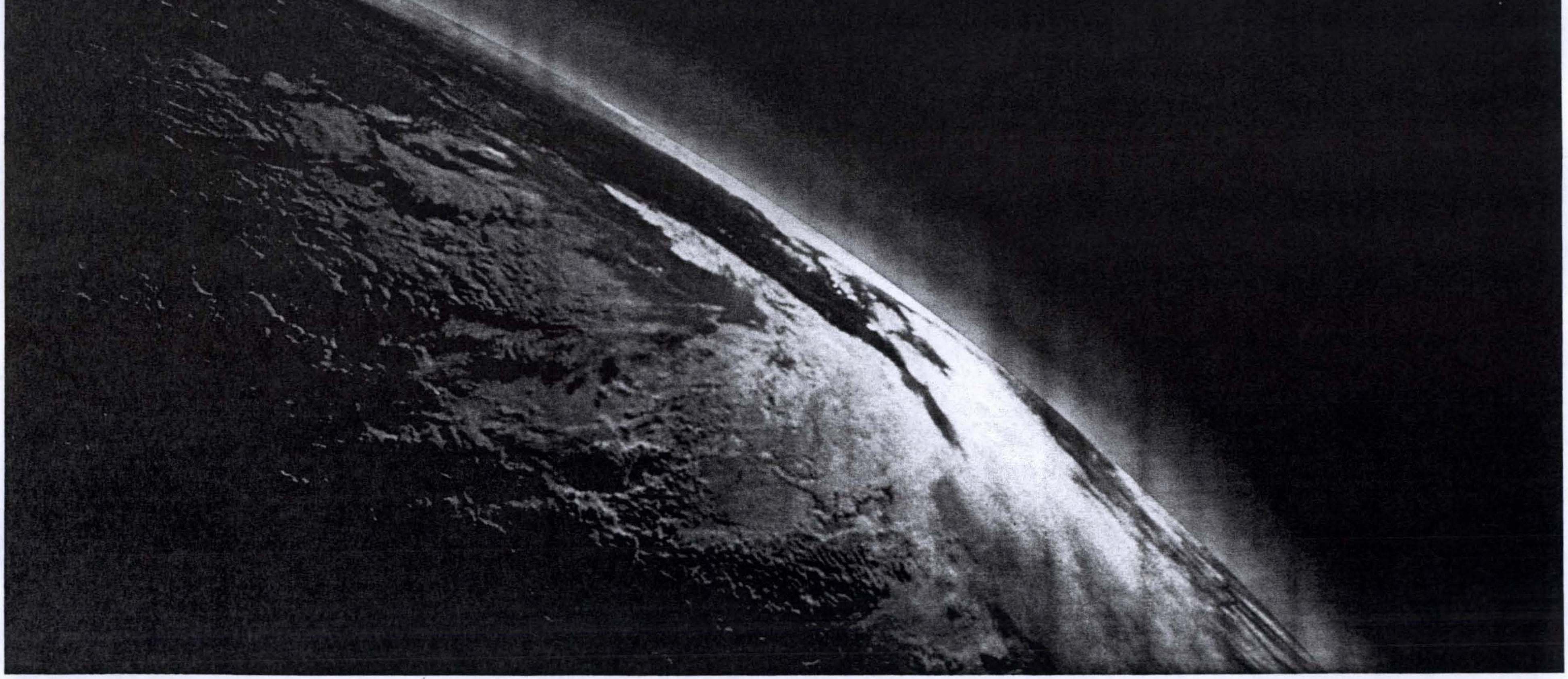
MSFC-771

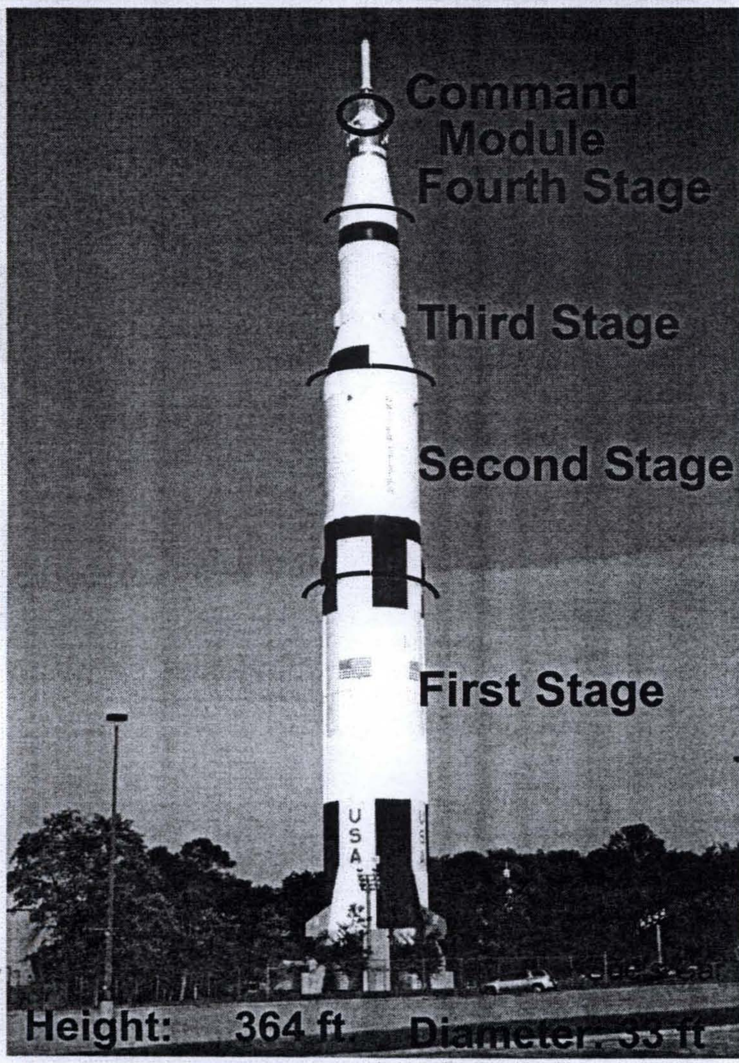
Overview of NASA Projects

Doug Rickman

Lead Applied Sciences Program
Marshall Space Flight Center




Regolith



	Weight (lbs.)	Altitude (miles)	Velocity (mph)
	12,807		
Service Module	54,064		
Lunar Module	32,299		
Trans Lunar Burn	265,000	239,000	24,500
Orbital Burn		115	17,500
	1,037,000	114	15,300
	4,881,000	38	6,000
	6,600,000		

D Rickman
April 16, 2008 6:07

Many simulants were made during the Apollo Program.

- Apollo made 34 different simulant materials.

Since then many more have been made.

Compositions have been extremely variable. Some with some rather "exotic" compositions.

How does one evaluate the suitability of a simulant for a purpose? By corollary, the question also arises: how can one compare different simulants?

The closest anyone has previously come to a quantitative comparative technique was Kanamori et al., (1998). They very briefly give a method of comparison which uses chemical analyses.

Five Parallel Efforts

- Define requirements
- Characterize Apollo Samples
- Identify resources
- Process Control
- Standards, including Figures of Merit

ASTM A269 Austenitic Stainless Steel vs. ASTM 3033 Aluminum

- Four characteristics
  1. Composition
     a) Lithic Fragments
     b) Mineralogy
     c) Glass
     d) Agglutinate
  2. Size Distribution
  3. Shape (may subdivide this)
  4. Density
- Measurement methods are stipulated
- Compares simulant to specific Apollo regolith samples (core and/or surface samples)
- As needs change, requirements and FoMs may be added, deleted or modified.

A *Figure of Merit* (FoM) is an algorithm for quantifying a single characteristic of a simulant and provides a defined measure of how a simulant and reference material compare.

The *Figure of Merit* termed "composition" defines the geologic constituents of the simulant without reference to textural features, such as particle shape and particle size.

Composition includes the following constituents:

- lithic fragments,
- mineral grains,
- glasses and
- agglutinates.

Composition addresses the mineralogic and chemical makeup of the simulant. The *Simulant Requirements Document* (Rickman and Howard, 2006 draft) specifies the rock types, minerals, glass composition which may or may not be used to establish a simulant.

The composition of a material (reference or simulant) may be viewed as a vector of the fractions of the various constituents of the material.

Observation 1 - The elements of a composition vector must necessarily sum to unity (the sum of the fractional parts must equal the whole) **excluding** contaminants. Mathematically, this may be stated as the L1-norm of a composition vector is always 1.

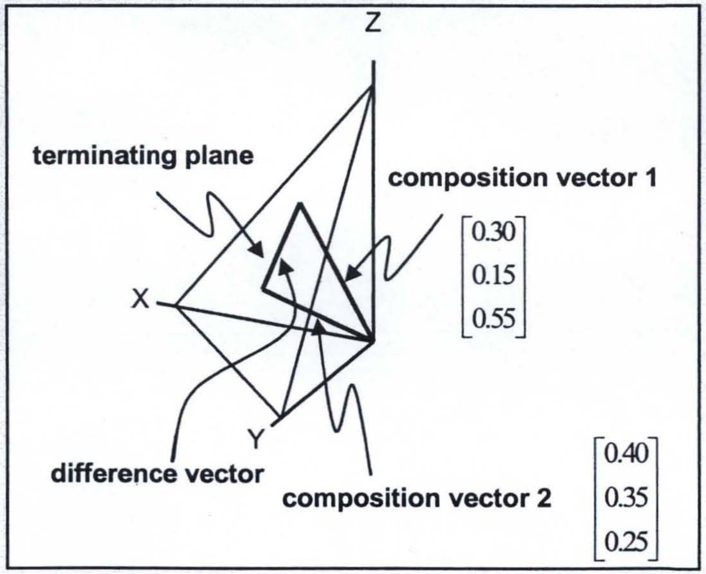
Observation 2 - A composition vector always terminates on a line (2 dimensions), a plane (3 dimensions) or hyper-plane (4 or more dimensions) which intersects the composition space coordinate frame axes at the unity coordinate points. This follows from the fact that we may write the following equation for the L1 norm of the composition vector:

$$x+y+z = 1$$

where x is the fraction of the 1st component, y is the fraction of the 2nd component, z is the fraction of the 3rd component… which is the defining equation for a hyper-plane.

