Living on a Dusty Moon!

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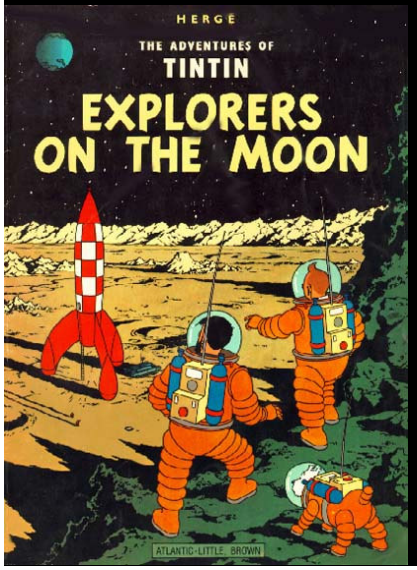
Workshop for the Lunar Applications of Mining and Mineral Beneficiation
October 5-7, 2010
Montana Tech of the University of Montana
Butte, Montana

To the Moon and Beyond

Space Exploration Initiative

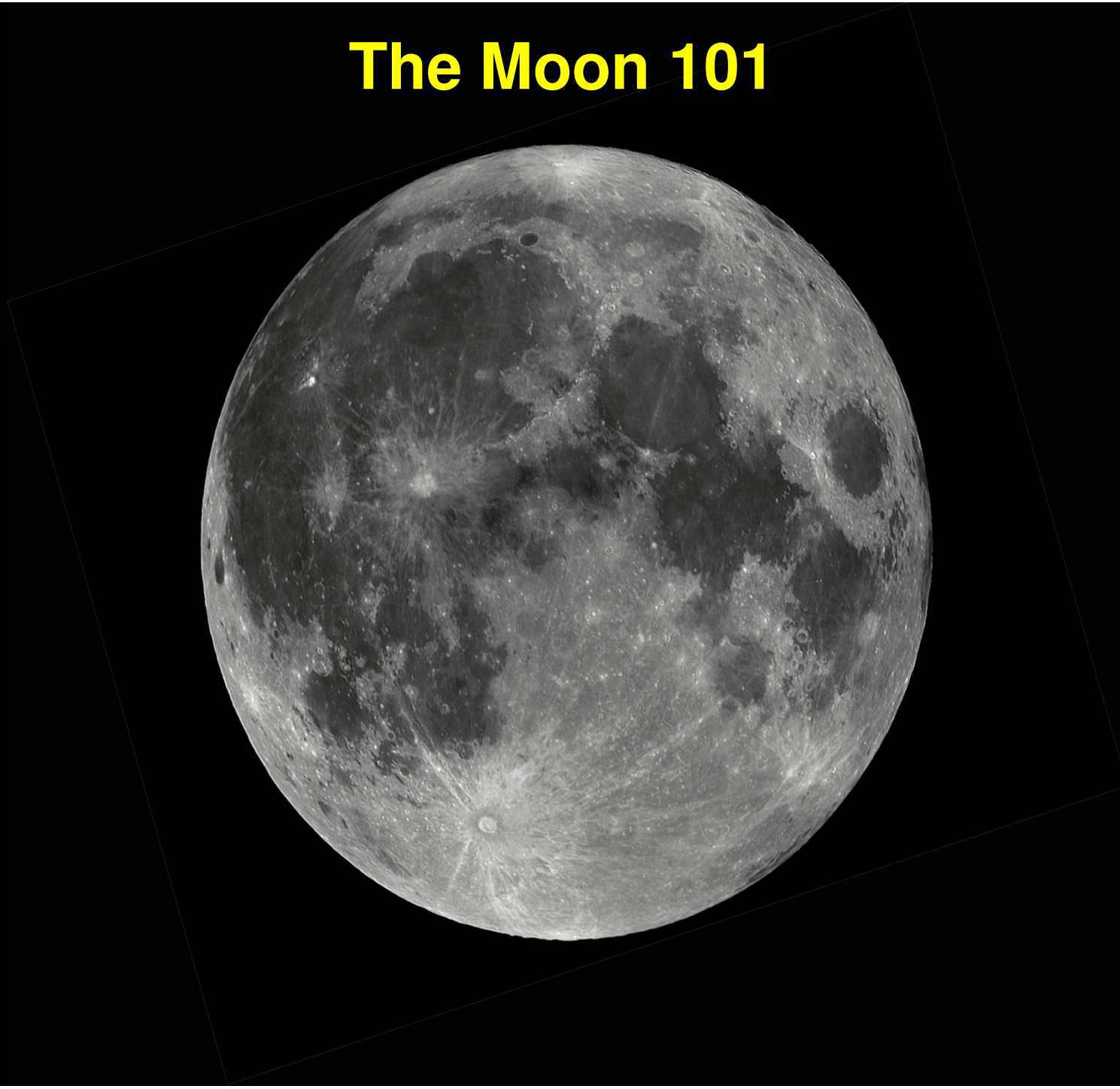
9/12/1962



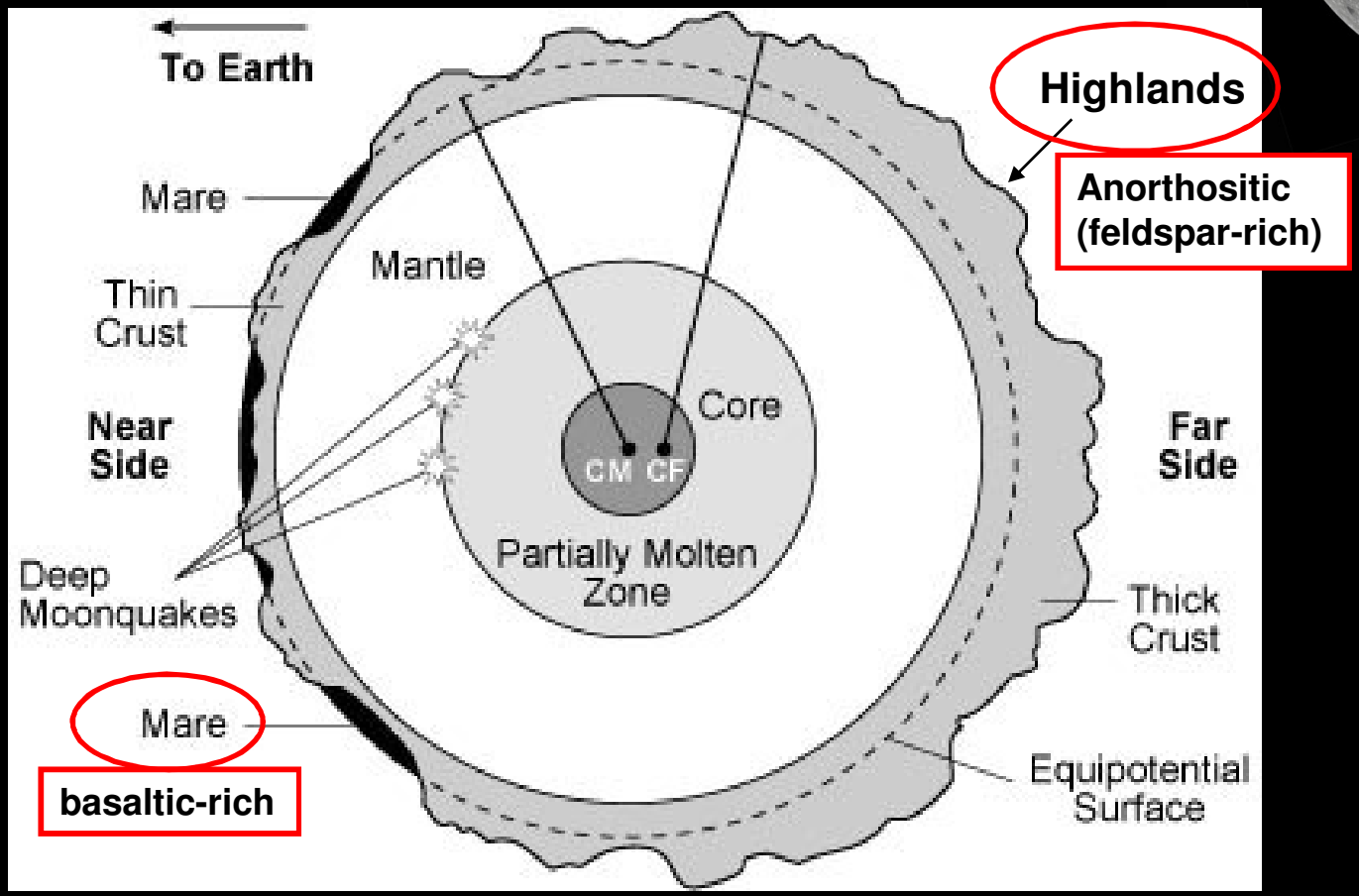
NASA's Vision for Space Exploration (NASA, 2004)
– undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system

2010 – President Obama's vision is a bit different!

