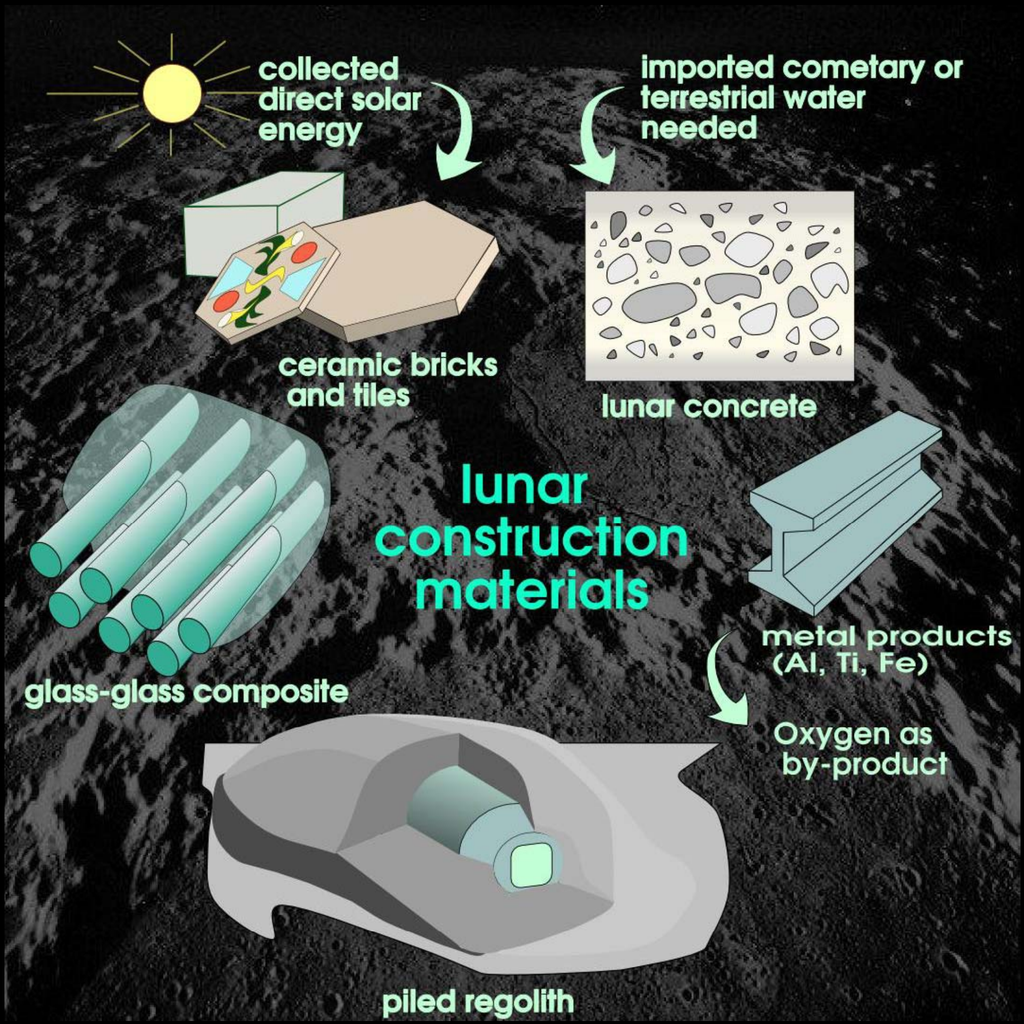


Landing and Launching Spacecraft

- **How will the dust be scattered by exhaust?**
  - Film data taken by Apollo
    - Dust scattered nearly horizontally
  - Theory
    - Wind tunnel tests of the 1960's
    - SBIR to develop finite element code
  - Experiment
    - KSC tests
- **How will scattered dust affect structures nearby?**
  - Surveyor III damage from Apollo 12
- **How can nearby structures be protected**
  - Berms and walls?
  - Distance
  - Orbital debris?