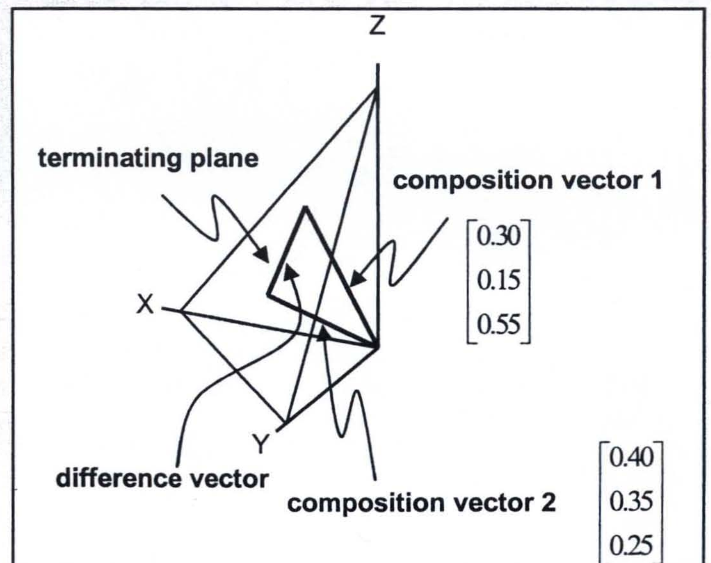
Remember a *Figure of Merit* is a comparison of a reference material to an actual material or better, the comparison of two materials.

The *Figure of Merit* (r) is defined as the normalized difference of two composition vectors subtracted from unity. Normalization forces the difference of two composition vectors to lie between 0 and 1, and subtraction from unity results in a *Figure of Merit* of 1 for a perfect match to 0 for no match at all (as opposed to the other way around).



The difference of two composition vectors must always lie in the terminating hyper-plane (because this is where both vectors terminate).

It is obvious that the maximum difference between two vectors results if one material is entirely of one composition, and the other entirely of another. The two composition vectors for such a case would lie along any two of the coordinate frame axes defining the composition coordinate space (and would necessarily be orthogonal).



Two such vectors form the sides of an isosceles triangle, whose hypotenuse is of length $\sqrt{2}$ since the length of each composition vector is 1. Thus the maximum difference between any two composition vectors is $\sqrt{2}$ and this is the normalization factor for their difference.

The *Figure of Merit* defined for composition also has a weighting vector to weight the composition vector difference. This allows favoring certain components of composition over others. This is equivalent to scaling the axes of the composition space, which has the result that the maximum difference between two different compositions may be other than $\sqrt{2}$

However, it may be shown that in this case the maximum difference between two different composition vectors is the square root of the sum of the squares of the two largest weights:

$$\textit{normalization factor} = \sqrt{\max_1{}^2(w) + \max_2{}^2(w)},$$

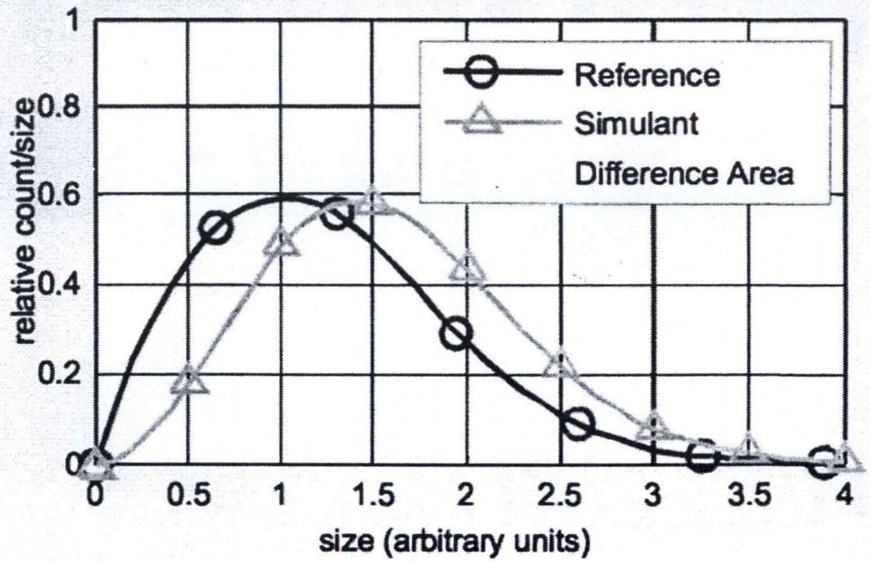
Where $\max_1{}^2(w)$ is the i[th] largest element of the weighting vector *w* whose weighted square will be computed for the *Figure of Merit*

The *Figure of Merit* for particle size distribution is similar to the one for composition. In place of composition vectors, we have particle size relative frequency distributions for the two materials under comparison.

The process is reminiscent of a least squares fit, the difference being that we compute the sum of the squares of the difference, rather than minimize it.

1. Compute the square root of a weighted sum of the squares of the difference between the two distributions (an integral),
2. normalize by the maximum possible square root of the weighted sum of the squares of the difference and
3. subtract from unity,

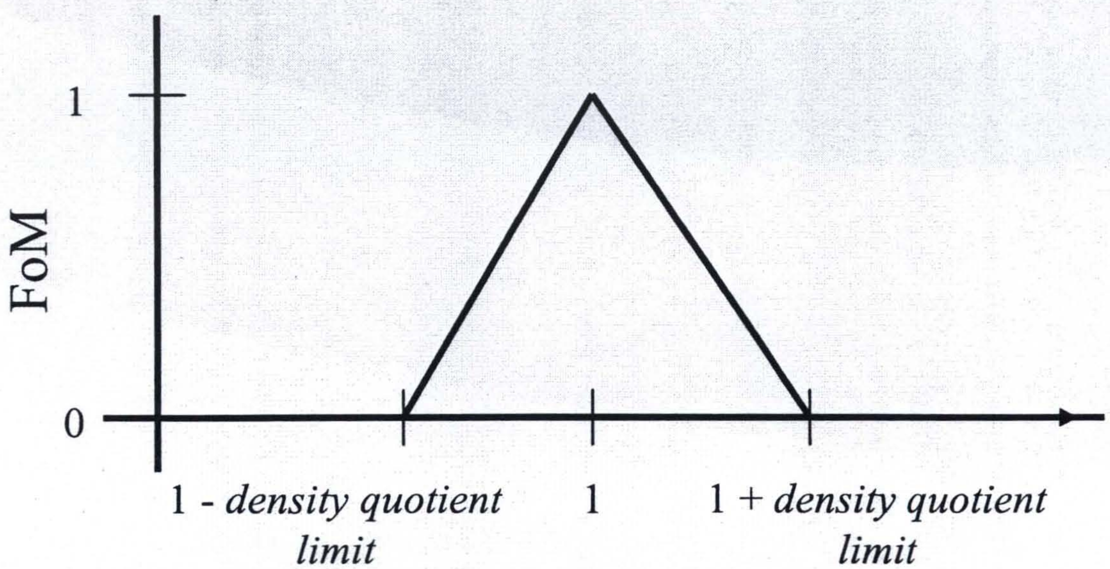
The figure shows the difference area in yellow.



D Rickman
April 16, 2008 6:07

The *Figure of Merit* for density (there are several possible) is computed from the ratio of the densities of two materials. A penalty factor (whose magnitude is between 1 and 0 depending on the distance from 1) is used to force the quotient to go to zero at a user specified point.

The density *Figure of Merit* graphically is



FoMs are critical to defensible specifications for procurement of simulant. Some users will need higher FoMs than others. Note a FoM is a tolerance.

- Numbers approaching 1 are better reproductions of the reference material. This implies:

  - closer tolerances
  - additional quality control in
    - collection, processing, and blending,
  - and particular attention to minimizing contamination.

- Potential vendors may use offsite analytical techniques to verify the simulant FoMs.

- Tighter production tolerances or secondary processing are expected to drive higher costs to the end user.

Contamination

Measurement technology

FoM for Shape

- Expressed as a computer algorithm with fixed inputs.
- Designed to be extensible in response to new knowledge or needs
- Many, many practical virtues
    - •Can compare between simulants
    - •Standardized, objective method
    - •Users do not have to understand the all the details of the background skills which go into making the simulant
    - •Producers shielded from vague specifications

Some Expected Mechanical Characteristics of Lunar Dust: A Geological View

Doug Rickman
National Space Science and Technology Center
NASA - Marshall Space Flight Center
Huntsville, AL 35805 USA
256-961-7889
doug.rickman@nasa.gov

Kenneth W. Street
Tribology and Surface Science
NASA – John Glenn Research Center
Cleveland, OH 44135 USA
216-433-5032
kenneth.w.street@nasa.gov

Lunar Geologic History

Initial lunar rock ~ norite.

Subsequent basaltic volcanic (& other)flows.

Hypervelocity impacts largely destroyed original rock.

Resulting broken material covering surface = Regolith.

Except for some outcrops in or around the mare,
all interactions (people, equipment, etc.)
will be with regolith!

Subsequent Geologic Processing

Particle Size -

Net result of continuing meteor bombardment.

Surface of Moon is ground mixture of fragments.
Size range: nanoscopic to large blocks of rock.

Mixture believed to be meters deep everywhere.

For Apollo mission samples
typical <u>average</u> particle sizes from ~ 30 to 100 um.

Subsequent Geologic Processing

Sorting -

All Terrestrial particles are sorted.
Based on size, shape and composition.

No Terrestrial segregation processes operate in a vacuum.

Energy input lunar surface sufficient to cause particle motion.
Can mix but not sort.

What designers can expect:
for any reasonable sized sample
from top few meters
it is possible, and even probable to have:
Particles of all size ranges and
Any lunar component in the sample.

Subsequent Geologic Processing

Particle Composition -

Lunar dust fraction (material < 20μm):
currently not well characterized.