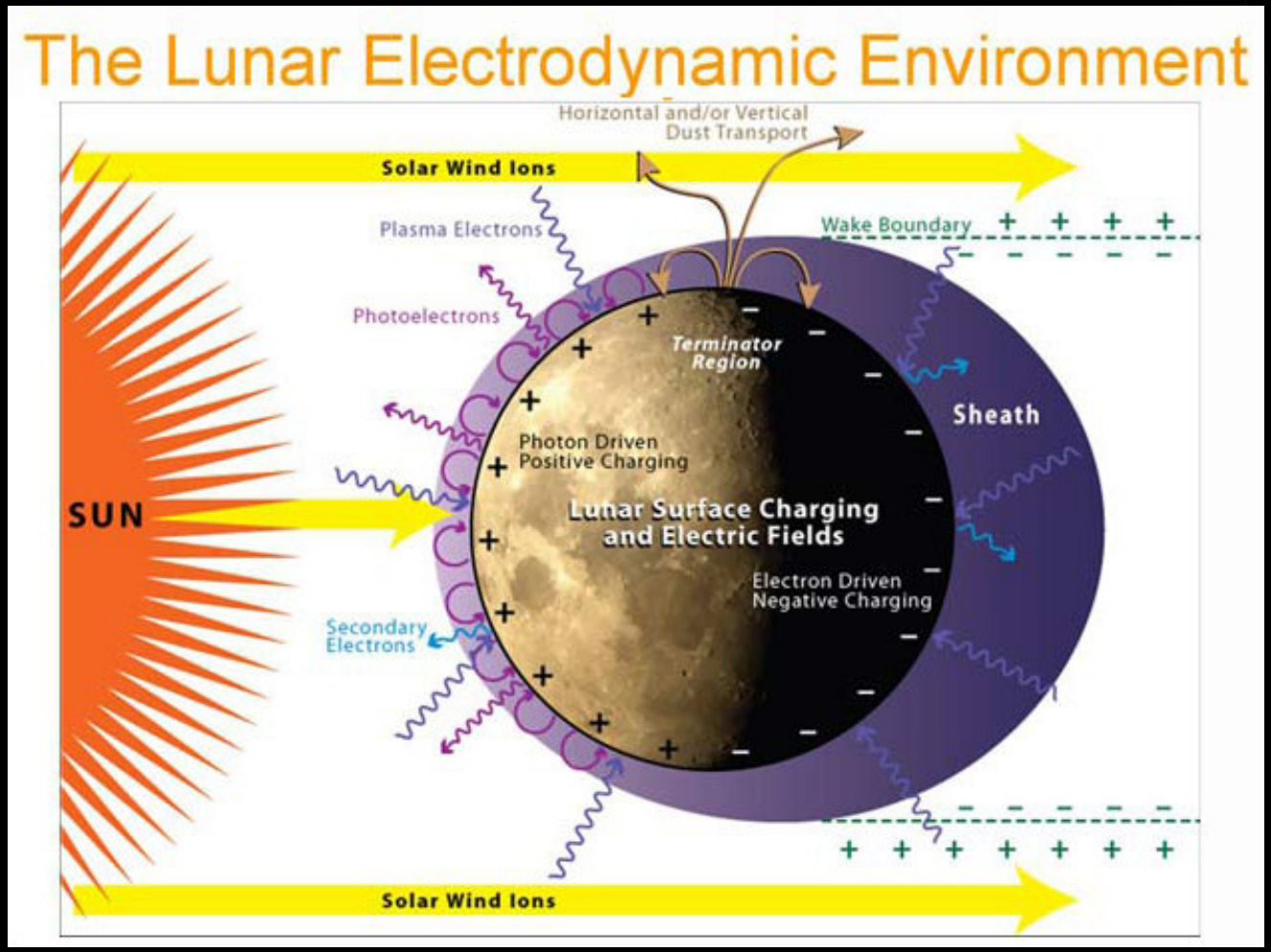
The Moon 101



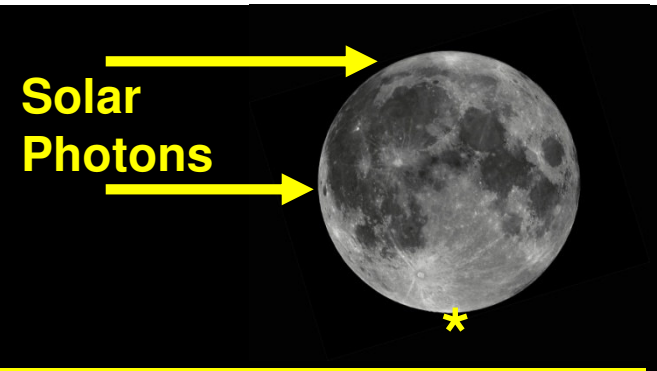
The Moon 101


To Earth
Highlands
Anorthositic
(feldspar-rich)
Mare
Mantle
Thin
Crust
Core
CM
CF
Near
Side
Far
Side
Partially Molten
Zone
Deep
Moonquakes
Thick
Crust
Mare
basaltic-rich
Equipotential
Surface

The Lunar Environment



The Lunar Environment



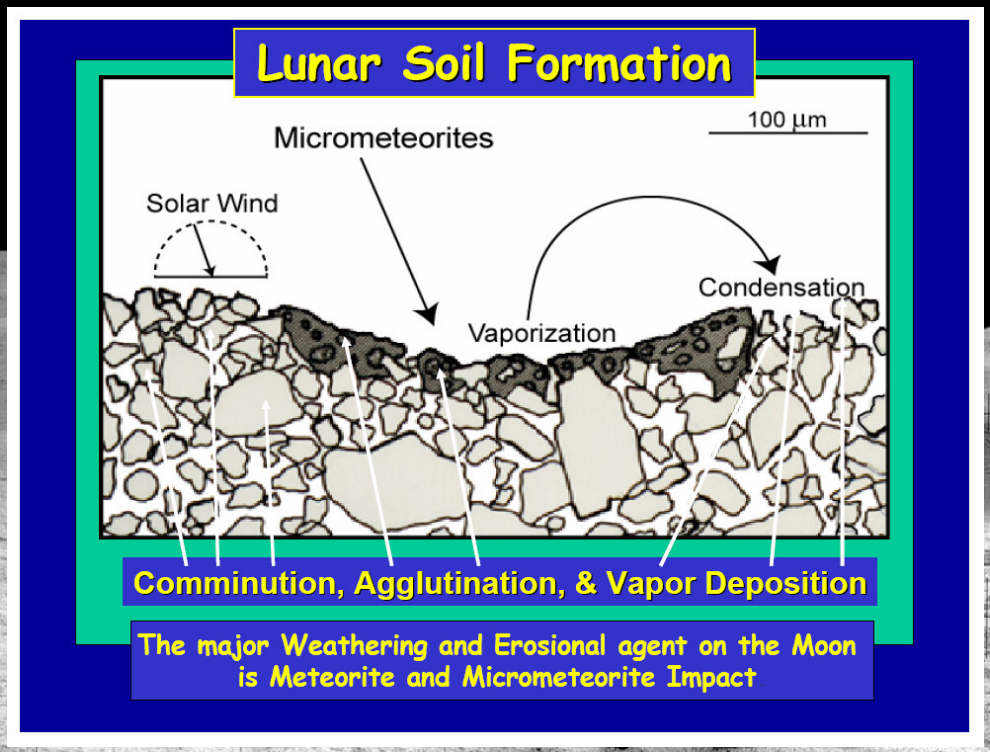
	Non Polar	Polar
Temperature	-150°C to +100°C	-50°C ± 10°C *
Sunlight	~354 hours ± 90° Incidence Angle	~ 530 to 708 hours ± 1.7° Incidence Angle
Darkness	~354 hours	0 to 148 hours (discontinuous)
H Content (avg.)	10-90 ppm	>150 ppm
Resource Potential	Solar wind gases Bound oxygen	Solar wind gases Bound oxygen Shadowed volatiles
Direct Earth Communications	Continuous on near side	Discontinuous but predictable (~ ½ time in Earth view)

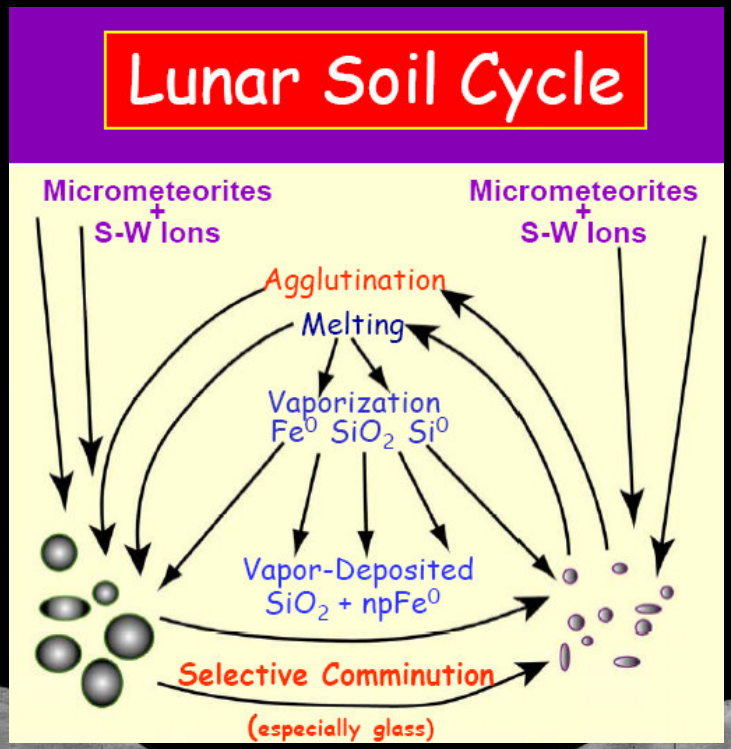
* Shackelton Crater = Totally shadowed and 40K (-233°C)!

Our Unhappy Moon

20 km/s = 44,000 mph!