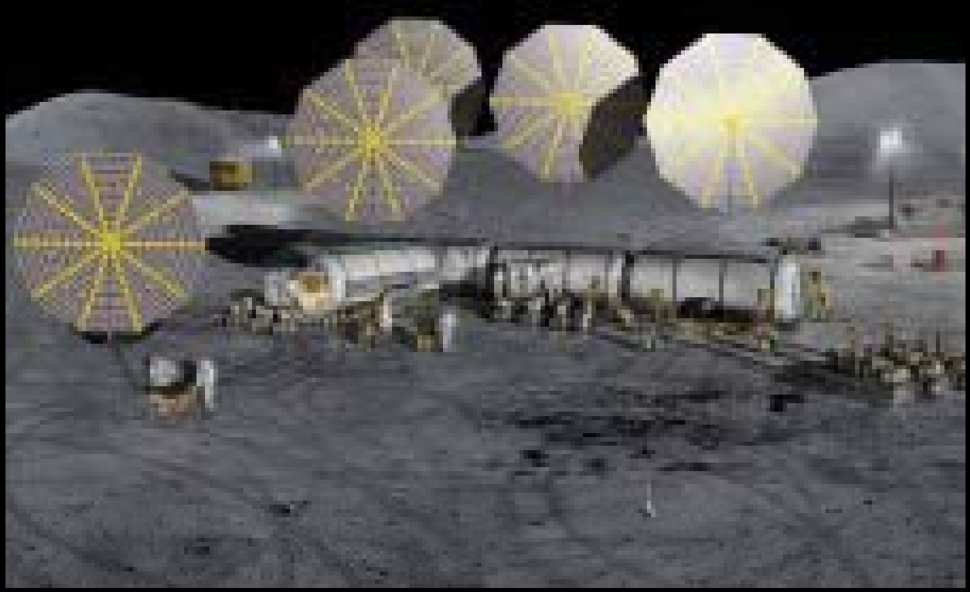
Outpost Construction

- How will the soil interact with equipment?
- Scraping
- Digging
- Drilling
- Dust transport



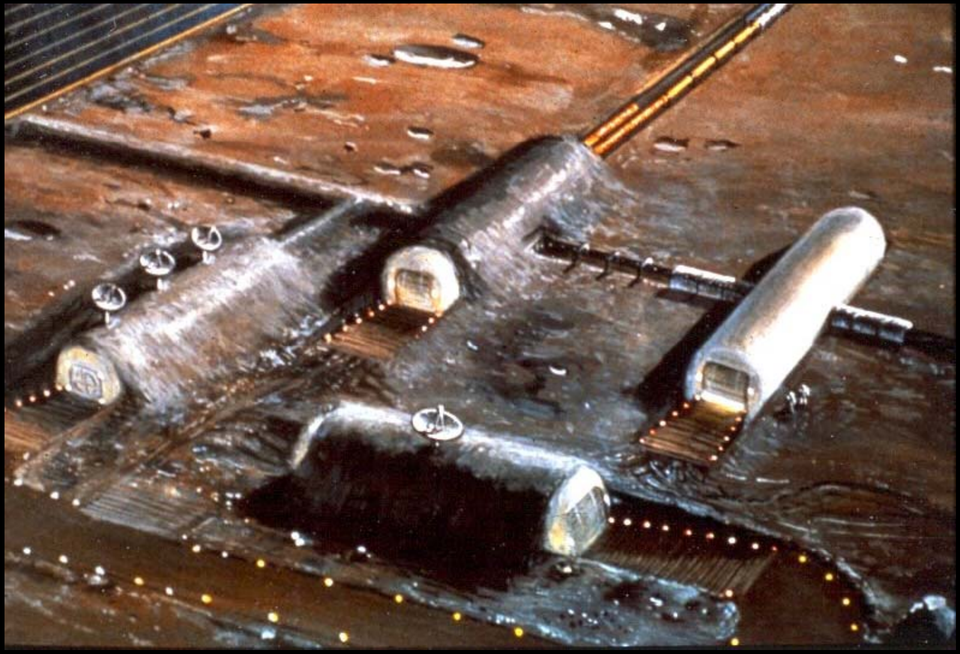
Outpost Power Generation

- **Effects of Dust on PV cells**
- **Grounding plane**
  - Soil very insulating
  - Couple to the plasma?
- **Effects of dust on radiators**
  - Efficiency depends on T_{cold}
- **Dust on thermal control surfaces**



Can we use soil for radiation protection?