Some aspects may or may not be important:
presence of nanoscopic Fe.
vapor deposited rims.

Regolith (macroscopically) is minerals and silicate glass.

Mineral is:
naturally occurring substance.
characteristic, limited chemical composition.
highly ordered atomic structure.

Therefore the range of each mineral's properties is:
limited.
properties basically source independent (lunar or terrestrial).

Rock Names

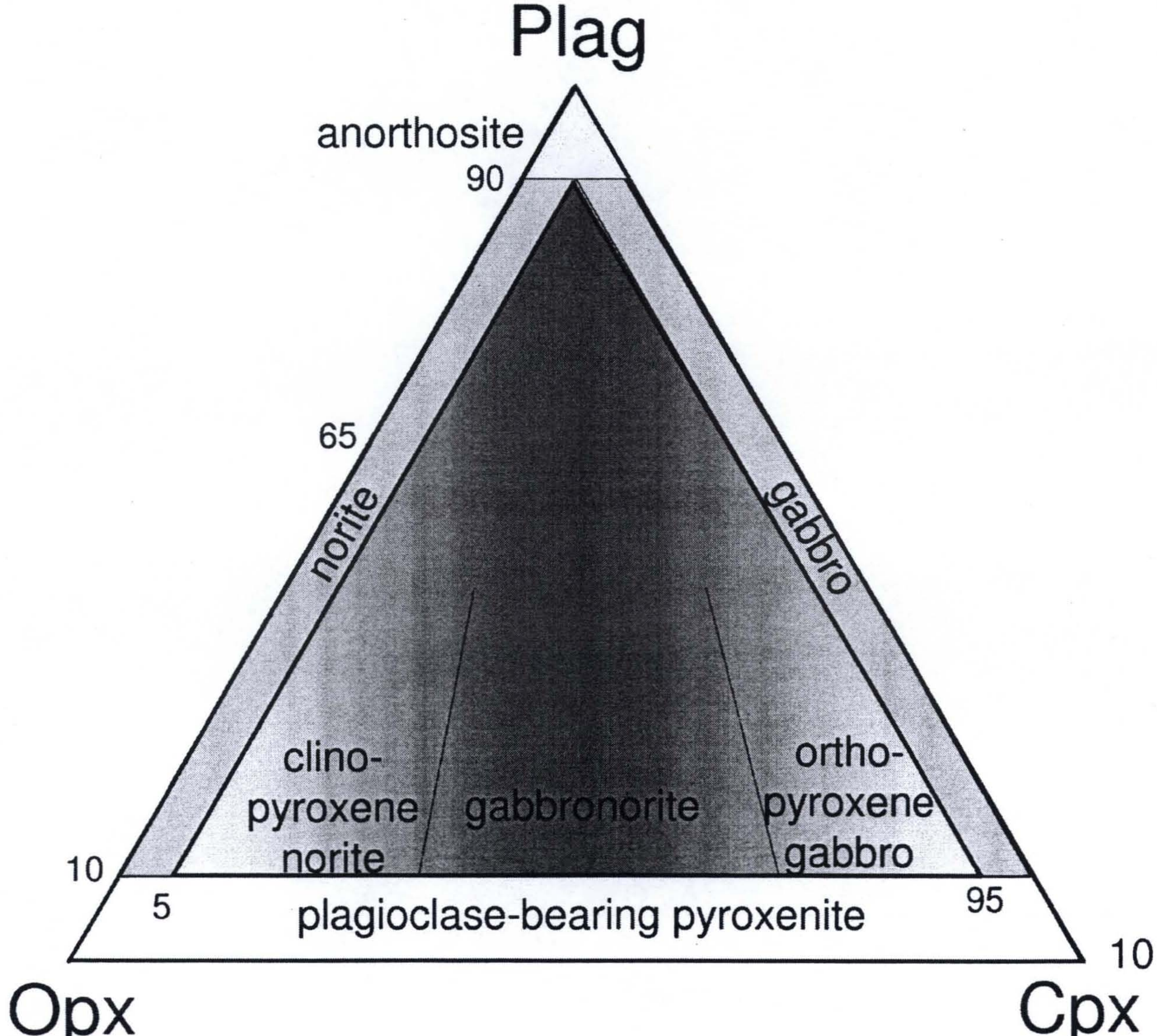

Plag
anorthosite
90
65
10
norite
gabbro
clino-
pyroxene
norite
gabbronorite
ortho-
pyroxene
gabbro
5
95
plagioclase-bearing pyroxenite
10
Opx
Cpx

TABLE 1. Significant Lunar Minerals..

	Mineral	Dana #	Mohs	Spec Gravity	Chemical Composition
Plagioclase	Anorthite	76.1.3.6	6	2.75	$CaAl_2Si_2O_8$
	Bytownite	76.1.3.5	6.0-6.5	2.73	$(Ca,Na)(Si,Al)_4O_8$
	Labradorite	76.1.3.4	7	2.71	$(Ca,Na)(Si,Al)_4O_8$
Olivine	Fayalite	51.3.1.1	6.5-7.0	4.39	Fe_2SiO_4
	Forsterite	51.3.1.2	6.5-7.0	3.24	Mg_2SiO_4
Pyroxene	Clinoenstatite	65.1.1.1	5.0-6.0	3.4	$Mg_2\,[Si_2O_6]$
	Pigeonite	65.1.1.4	6	3.3	$(Mg,Fe^{+2},Ca)_2[Si_2O_6]$
	Hedenbergite	65.1.3a.2	6	3.5	$CaFe^{+2}[Si_2O_6]$
	Augite	65.1.3a.3	5.5-6.0	3.3	$(Ca,Na)(Mg,Fe,Al,Ti)[(Si,Al)_2O_6]$
	Enstatite	65.1.2.1	5.0-6.0	3.4	$Mg_2[Si_2O_6]$
Spinel	Spinel	7.2.1.1	7.5-8.0	3.56	$MgAl_2O_4$
	Hercynite	7.2.1.3	7.5-8	3.93	$Fe^{+2}Al_2O_4$
	Ulvospinel	7.2.5.2	5.5-6.0	4.7	$TiFe^{+2}{}_2O_4$
	Chromite	7.2.3.3	5.5	4.7	$Fe^{+2}Cr_2O_4$
	Troilite	2.8.9.1	4	4.75	FeS
PO4	Whitlockite	38.3.4.1	5	3.12	$Ca_9(Mg,Fe^{+2})(PO_4)_6(PO_3OH)$
	Apatite	41.8.1.0	5	3.19	$Ca_5(PO_4)_3(OH,F,Cl)$
	Ilmenite	4.3.5.1	5.5	4.72	$Fe^{+2}TiO_3$
	Native Iron	2.9.1.1	4.5	7.87	Fe

TABLE 1. Significant Lunar Minerals. %: A-abundant, M-major, m-minor, t-trace.

	Mineral	Mohs	Mode: Cleavage	Mode: Fracture	%
Plagioclase	Anorthite	6	{001} p, {010} g	Conchoidal to uneven; brittle	A
	Bytownite	6.0-6.5	{001} p, {010} g	Conchoidal to uneven; brittle	M
	Labradorite	7	{001} p, {010} g	Conchoidal to uneven; brittle	M
Olivine	Fayalite	6.5-7.0	{010} moderate, {100} weak	Conchoidal	-
	Forsterite	6.5-7.0	{100}, {010} i - g; {001} po -f	Conchoidal	-
Pyroxene	Clinoenstatite	5.0-6.0	{110} g - p	Brittle	M
	Pigeonite	6	{110} p	Conchoidal to uneven; brittle	M
	Hedenbergite	6	{110} g	Conchoidal to uneven	M
	Augite	5.5-6.0	{110} g	Uneven	M
	Enstatite	5.0-6.0	{210} g - p	Conchoidal	A
Spinel	Spinel	7.5-8.0	No cleavage	Conchoidal	m
	Hercynite	7.5-8	No cleavage	Uneven	m
	Ulvospinel	5.5-6.0	No cleavage	Uneven	m
	Chromite	5.5	No cleavage	Uneven	m
	Troilite	4	No cleavage	Uneven	t
PO4	Whitlockite	5	No cleavage	Uneven to sub-conchoidal	t
	Apatite	5	No cleavage	Uneven to conchoidal	t
	Ilmenite	5.5	No cleavage	Conchoidal	m
	Native Iron	4.5	{001} i - f	Hackly	t