Lunar Gardening

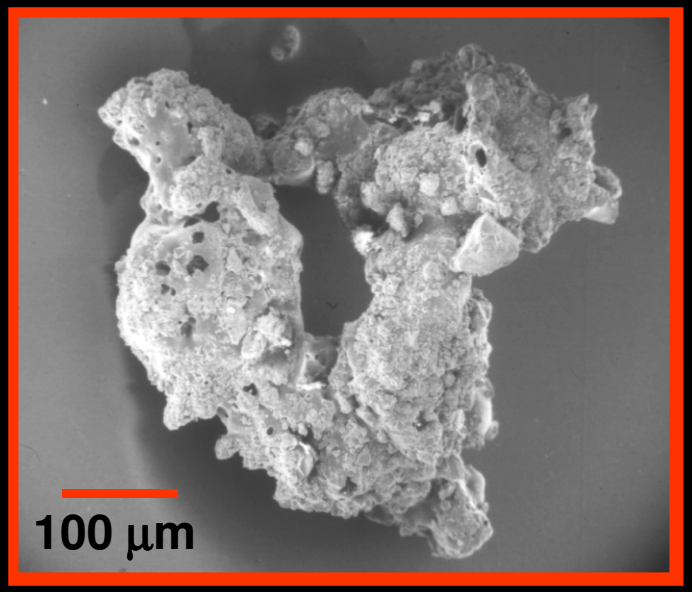


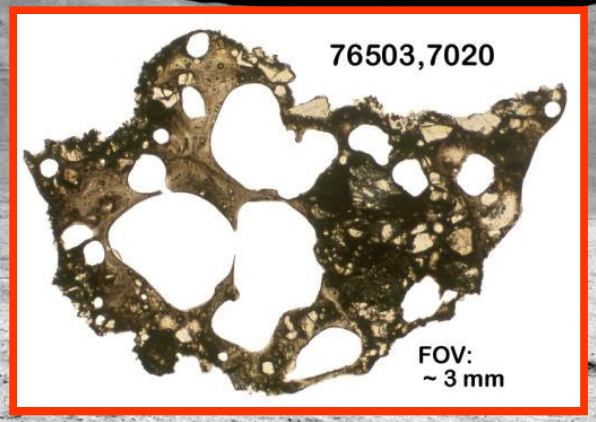


In the absence of atmosphere (10^{-12} Torr)…

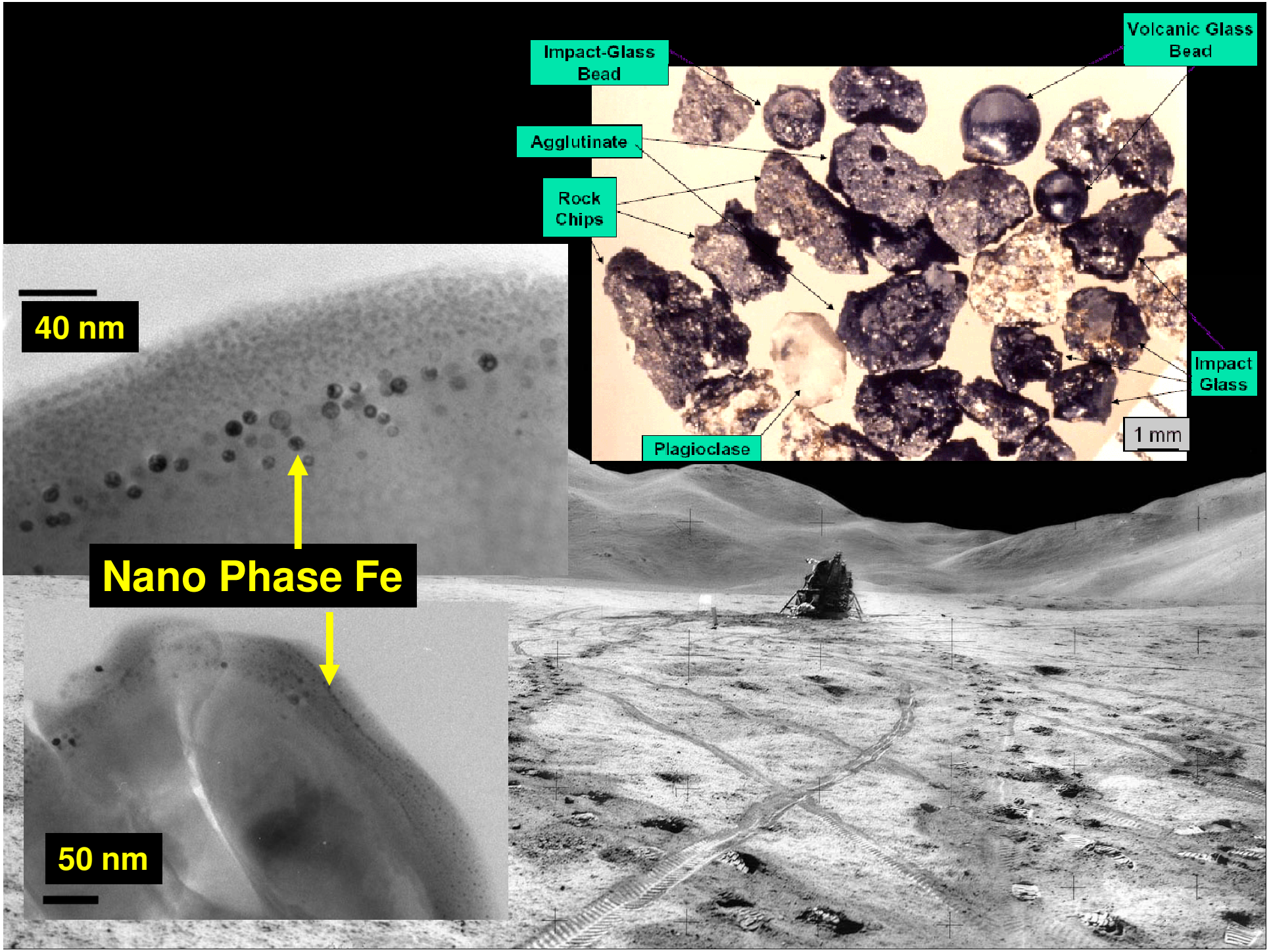
Agglutinates

Individual particles – aggregates of smaller particles (mineral grain, glass, rocks, older agglutinates) bonded together by vesicular flow banded glass in varying proportions. 30-80% glass





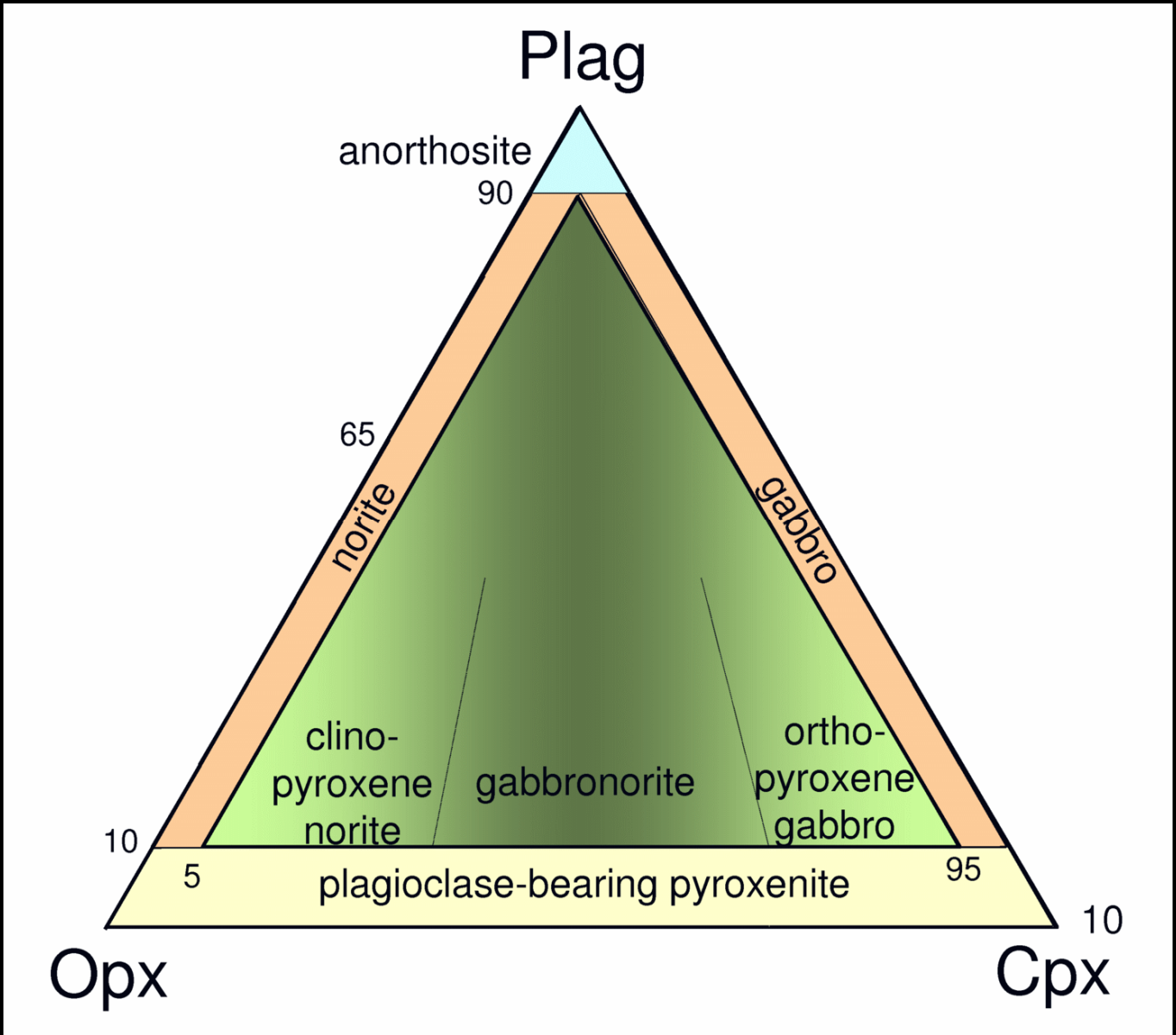
Vesicles (holes): liberated solar wind gases and generated H_2O ($FeO + 2H = Fe + H_2O$)
Contain minute droplets of near pure Fe metal (very fine grained single domain Fe^0, 30-100Å
mounds and trains of metal Fe, attached to grains


Impact-Glass Bead
Volcanic Glass Bead
Agglutinate
Rock Chips
Impact Glass
Plagioclase
1 mm
40 nm
Nano Phase Fe
50 nm