- **Cheap and plentiful**
- **Must move into position**
- **Weight may be a factor**
  - Strength of structures must be increased
  - Makes inflatables more difficult

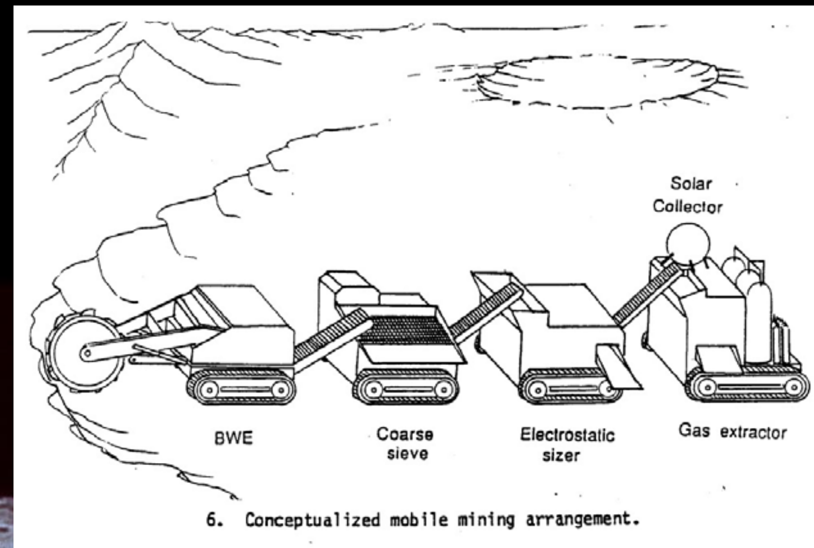


What We Need to Know About Building and Operating an Outpost

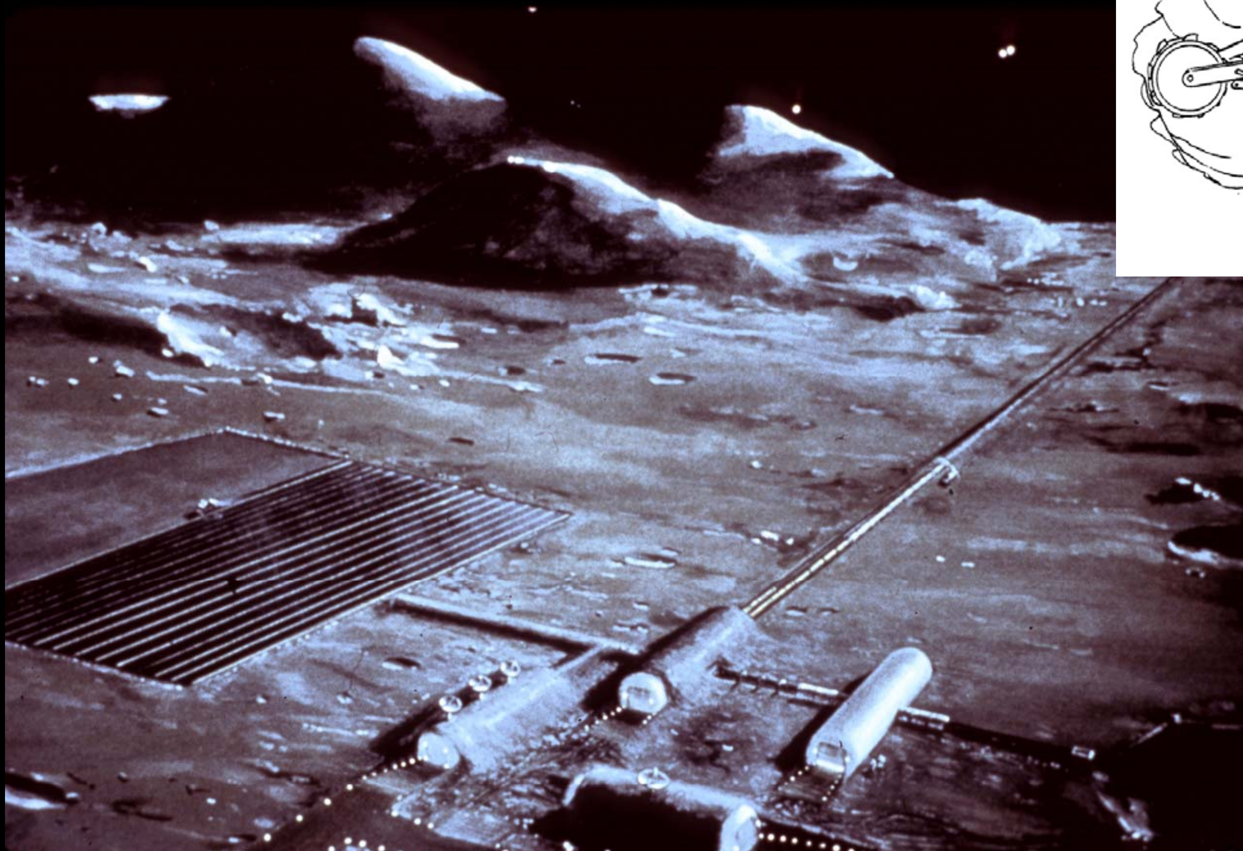
- **Dust transport properties**
  - Landing and launch
  - Mining and construction
- **Geotechnical properties**
- **Bulk transport properties**
  - Electrical and thermal conductivity