p = perfect; g = good; f = fair; I = indistinct; po = poor

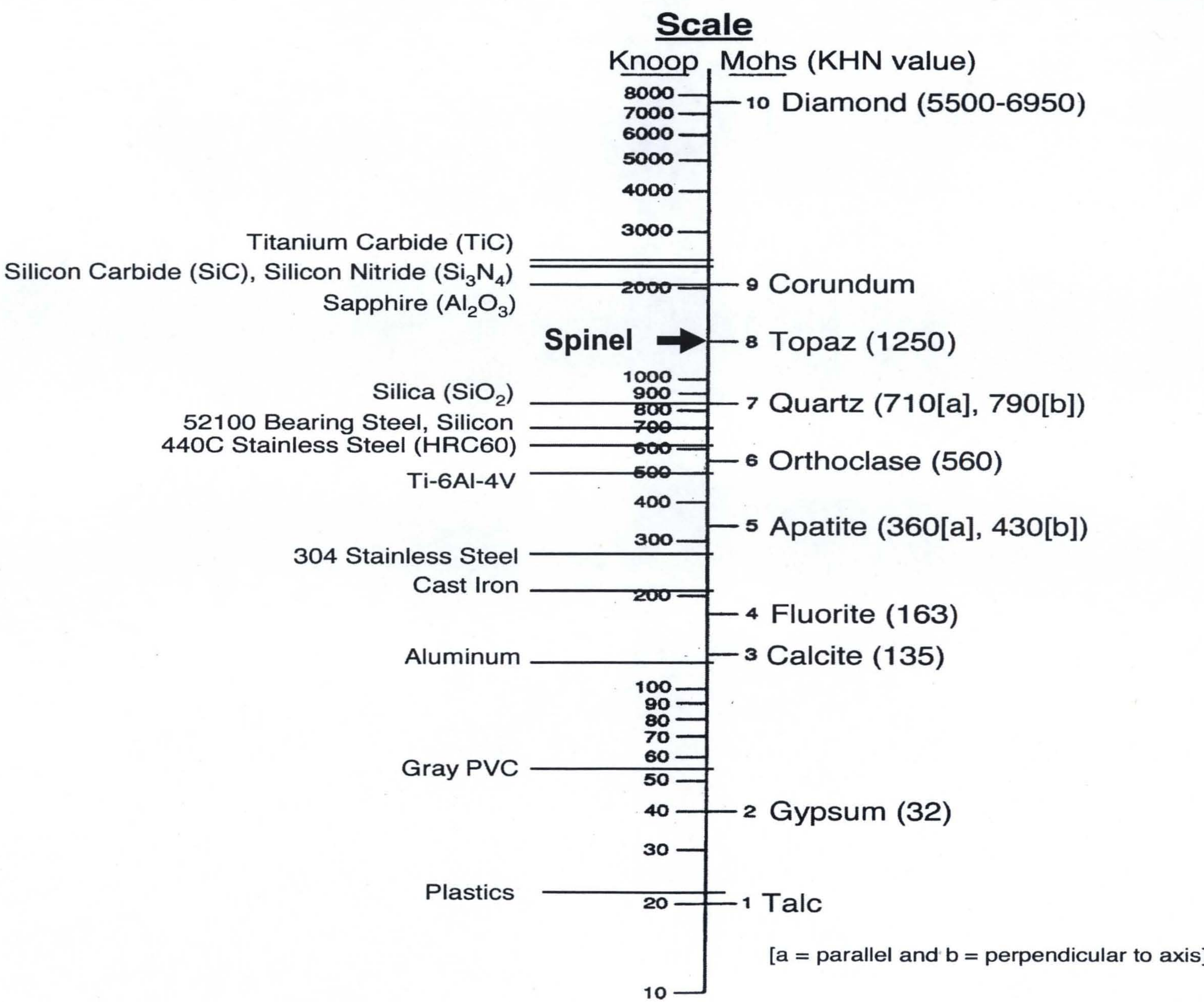
Material Testing Methods

- Indentation: Hardness
  - Brinell, Knoop, Rockwell, Vickers, …..
    (plasticity)

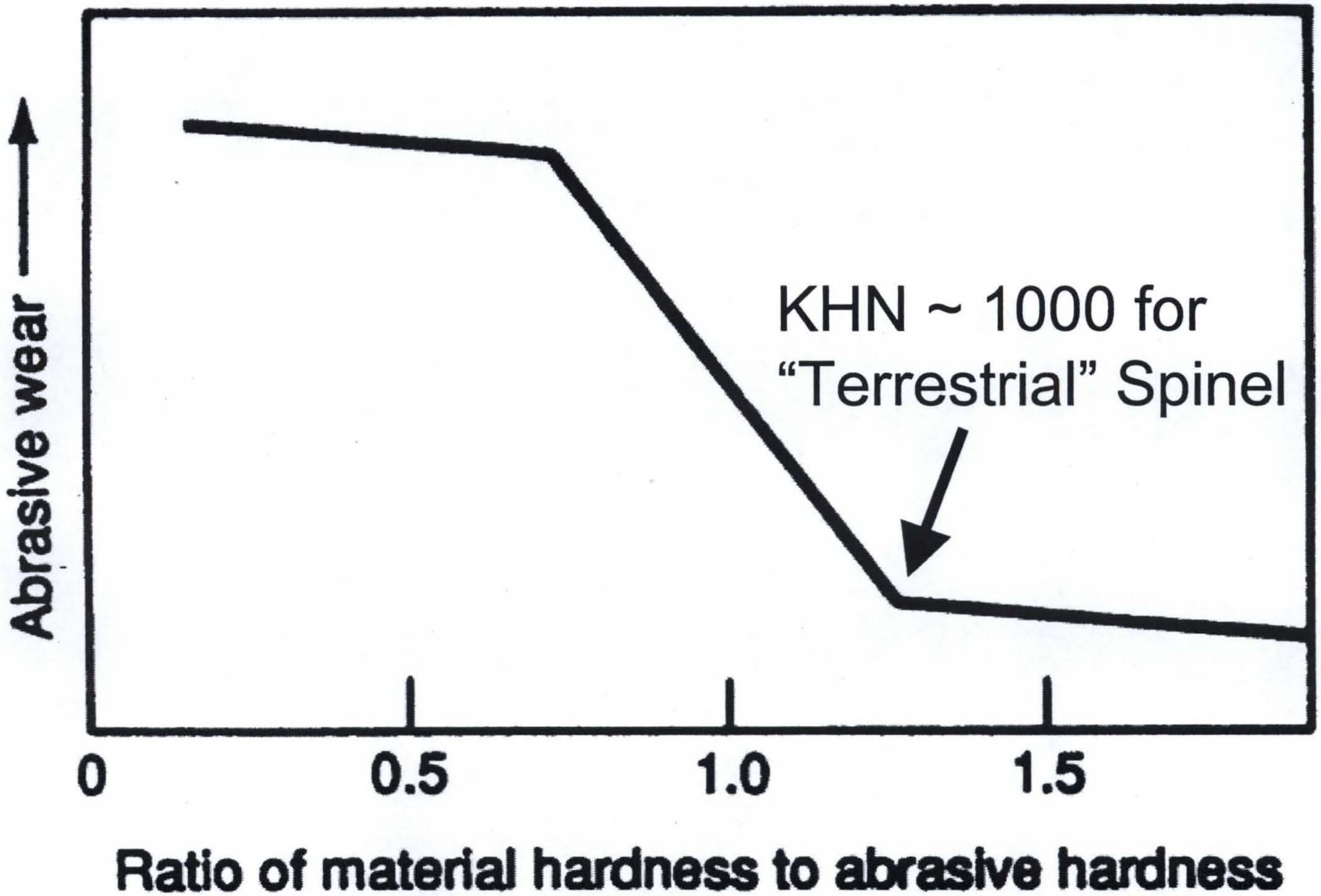
- Impaction: Brittleness
  - Falling Weight, Incline Impact, ….
    (toughness)

- Scratch
  - Mohs, Diamond Stylus, ….
    (abrasion – A key issue in Lunar exploration!)

Relating Hardness Scales:
Mineral (scratch) vs. Metal (indentation)

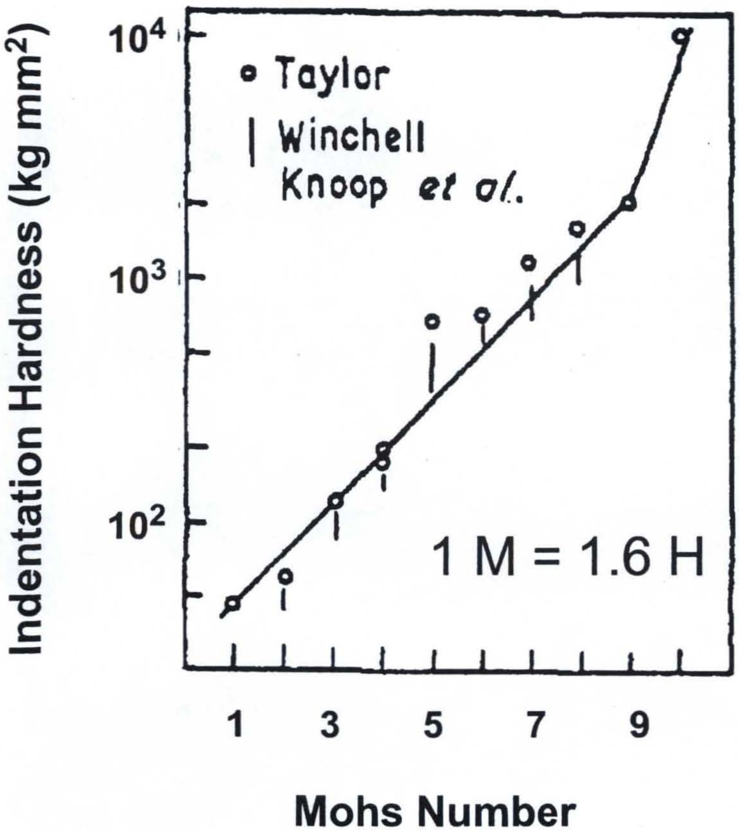


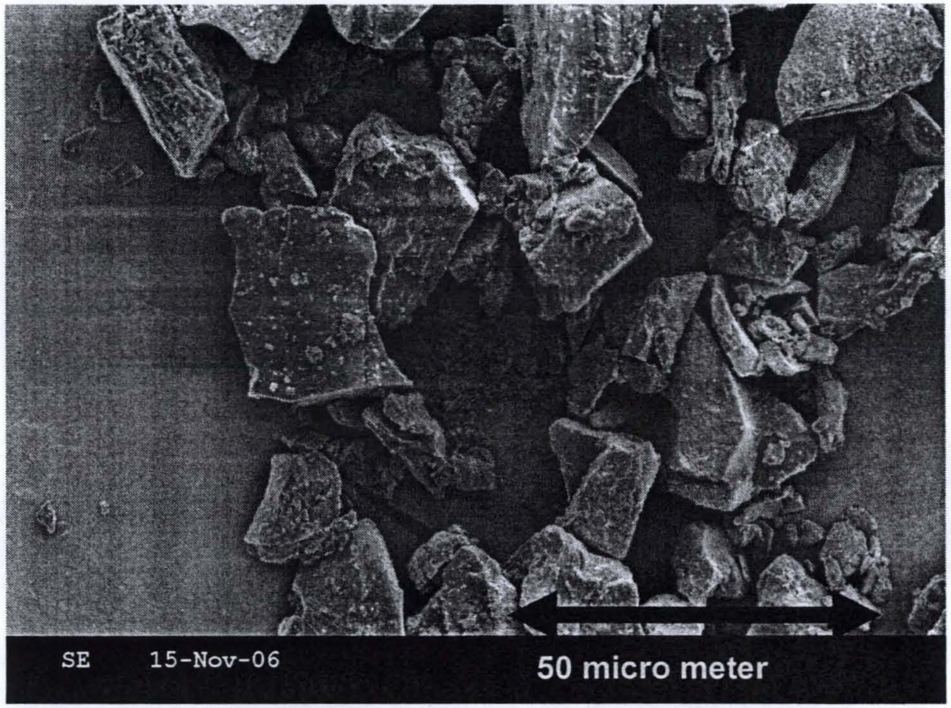
Effect of Hardness on Abrasiveness



The microhardness of synthetic corundum is significantly lowered by water adsorbed from the air. Such softening is commonly experienced by a wide variety of nonmetallic materials (although not by metallic substances). **On the moon things will be worse!!!**