Composition - Minerals

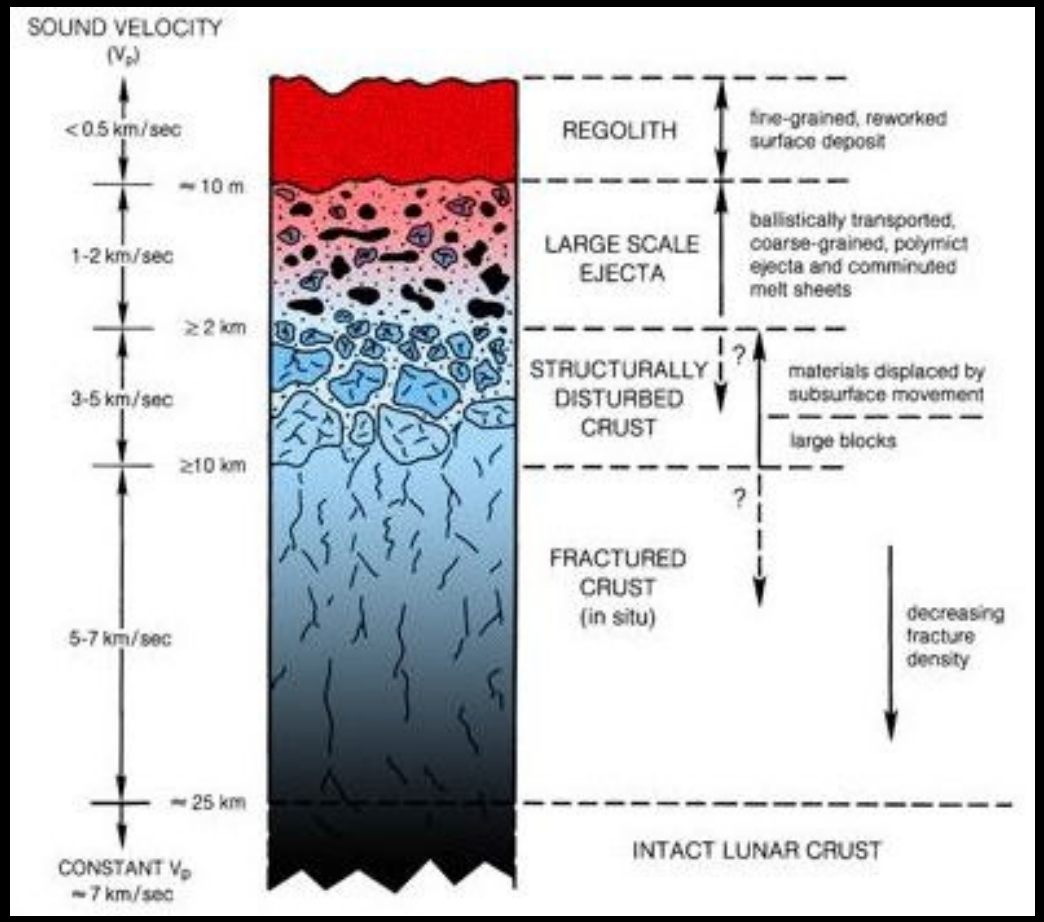
Anorthite	$CaAl_2Si_2O_8$ **$(Ca,Na)(Si,Al)_4O_8$**
Bytownite	$(Ca,Na)(Si,Al)_4O_8$
Labradorite	$(Ca,Na)(Si,Al)_4O_8$
Olivine	$(Mg,Fe)_2SiO_4$
Fayalite	Fe_2SiO_4
Forsterite	Mg_2SiO_4
Clinoenstatite	$Mg_2[Si_2O_6]$
Pigeonite	$(Mg,Fe^{+2},Ca)_2[Si_2O_6]$
Hedenbergite	$CaFe^{+2}[Si_2O_6]$
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)[(Si,Al)_2O_6]$
Enstatite	$Mg_2[Si_2O_6]$
Spinel	$MgAl_2O_4$
Hercynite	$Fe^{+2}Al_2O_4$
Ulvospinel	$TiFe^{+2}{}_2O_4$
Chromite	$Fe^{+2}Cr_2O_4$
Troilite	FeS
Whitlockite	$Ca_9(Mg,Fe^{+2})(PO_4)_6(PO_3OH)$
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$
Ilmenite	$Fe^{+2}TiO_3$
Native Iron	Fe

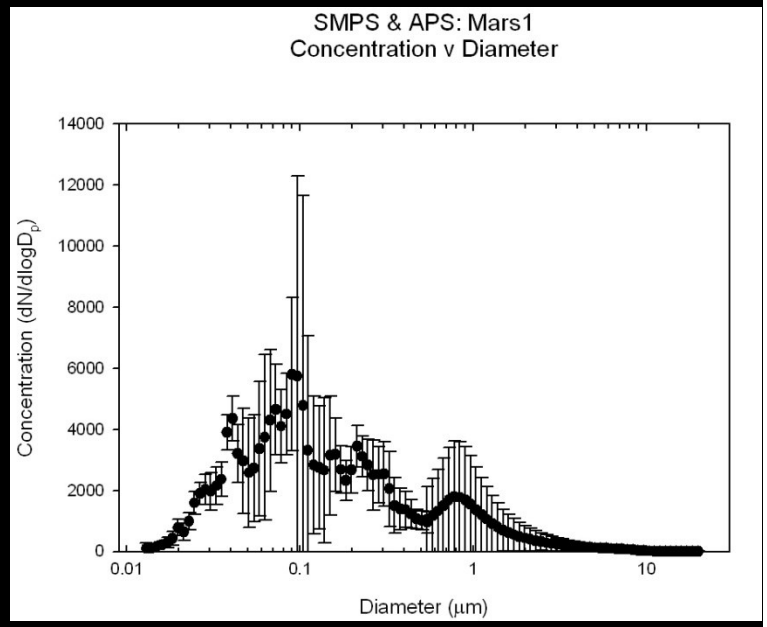
Composition - Rocks

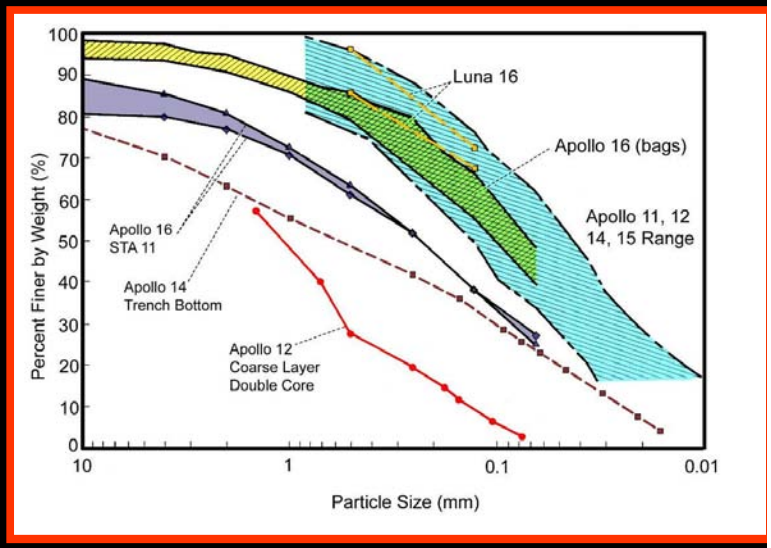


Depth of Lunar Regolith (Dirt)

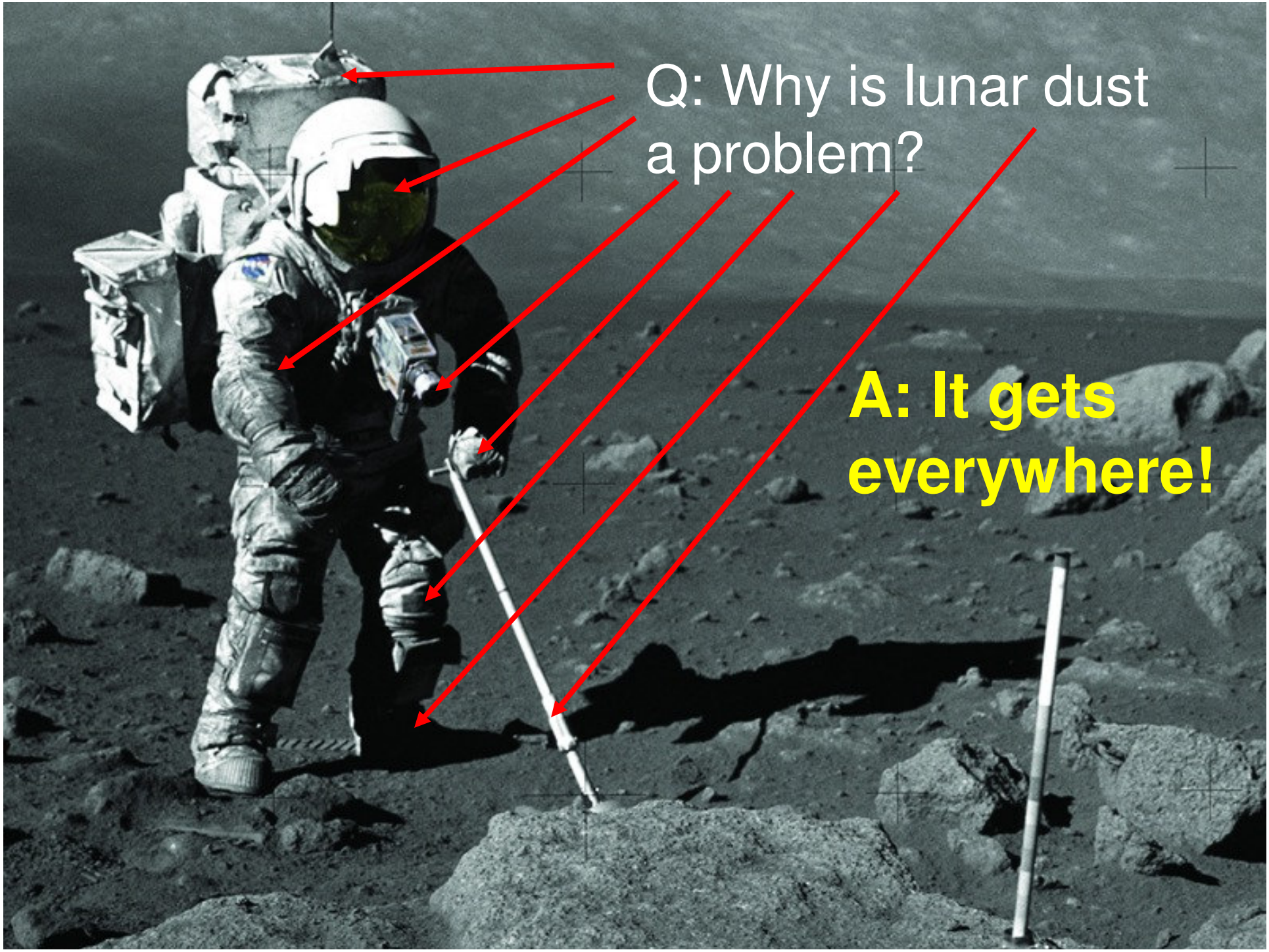
Mare ~5 m
Highland ~10 m







Dust: <50 um size fraction
consists largely of impact produced glass
complicated shapes, jagged edges,
large surface area
<20 micron size fraction: 20 wt % of soil


Q: Why is lunar dust a problem?
A: It gets everywhere!