- **Radiation shielding properties**

What Do We Know About Utilizing the Moon's Resources?

- Mineral Mining
- Regolith Processing



6. Conceptualized mobile mining arrangement.

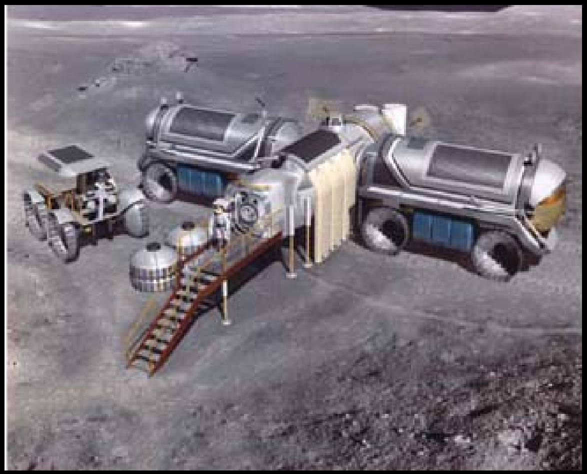


What do we need to know mine the moon?

- **Must move soil like construction**
- **Probably want to do beneficiation**
  - We don’t extract Fe from sand
- **Geological processes make finding ores less likely**

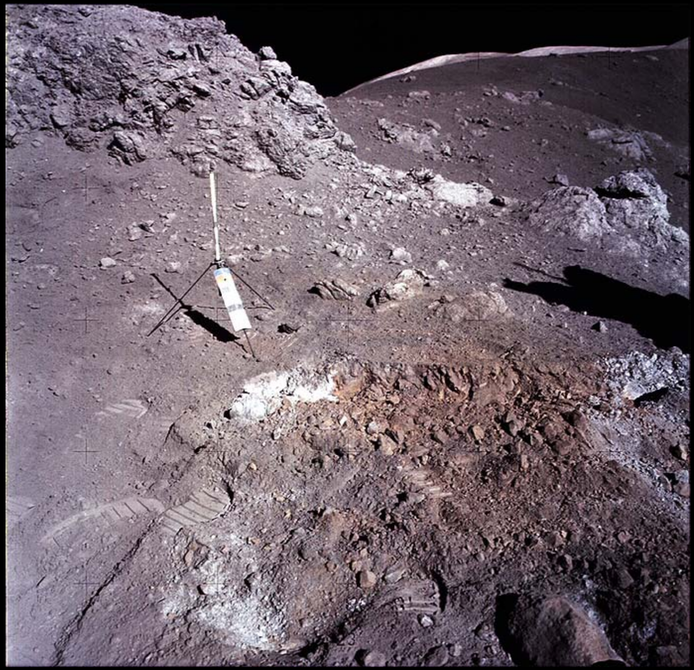
How do we process the regolith?