Hardness and Geometry

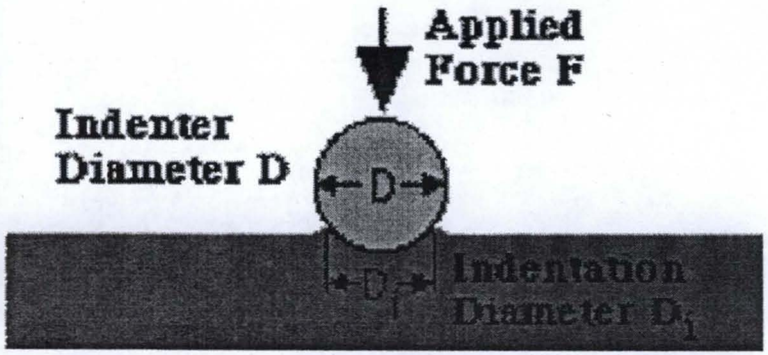




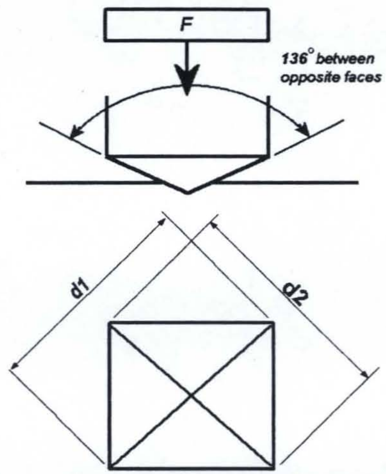
SEM of JSC-1a

Hardness Measurements

Brinell Hardness

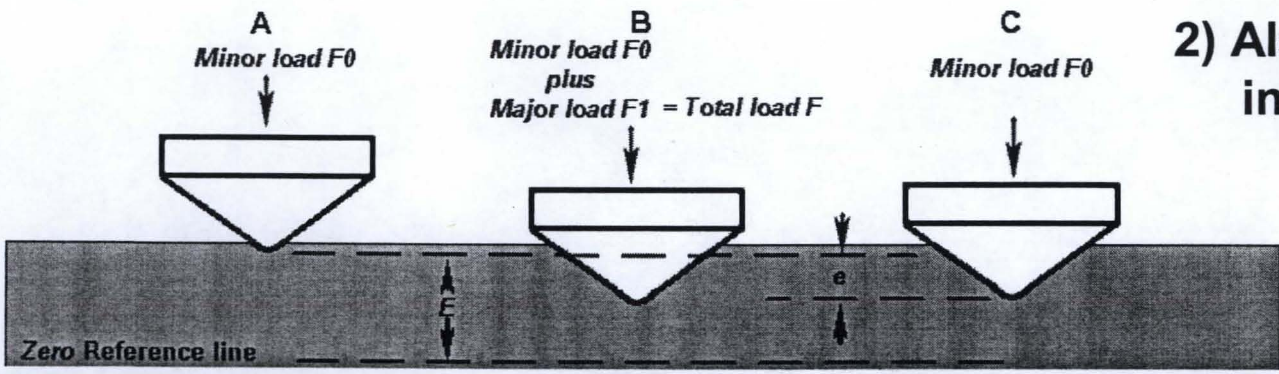


Vickers Hardness



Knoop Hardness

Rockwell Hardness



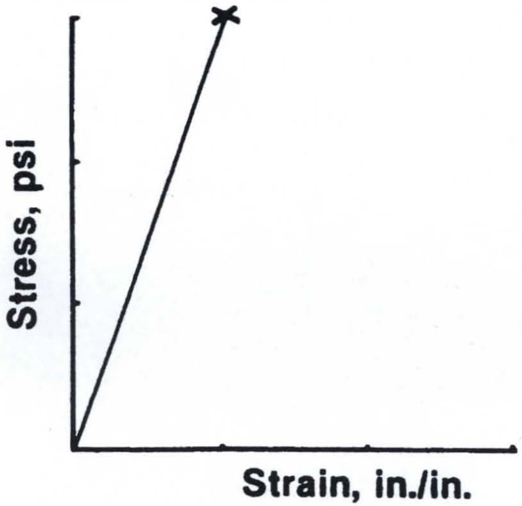
1) Incremental indent
2) Also uses spherical indenter

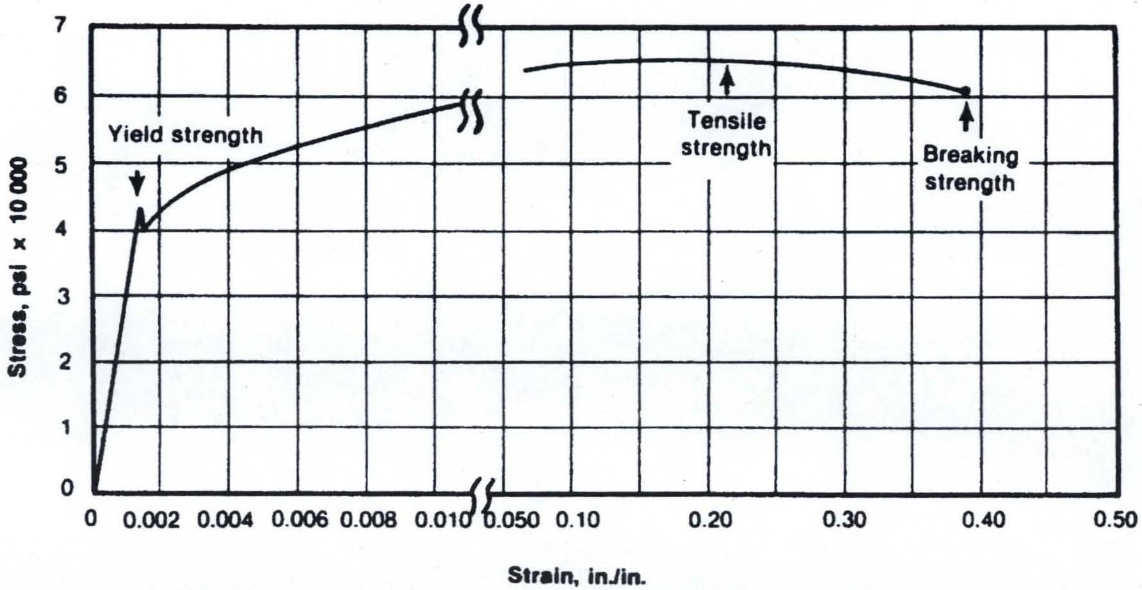
Table 2. Approximate Correlation Between Hardness Scales.

Hardness Values (load)						
HV (10 kg)	HB (500g)	HB (3 kg)	HRB	HRC	KHN (10 g)	KHN (1 kg)
1865	-	-	-	80	-	-
832	-	739	-	65	-	-
595	-	560	120	55	840	605
254	201	240	100	23	376	250
156	133	153	81	0	223	145
70	53	-	0	-	-	60