Lunar Dust - Apollo Era Issues

Vision obscuration
- landing blew dust starting at 100 ft

False instrumentation readings
- velocity trackers locked onto dust at 30 ft

Loss of traction
- adherence to boot soles

Clogging of mechanisms
- conveyor, lock buttons, camera, …..

Abrasion
- outer layer of insulation, pressure failures, face plate scratched, ….

Thermal control
- radiator shields covered

Seal failures
- pressure decay on Pete Conrad's EMS

Inhalation and irritation
- pungent odor, eye and lung irritant

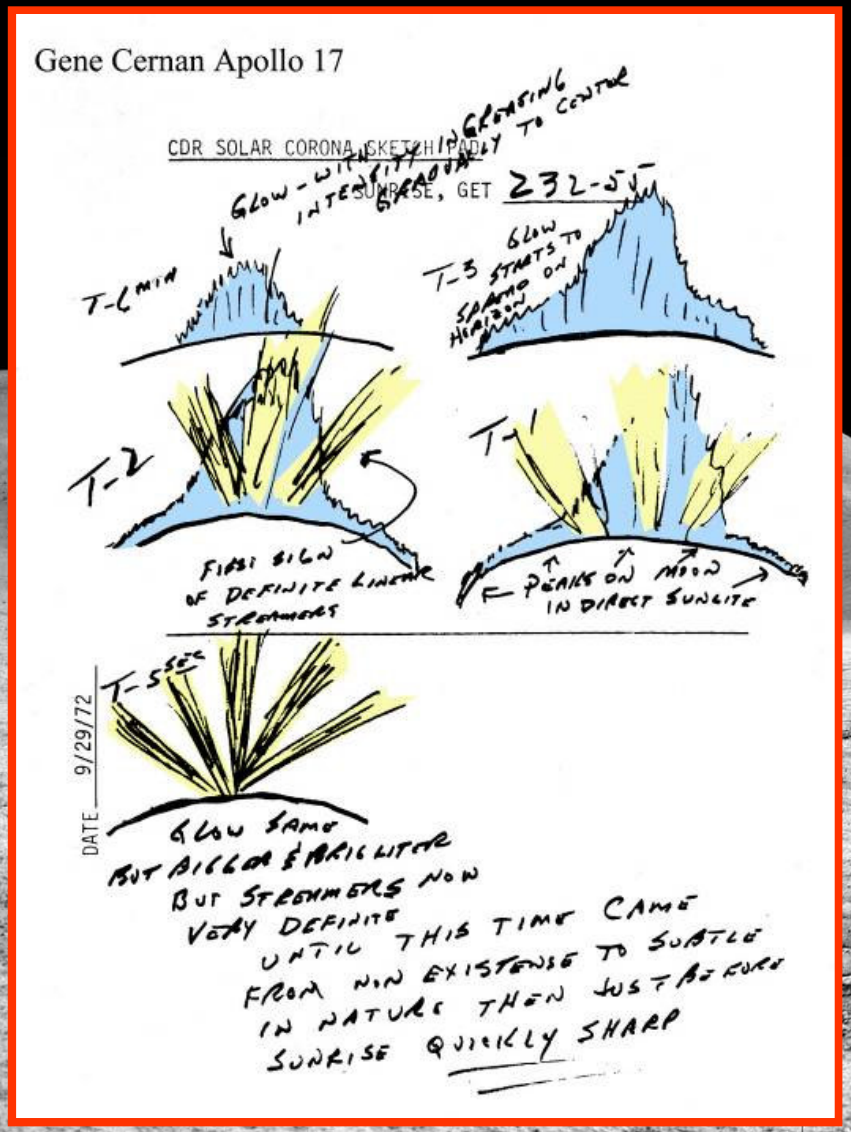
Excessive cleaning time
- brushing off, wiping down

Electrical conductivity
- discharge harming electronic/radio systems

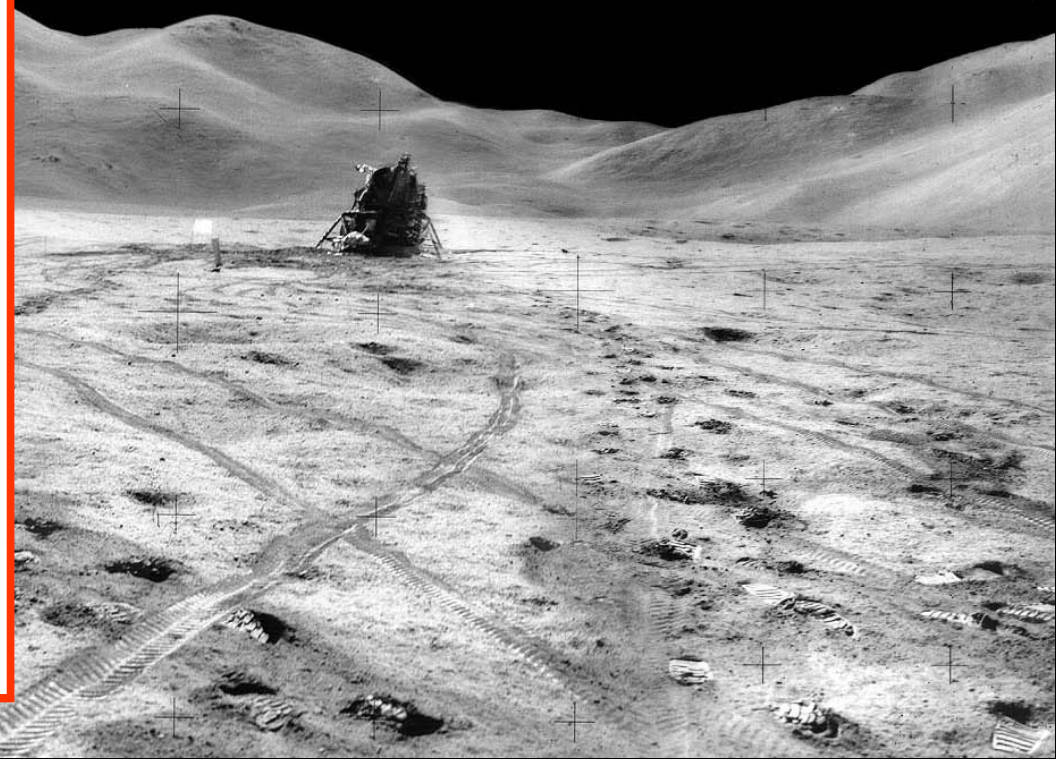
EVA: Extra Vehicular Activity

BIOASTRONAUTICS

The Terminator Cometh



- Solar Photons exceed the work function of atoms
- Particle charge approaches 10^4
- Dust levitates to altitude of over 1 km



NASA TRLs

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of- concept
TRL 4 Component and/or breadboard validation in laboratory environment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7 System prototype demonstration in a space environment
TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9 Actual system "flight proven" through successful mission operations

TRL: Technology Readiness Level

The Dreaded TRL 6!

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of- concept
TRL 4 Component and/or breadboard validation in laboratory environment
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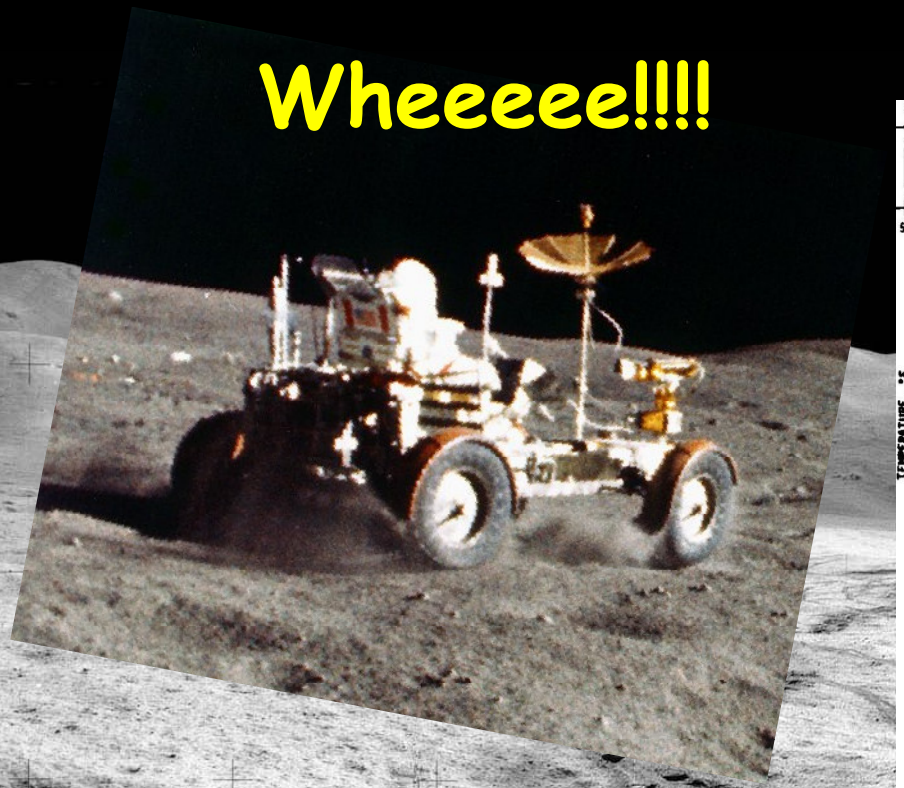
TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9 Actual system "flight proven" through successful mission operations