- **First steps are grinding and sorting (hardness, variation)**
  - Energy intensive
  - Transports dust
- **Most steps require high temperature (specific heat, thermal conductivity, α, ε)**
  - 1370 W/m^2 available from sun
  - Probably need to concentrate
  - Hot seal to control atmosphere
- **Sophisticated thermal control**
  - Have to heat tons to > 1000 °C
  - Have to cool products
  - Gases use cryogenic storage

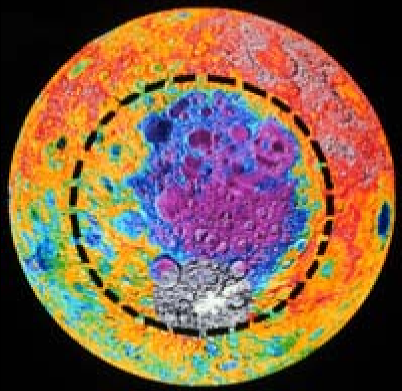


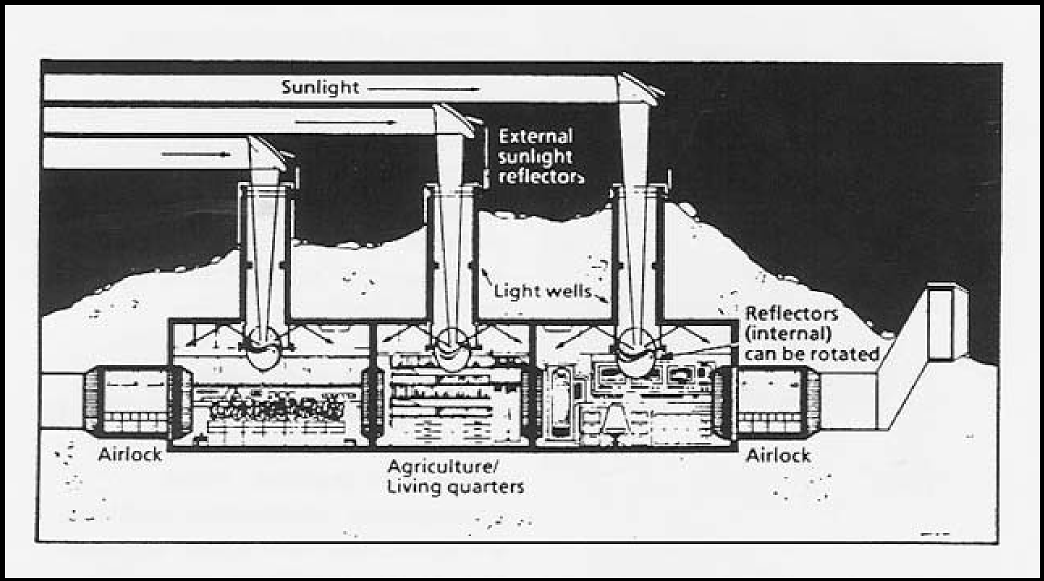
- **How do we deal with slag (phase diagrams, incongruent melting)**
  - Harvest heat
  - Process into bricks, etc.?
  - Use for radiation shields, etc.?