Note: ASTM Tables available for more exact conversion

Hardness vs. Toughness





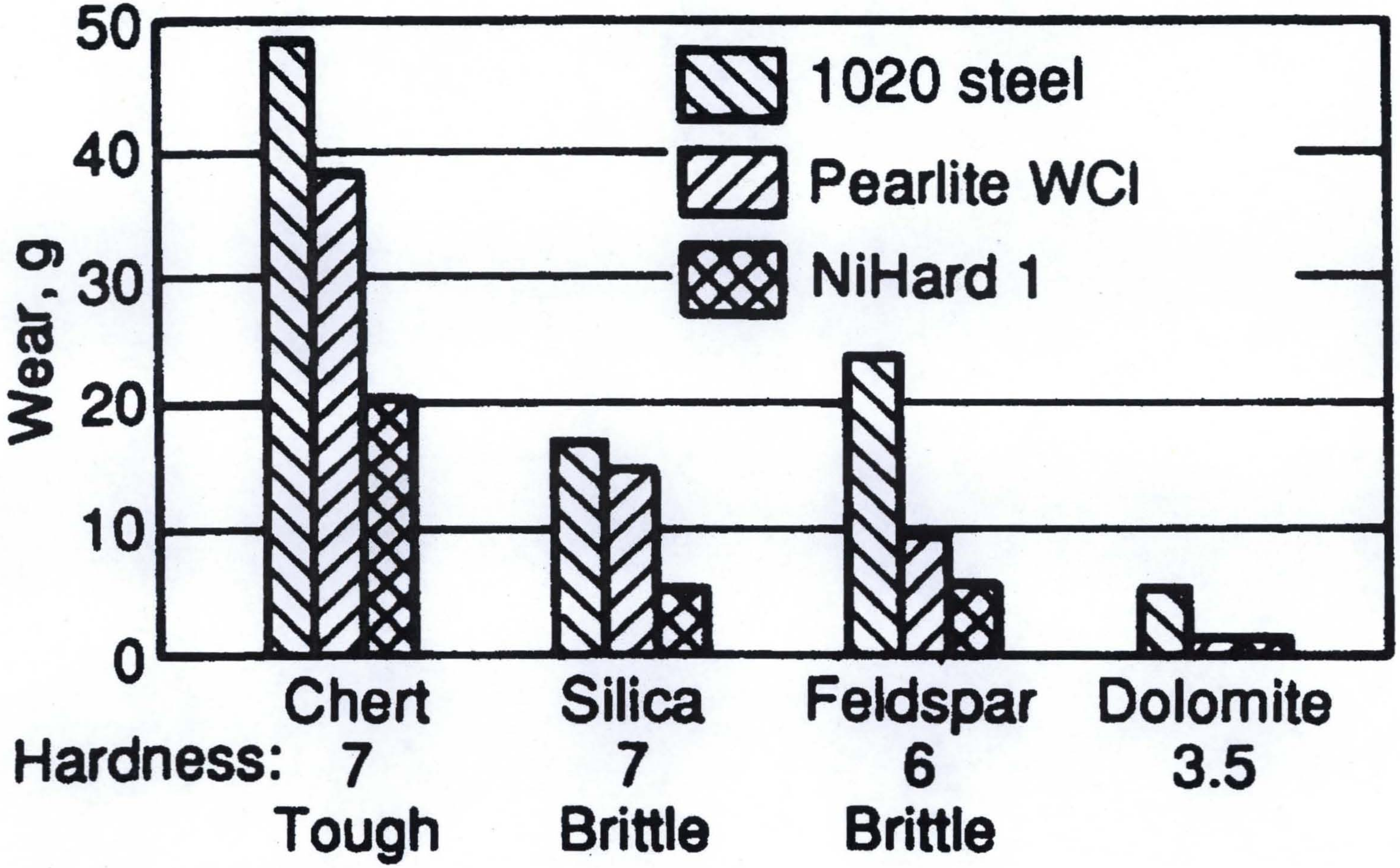
Brittle: **Ceramics, Minerals**

Tough (Ductile): **Metals (Carbon Steel)**

Hardness ≠ Toughness

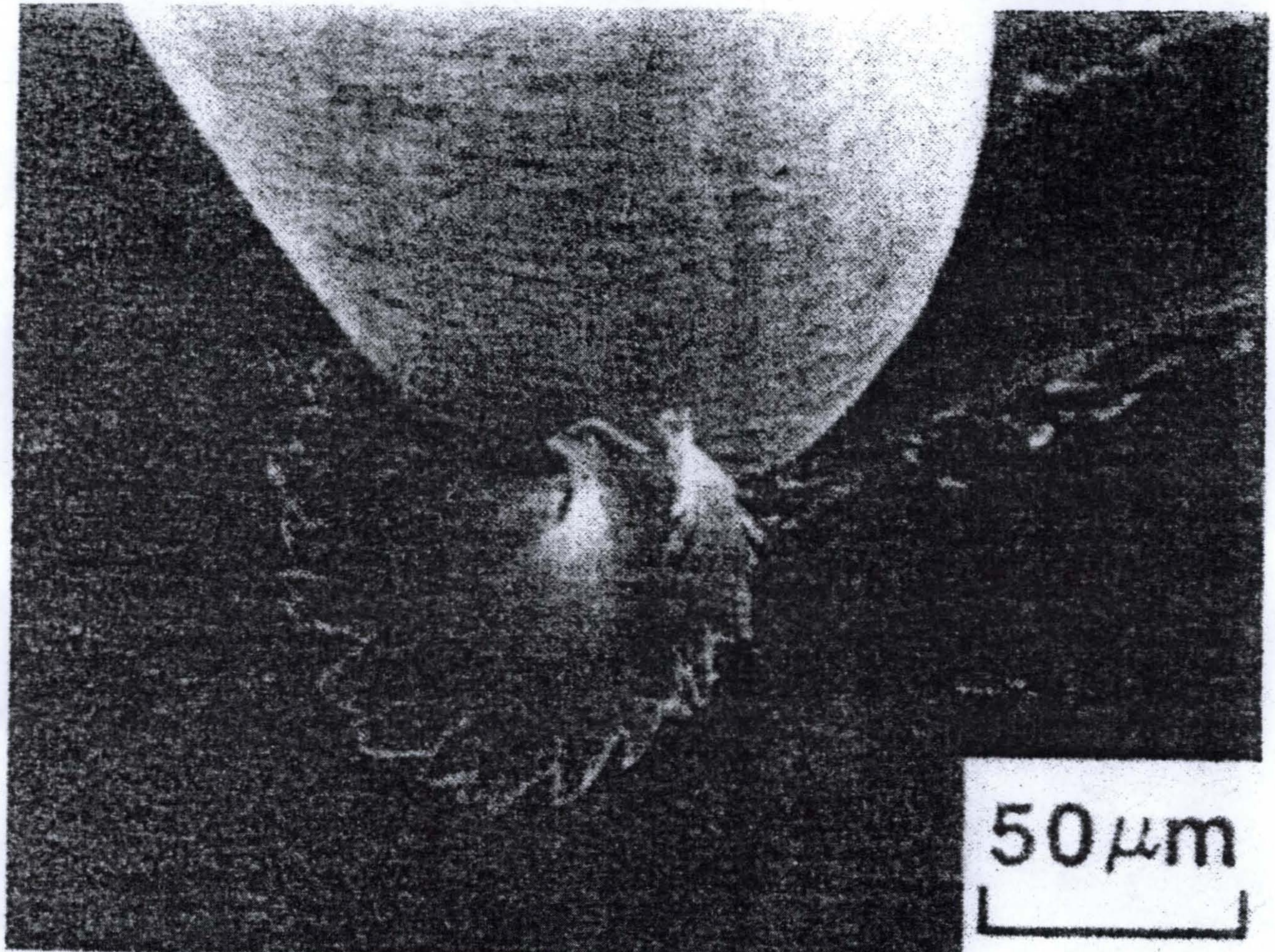
Toughness = Area under Stress-Strain curve

Toughness vs. Hardness (For Minerals)



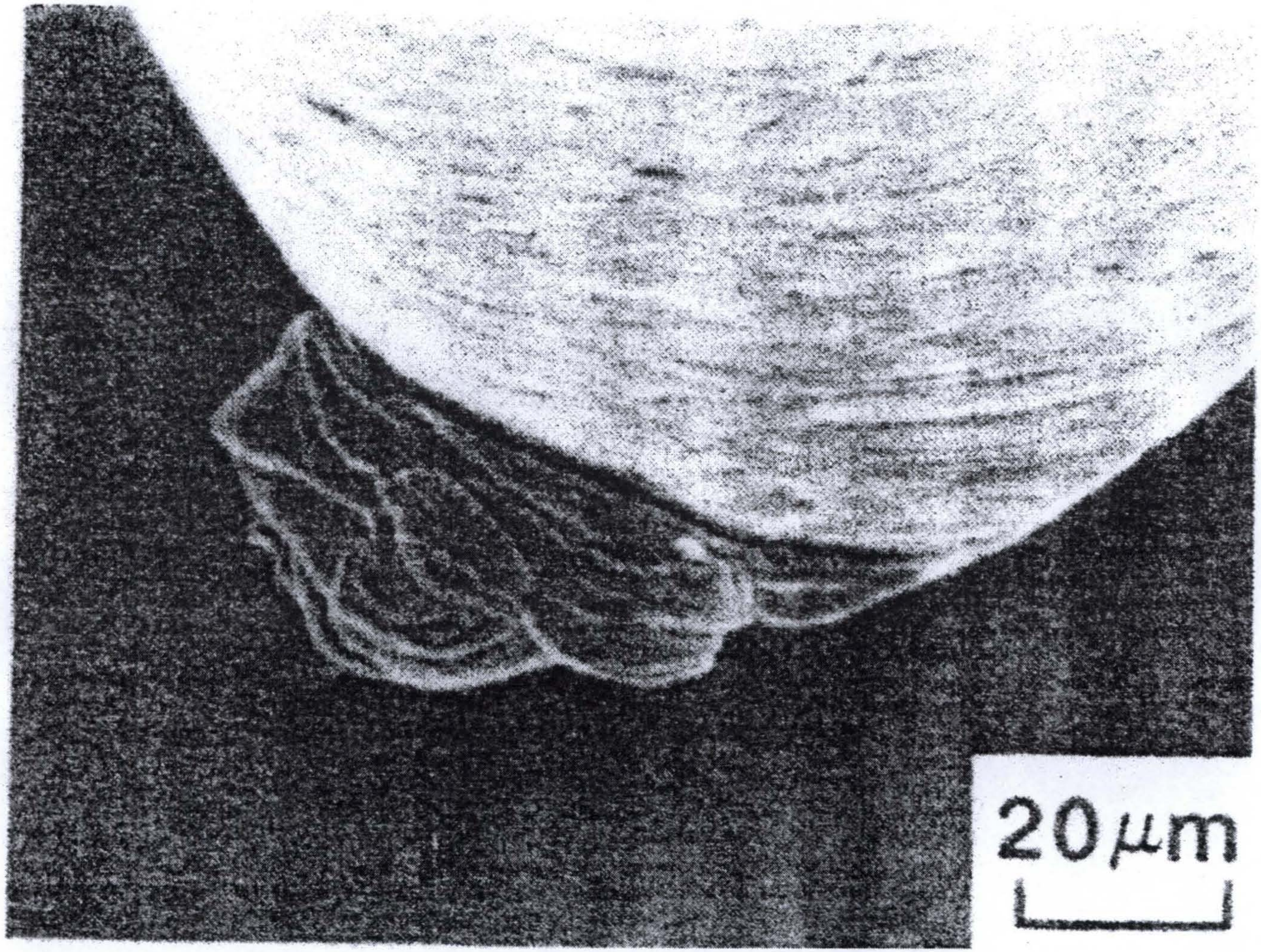
The third part of the answer is geometry!