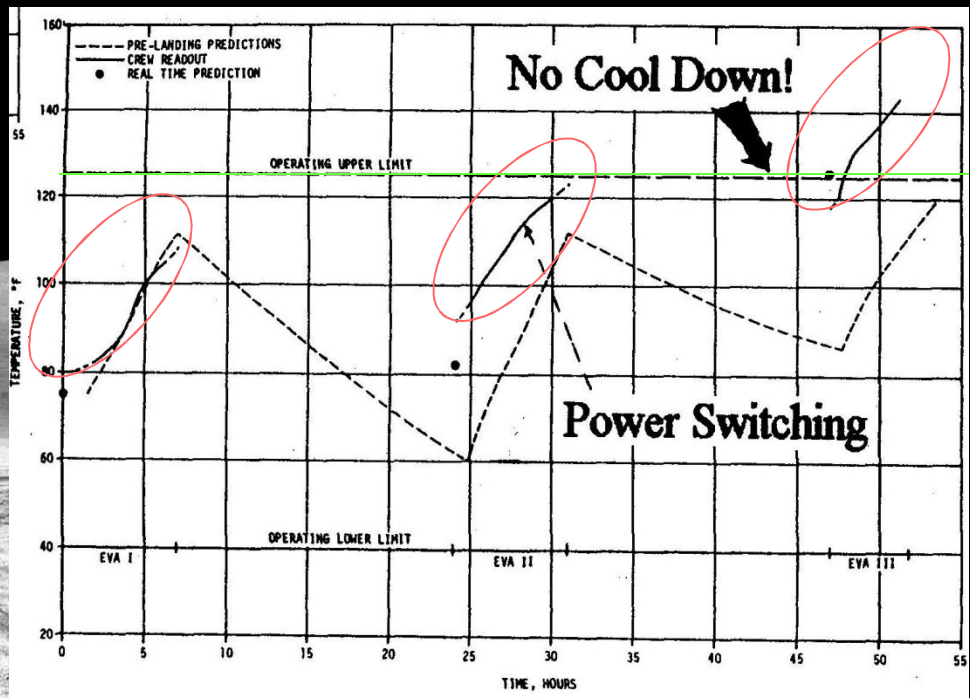
Cost to ship equipment to moon = ~$1M/Lb (circa 2009)

A Case Study in TRL 6

Oops.

Wheeeee!!!!





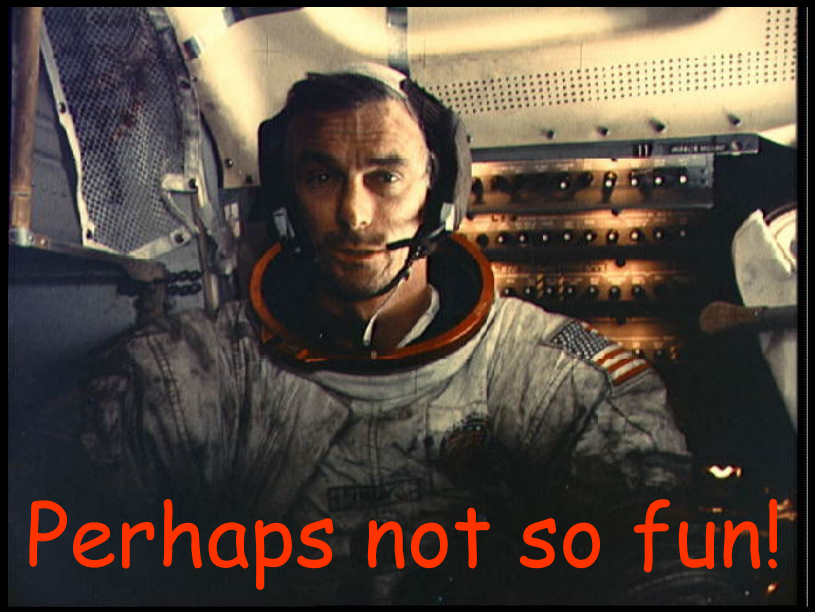
Battery No. 2 Temperature

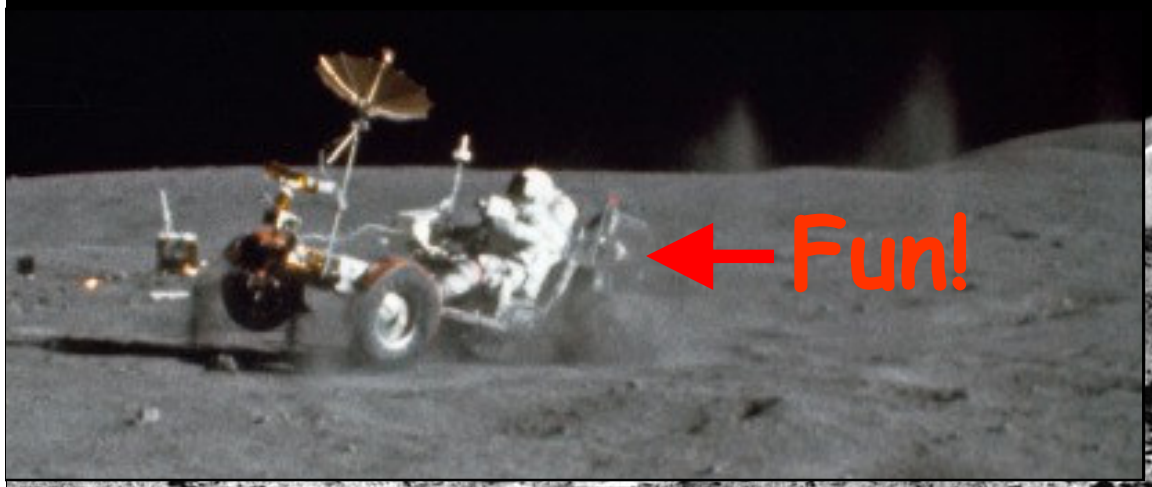
Dust Toxicology

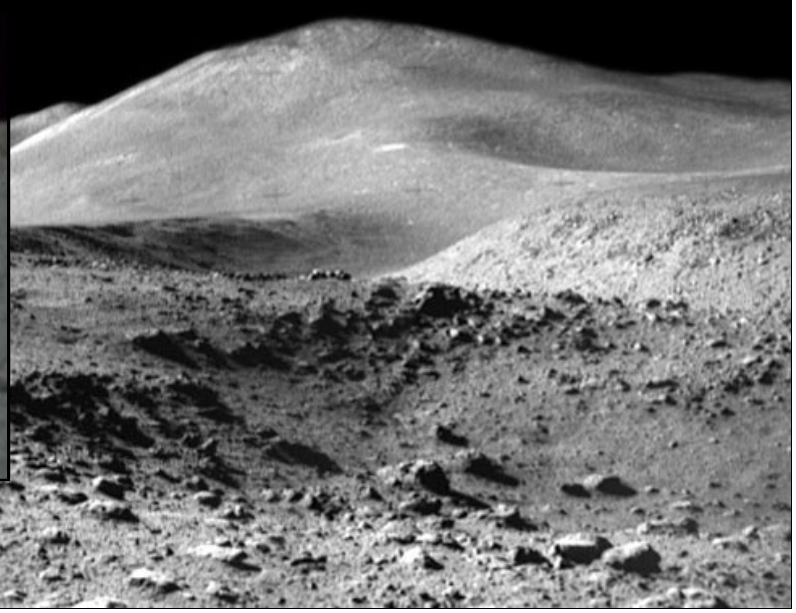
Dust gave off a distinctive, pungent odor

(Scott - it smelled a bit like gun powder)

Apollo 12 dust was an eye and lung irritant during the entire trip back.







Back to TRL 6

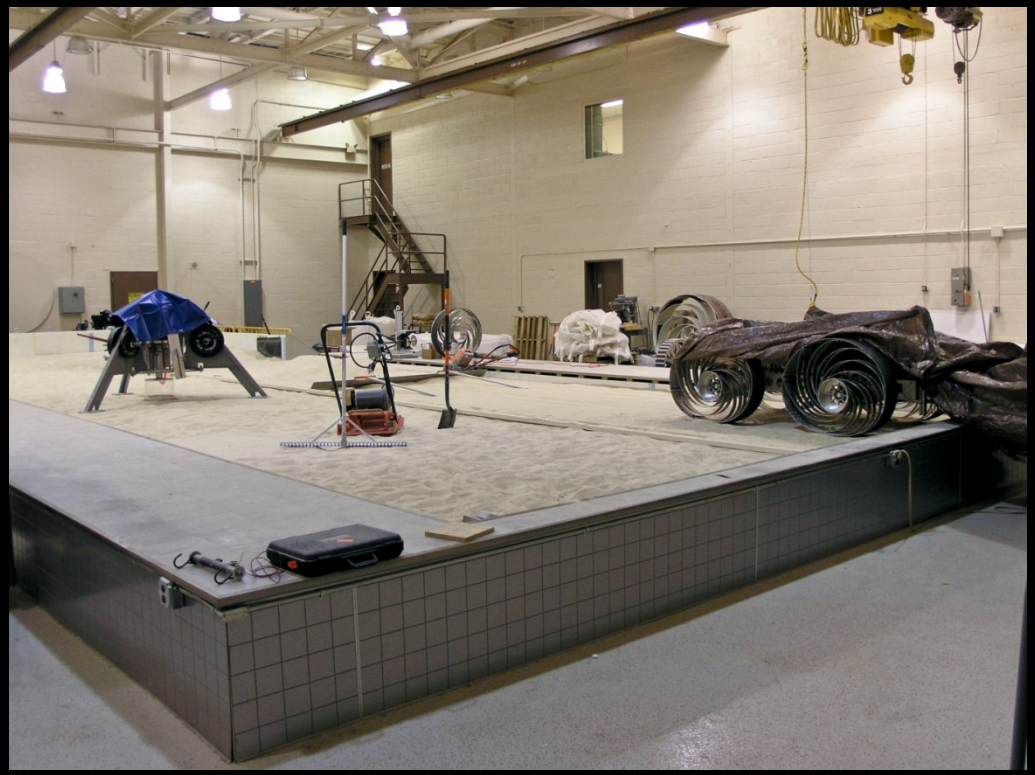
Between 1969 and 1972 six Apollo missions

382 kilograms (842 pounds)

lunar rocks, core samples, pebbles, sand and dust

Back to TRL 6

382 kg (842 pounds)
does not make the 40 Tons (80,000 Lb)
required to fill a sandbox!



Simulants!

BP-1

MLS-1 & 2

JSC-1…. and 1A!

NU-LHT

GRC 1& 3

KOHLS-1

OB-1

ChEn-OB

JSC-Mars-1A
And now for that
Quiz!

FJS-1
MKS-1

CAS-1 and
now 2 more

Simulants!

BP-1

MLS-1 & 2

JSC-1…. and 1A!