What We Need to Know About Utilizing the Moon's Resources



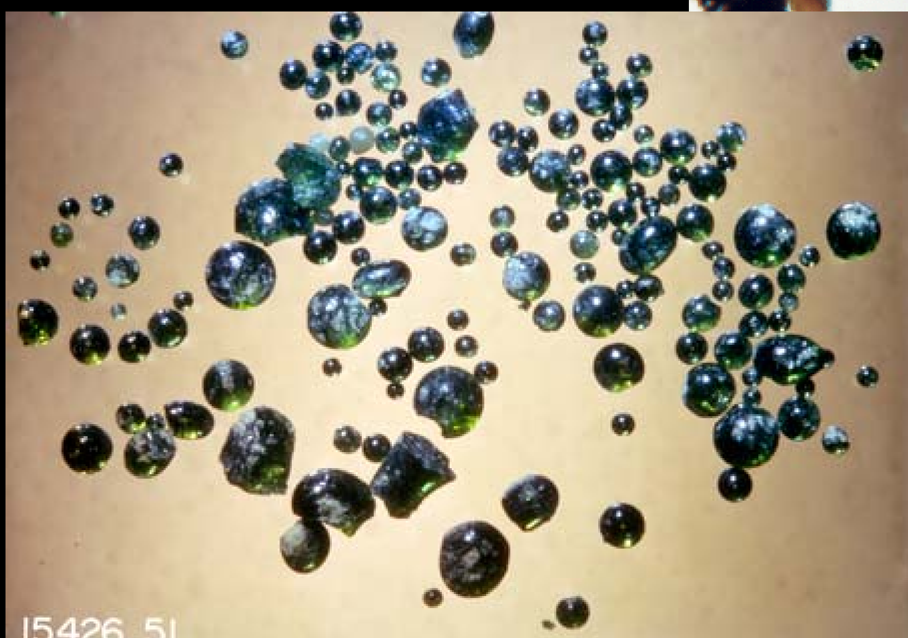
- **Dust transport properties**
  - Mining operations
  - Construction operations
- **Ore identification**
  - Ore distribution
- **Processing behavior**
  - Volatile distribution and extraction
  - Thermal properties
  - Melting behavior





What We Know About Basic Regolith Properties

- **Intrinsic properties**
- **Granular properties**
- **Environment dependent properties**
  - Granular
  - Surface dependent