Plastic Deformation - Cutting

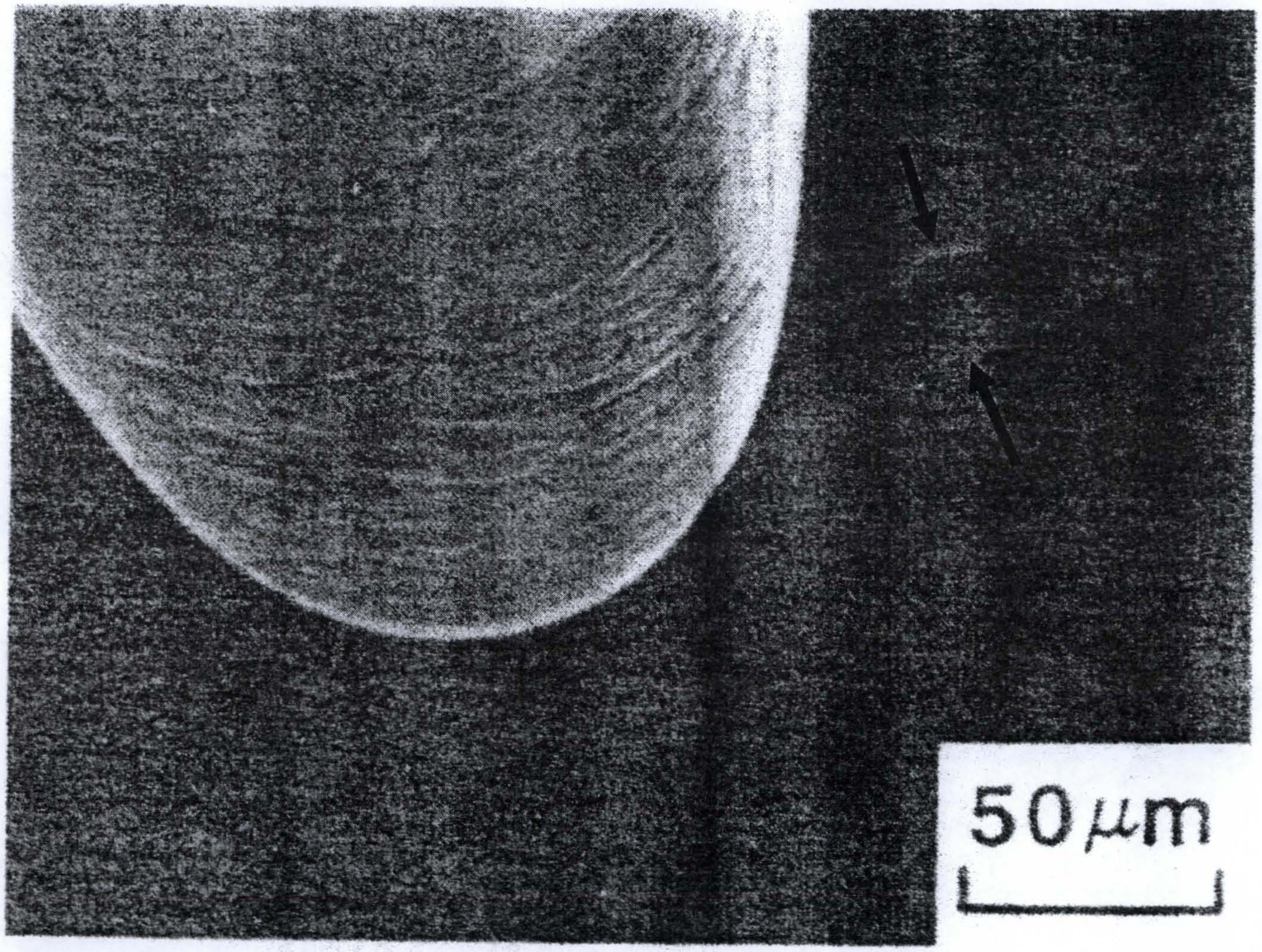


Note: Elasticity (polymers) vs. Plasticity (metals)

Plastic Deformation - Wedge



Plastic Deformation - Plowing



Major Omissions !!!

- **Polymers (elastic)**
- **Surface coatings, treatments and substrate effects**

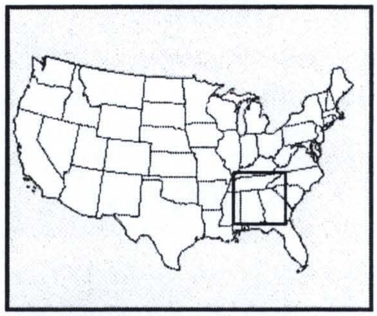
Conclusions:

- Engineering is constrained by Regolith properties
- Preliminary geologic data can be useful in engineering design
- A comparison of geologic properties to engineering material is presented
- Some Lunar minerals are hard, tough and sharp (abrasive)
- Some processes may concentrate trace components

Acknowledgement: **J.R. Skok & Ashley Boudreaux for compiling and developing literature data on mineral properties and lunar mineral abundances.**

HELIX-Atlanta

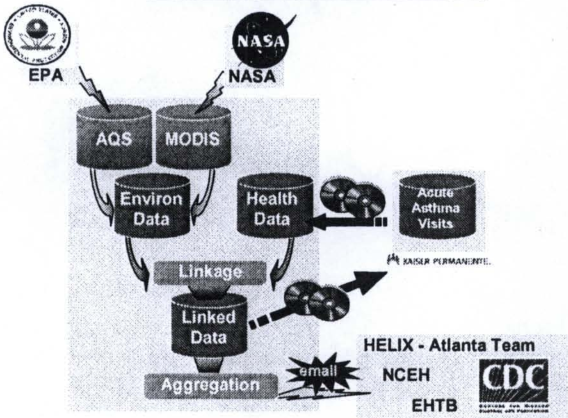
- Health and Environment Linked for Information eXchange (HELIX)-Atlanta was a pilot linking project in Atlanta developed to support current and future state and local EPHT programs to implement data linking demonstration projects that could be part of the EPHT Network.
- NASA/MSFC and the CDC were partners in linking environmental and health data to enhance public health surveillance.
- Proving the feasibility of the approach was the main objective.



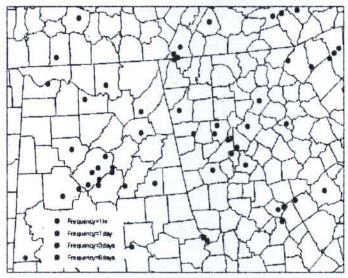
Southeastern U.S. study area

Year	MODIS-Terra	MODIS-Aqua
2000	0.579	
2001	0.643	
2002	0.559	0.401
2003	0.661	0.727

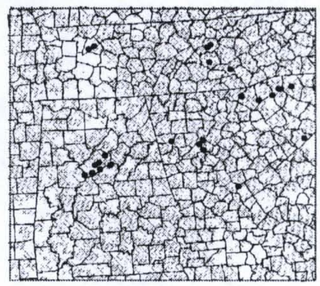
<u>Relating AQS ground-based PM2.5 to MODIS Aerosol Optical Depth measurements:</u>
Correlations between daily AQS $PM_{2.5}$ and MODIS AOD for April-September by year and satellite platform for 5 Metro Atlanta sites



Spatial analysis of $PM_{2.5}$ from ground and satellite observations:

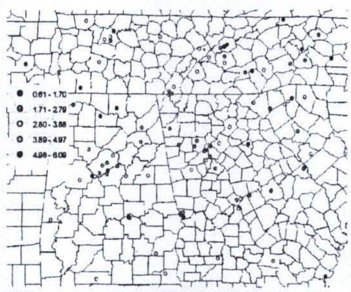


All AQS ground measurement sites showing observation frequency

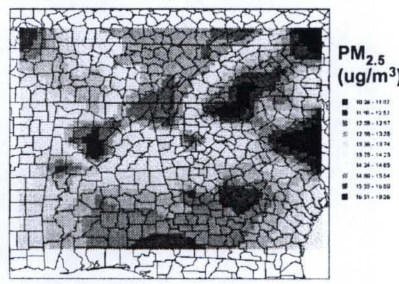


Data coverage from MODIS (red x's) and AQS ground observations (blue circles) for June 25, 2003

<u>Epidemiological findings for $PM_{2.5}$ and asthma:</u>
- Even with small numbers of acute asthma visits, statistical significance can be detected with Poisson Generalized Linear Model.
- There appears to be a relationship between $PM_{2.5}$ and acute asthma visits.
- Gender and age-group differences were found in relationships between $PM_{2.5}$ and acute asthma visits.
- Findings vary by grid cell and by county in significance, direction of association, and lags.



RMS errors in estimating $PM_{2.5}$ from MODIS data, determined by cross-validation approach at AQS sites



Mean $PM_{2.5}$ for year 2003 obtained from all daily B-spline surfaces

Linkage of environmental ($PM_{2.5}$) and health (asthma) data sets:

HMO Members

LON	LAT	ID	AGE	GENDER	YEAR/MO
-84.207	99.200	1	Child	M	200301
-84.802	99.359	2	Adult	M	200301
-83.798	99.993	4	Child	F	200301