NU-LHT

GRC 1& 3

KOHLS-1

OB-1

ChEn-OB

JSC-Mars-1A
Who can pronounce
"Pu'u Nene"

FJS-1
MKS-1

CAS-1 and
now 2 more

Dust Management Program

Task 1.4.1 – Regolith Characterization
Task 1.4.3 – Simulant Development and Characterization

The 5 Most Important Properties

Particle Size Distribution and Shape
Adhesion, Friability and Elasticity
Abrasion
Tribo-charging & Electrostatics
Surface Reactivity and Chemistry (especially Corrosion)
Composition
Magnetic susceptibility, dielectric function & conductance
Surface Energy
Thermal Properties & evolved Gases
Emissivity

The FOMS (an MSFC Effort)

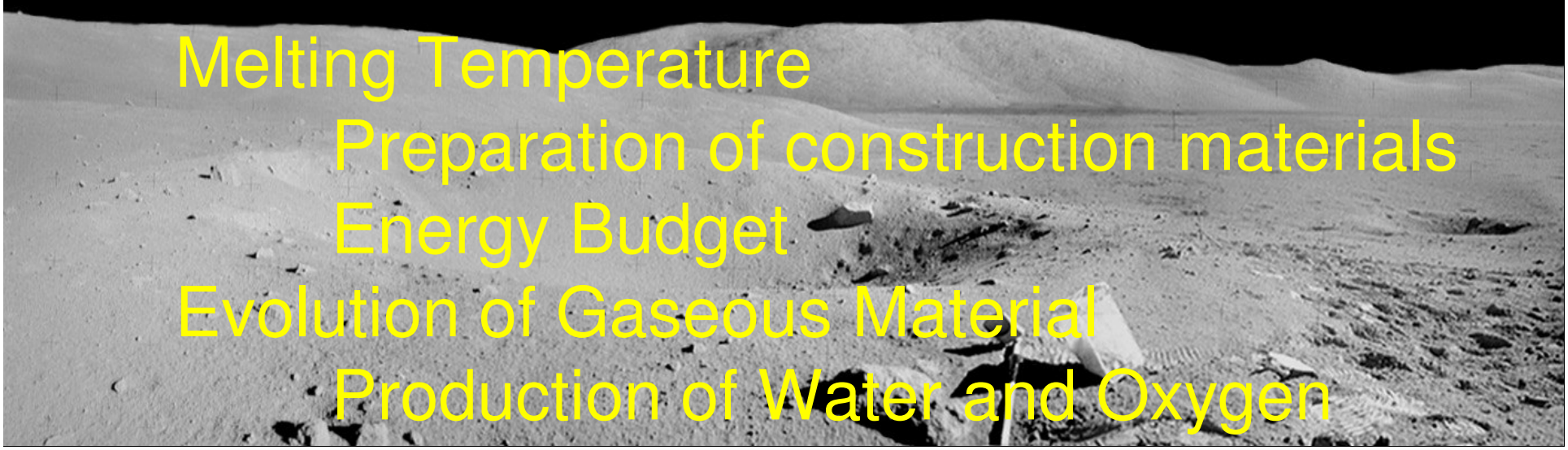
Figures of Merit (FOMs)
Prediction of simulant – Regolith similarity
Based on few key properties from which all other derived

- Particle Size
- Particle Shape
- Particle Composition
- Density (bulk)

Then there's the emissivity issue…

Thermal Properties of Interest

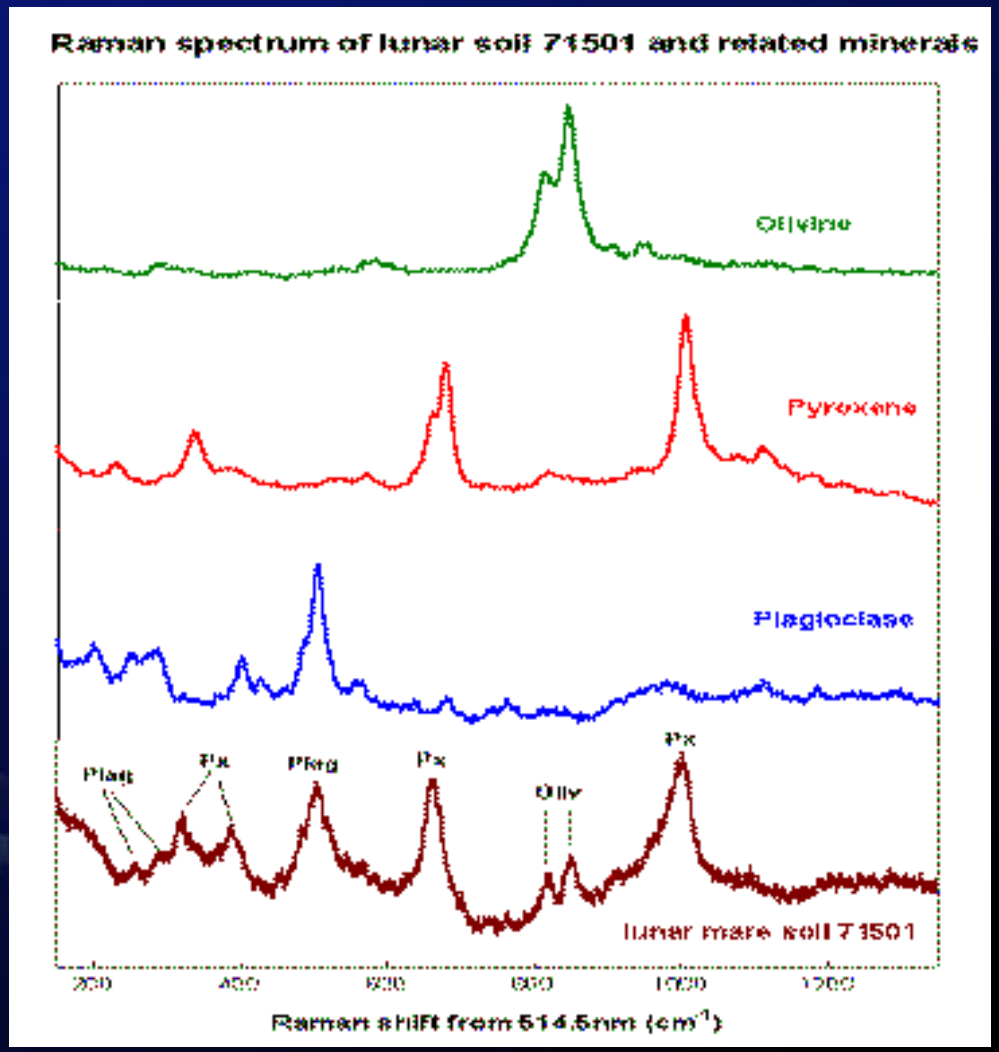
In order to achieve a sustainable presence on the Moon (or elsewhere) it will be necessary to process materials in-situ to provide shelter, bioconsumables, etc.



- Melting Temperature
  - Preparation of construction materials
  - Energy Budget
- Evolution of Gaseous Material
  - Production of Water and Oxygen

Lunar Composition

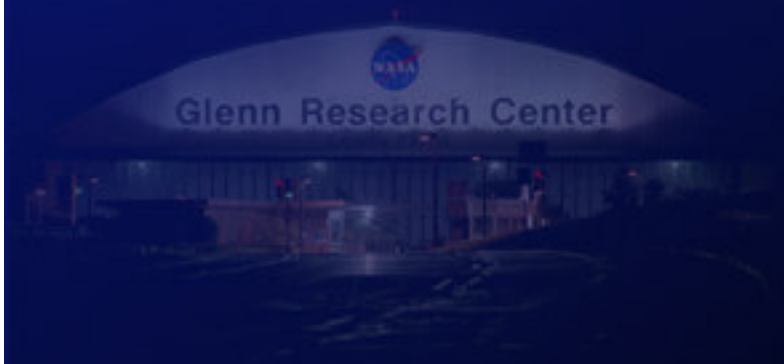
Mineral	%
Anorthite	A
Bytownite	M
Labradorite	M
Olivine	M
Fayalite	-
Forsterite	-
Clinoenstatite	M
Pigeonite	M
Hedenbergite	M
Augite	M
Enstatite	A
Spinel	m
Hercynite	m
Ulvospinel	m
Chromite	m
Troilite	t
Whitlockite	t
Apatite	t
Ilmenite	m
Native Iron	t
+ Norite Glass	**A**



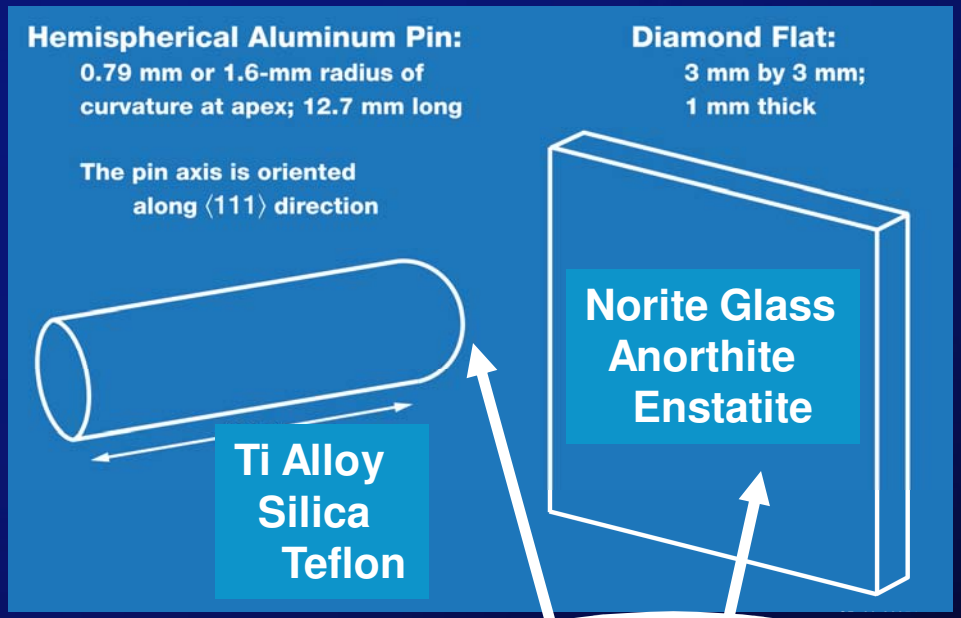
Equipment Design

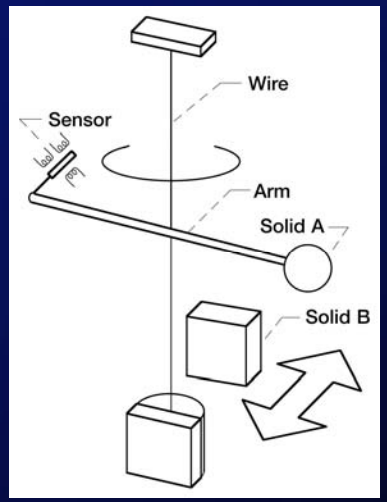
All interactions people and equipment will have with the surface of the Moon will be with the regolith.