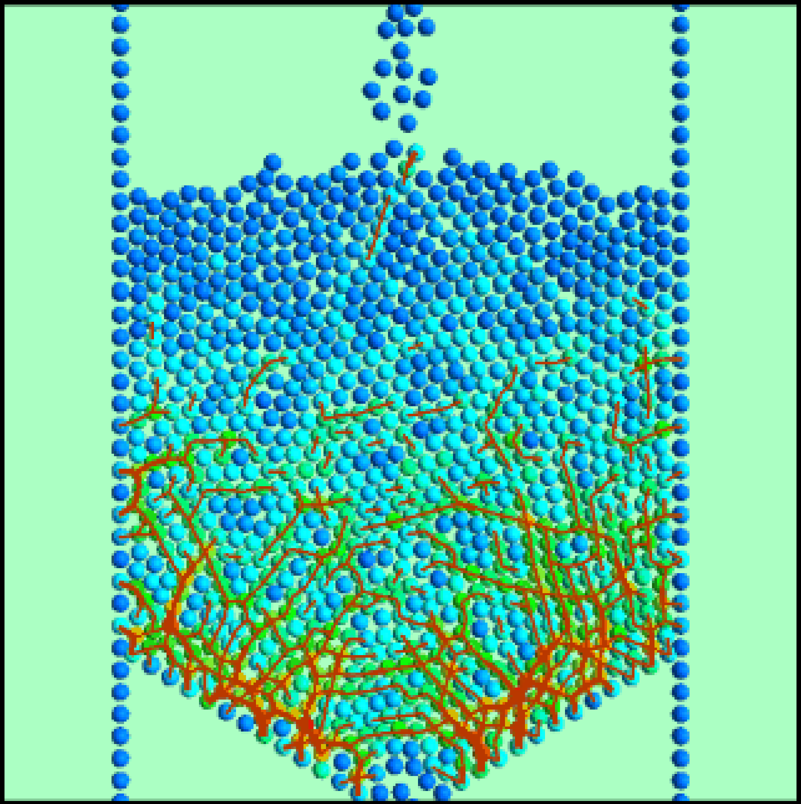


Intrinsic Properties

- **Dependant on the bulk chemistry and structure**
  - Grain density
  - Grain dielectric constant
  - Grain thermal conductivity
  - Grain magnetic susceptibility
  - Hardness
  - Shielding effectiveness
- **Variety of solid forms**
  - Mineral grains
  - Impact breccias
  - Glasses (including agglutinates)
- **Most progress from characterizing Apollo samples**

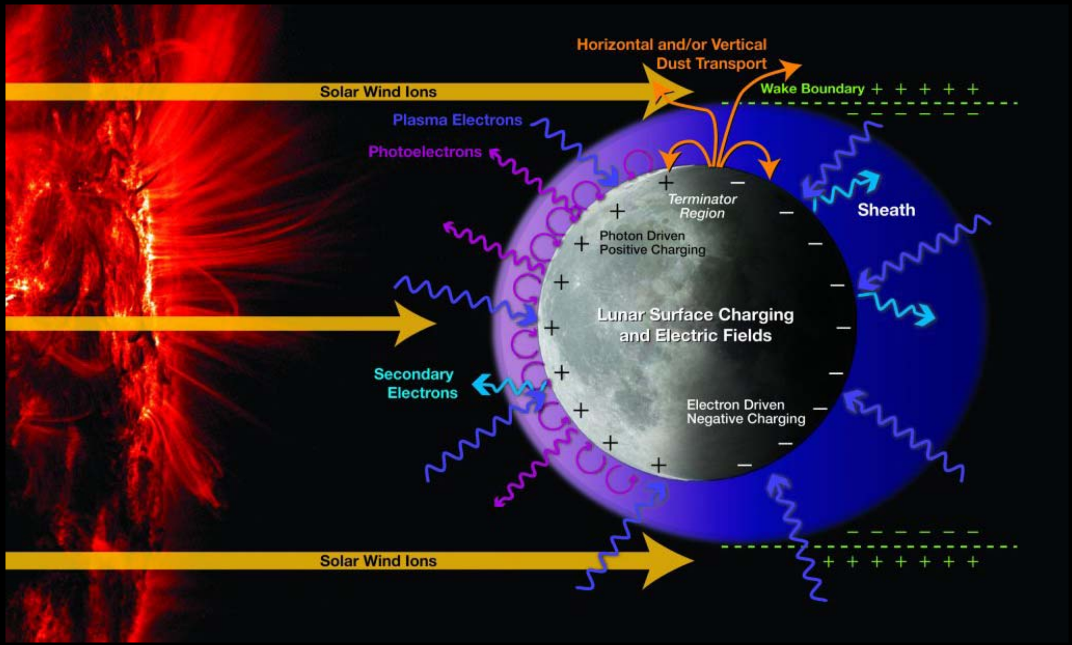
Granular Properties

- **Apollo samples well characterized**
  - Size distribution
  - Shape distribution
- **But analysis stops at 10-20 μm**
  - Fine fraction only beginning to be characterized



Environment-Dependant Properties

- **Bulk granular properties**
  - Bulk density
  - Bulk dielectric constant
  - Bulk thermal conductivity
  - Bulk magnetic susceptibility
  - Compressibility
  - Shear strength
  - Trafficability



- **Surface state dependant properties**
  - Activation state
  - Adhesion
  - Cohesion
  - Abrasion
  - Reactivity

CONCLUSIONS – We have a lot of work to do

- **Lunar dust transport**
  - Landing and launch
  - Mining and construction
  - Astronaut activities
  - Natural transport
- **Intrinsic properties are the best understood**
  - Geographical variation
- **Granular properties for < 10 μm particles**
  - Toxicity
  - Adhesion
- **Environment-dependant properties**
  - Granular
  - Surface state dependent **