Design engineers are now asking what materials and what over-design factors.



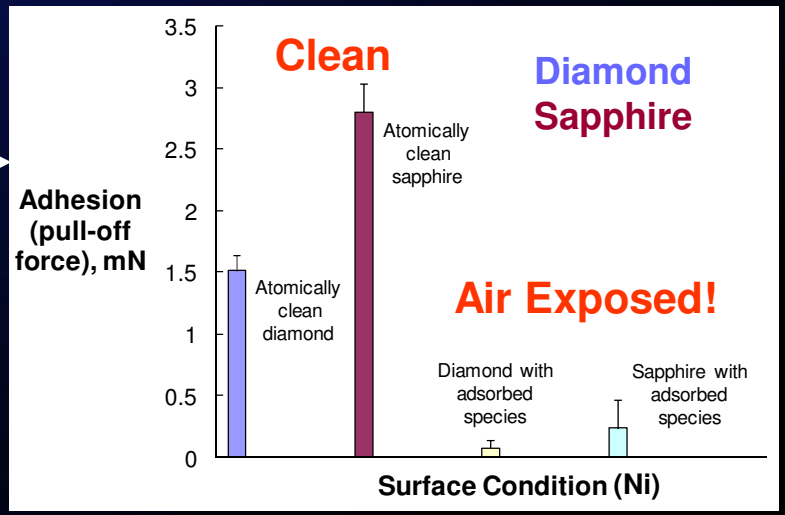
Adhesion





Miyoshi's Rig
~10^{-14} Torr

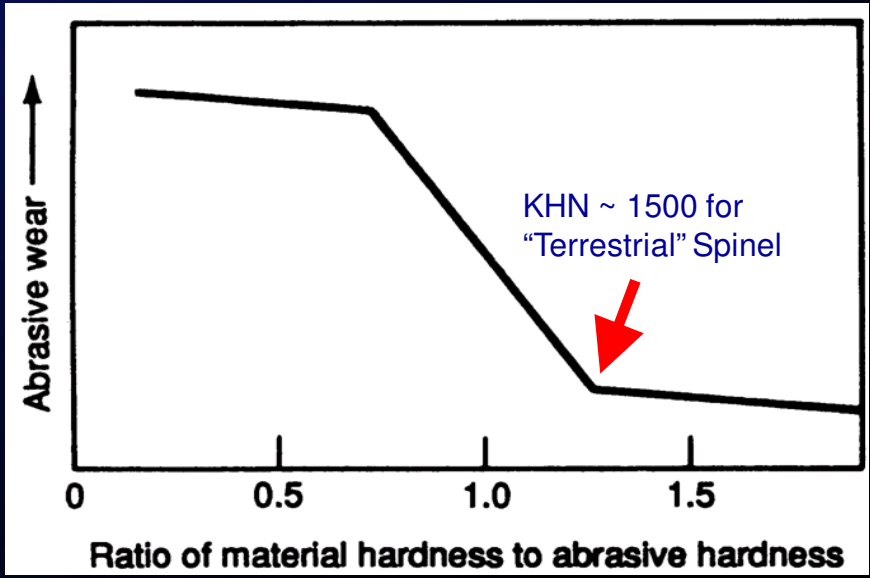
Auger Analysis



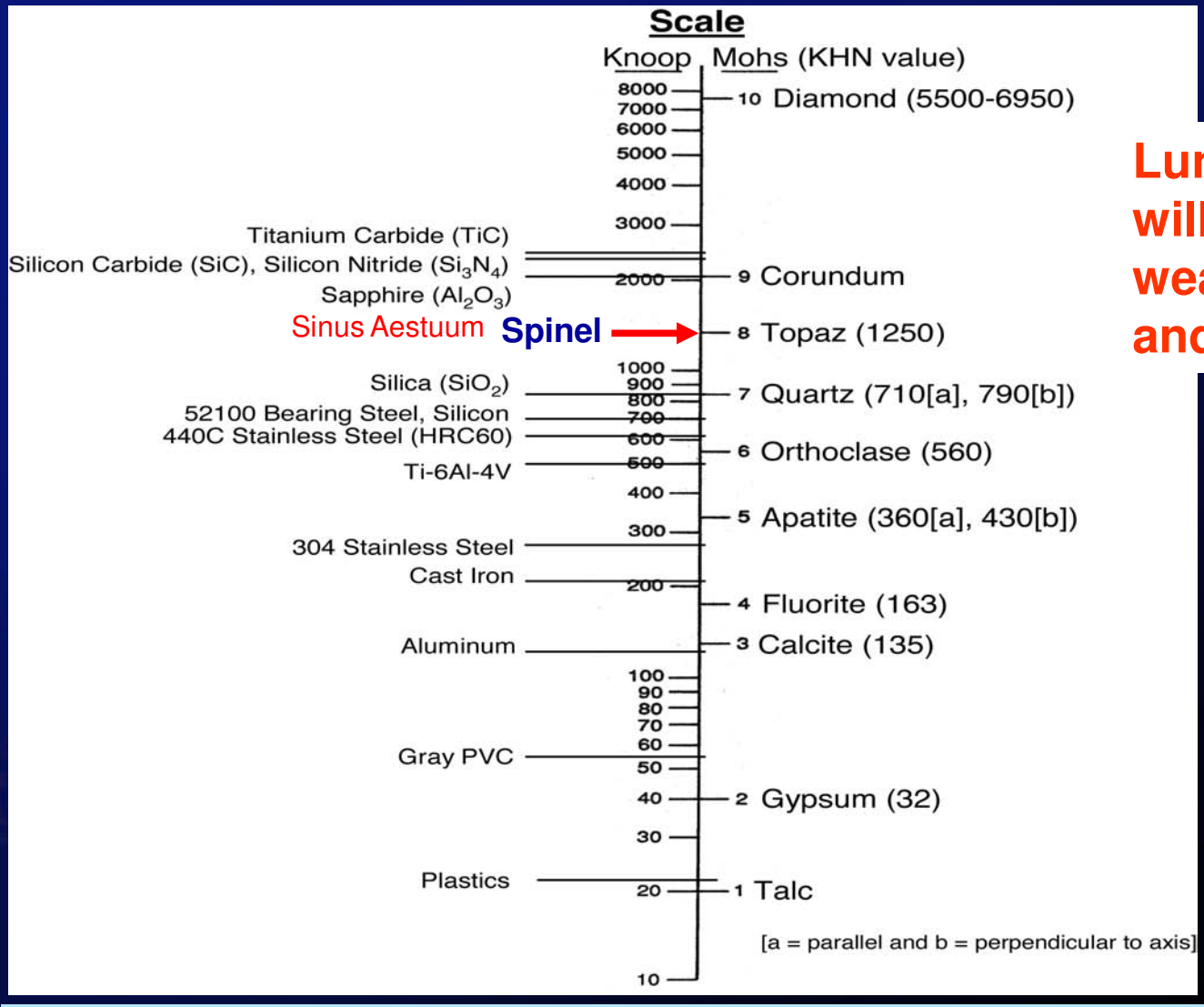
Abrasion

Mineral	Mohs	Mode: Fracture	%
Anorthite	6	Conchoidal	A
Labradorite	7	Conchoidal	M
Enstatite	5.0-6.0	Conchoidal	A
Spinel	7.5-8.0	Conchoidal	m
Hercynite	7.5-8	Uneven	m
Ulvospinel	5.5-6.0	Uneven	m

Relating Abrasivity to Hardness



Abrasion & Equipment Design



Lunar Regolith will cause extreme wear to Metals and Plastics

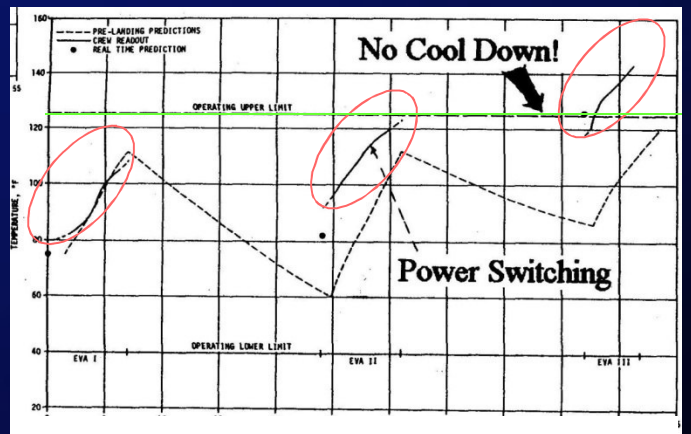
Emissivity (Emittance)

The Conservation Law:

$$\alpha(\lambda) + \rho(\lambda) + T(\lambda) = 1$$

where T = 0, absorptance = [1 - ρ(λ)]

through Kirchhoff's Law, α(λ) = ε(λ)



The Battery Cooling Problem

Regolith has high absorptance, low emittance

Dust is an insulator and also acquires heat from light

Thermal radiators have a big dust problem!

Conclusions

"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."

- Gene Cernan, Apollo 17 (technical crew debriefing)

We need to get to work!

- Regolith Evaluation
- Simulant Evaluation
- Figures of Merit (FoMs)
- Simulant Design & Production

Acknowledgements

Jeff Plescia – Applied Physics Lab, Johns Hopkins University
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Da-Ren Chen – Washington University in St. Louis
Ta-Chih "TC" Hsiao – Washington University in St. Louis
Kazuhisa "K" Miyoshi – GRC/Retired

Sponsored by the GRC DMP

And you for listening!