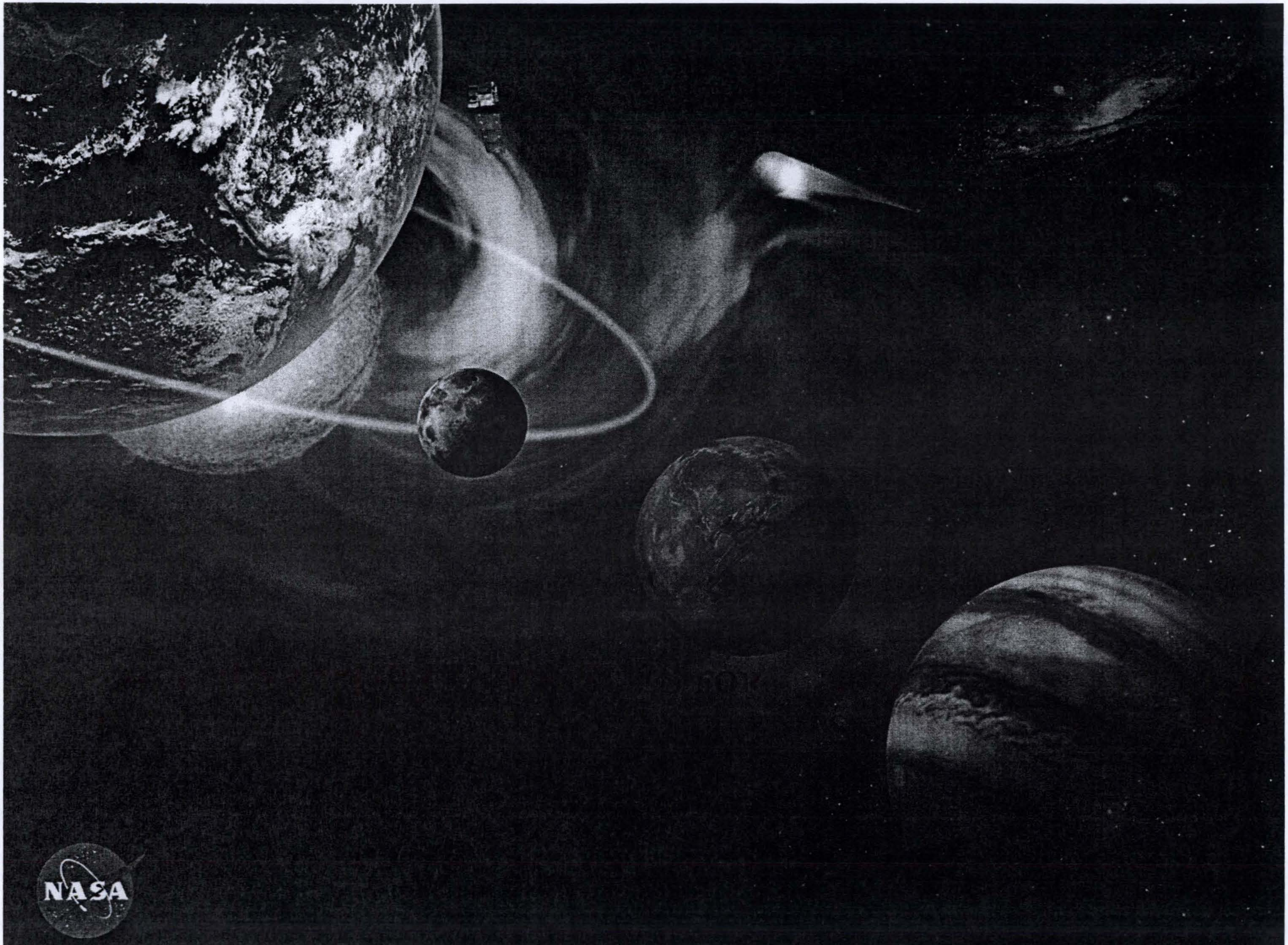
Acute asthma office visits

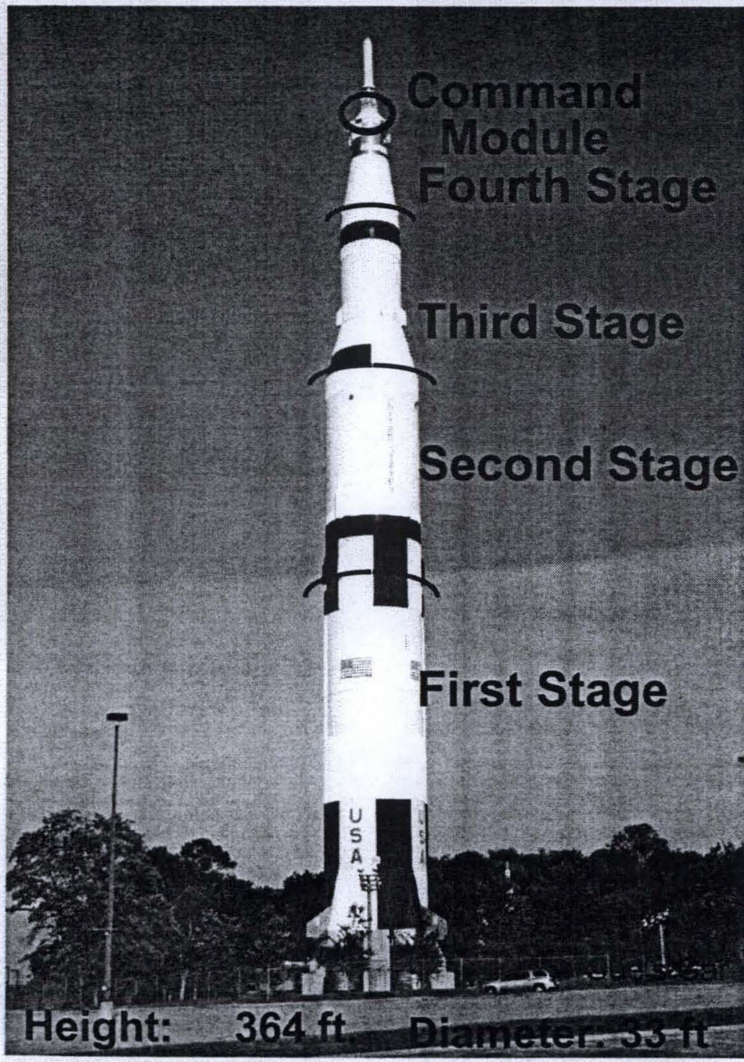
ID	AGE	LON	LAT	GENDER	DATE
1811	Child	-84.179	99.118	F	1/1/2003
54767	Adult	-84.625	99.802	F	1/1/2003
84580	Adult	-84.679	99.691	F	1/1/2003

Visit counts by grid cell

Date	Cell	PM2.5	FC	MC	FA	MA
200301	1	21.74	1	0	2	0
200301	2	12.79	0	0	0	0
200301	3	12.21	0	1	0	1

Simulated Data Set. F=female, M=male, A=adult, C=child


NASA



	Weight (lbs.)	Altitude (miles)	Velocity (mph)
	12,807		
Service Module	54,064		
Lunar Module	32,299		
Trans Lunar Burn	265,000	239,000	24,500
Orbital Burn		115	17,500
	1,037,000	114	15,300
	4,881,000	38	6,000
	6,600,000		

D Rickman
April 16, 2008 6:07 PM

- MSFC is responsible for making simulants of the Lunar regolith.

- A preliminary simulant, a replicate of the JSC-1 simulant, is currently be produced. This is considered a stop gap solution needed to satisfy immediate needs.

- MSFC team is currently -
  - writing a requirements document for a next generation of simulants.
  - in discussion (research) with multiple potential vendors of simulants.
  - There are obvious procurement sensitivities.

There are unanswered questions related to geology which need to be addressed prior to the creation of the simulants.

- What is the average composition of specific areas of the moon? Estimates for a "typical" Lunar Highlands rock range from hypersthene basalts to strict anorthosites.

- How useful is knowledge of the average?

- What is the range of heterogeneity and at what scales? Which types of heterogeneity are important, mineralogic/lithics, particle size, particle shape, spatial? Data from core samples are of prime significance. Grab samples are much less significant.

- What is the mineralogy? Weight percent oxides are of no specific interest, save how they reflect mineralogy.

- What is the calcium content of the plagioclase and how does it affect user's processes?

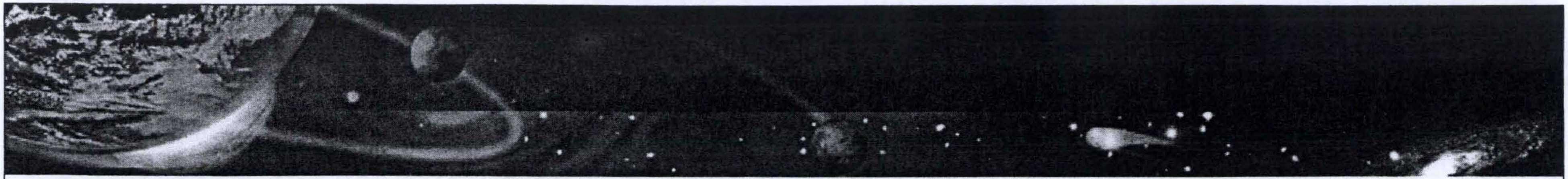
- What is the importance of the various mechanical and chemical shock-induced features?

- Impact melt glass has an enormous range of characteristics. How much impact will does this variability have? (punishment intentional)

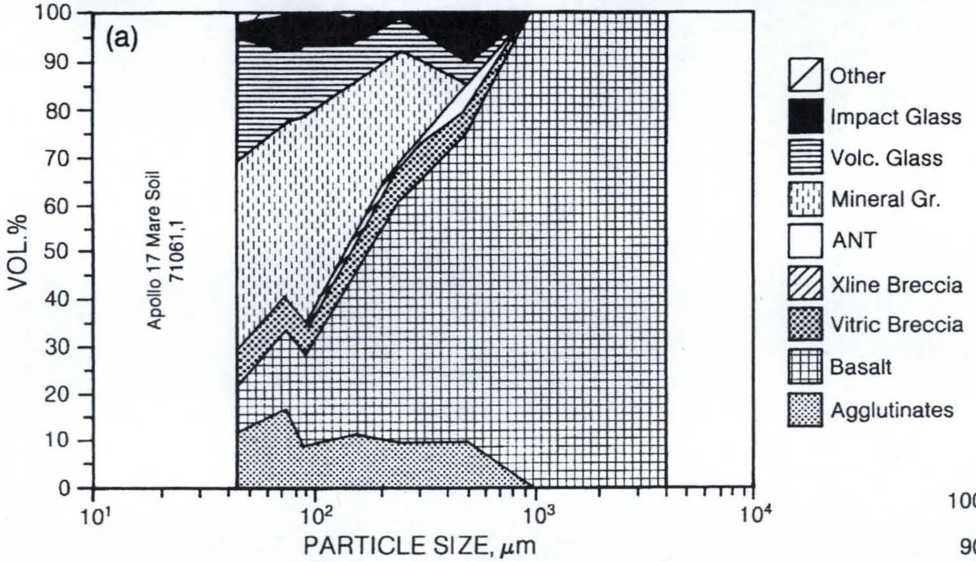
- Agglutinates are presumed to be important.

- This is also true for some minor minerals, such as the spinels, apatite and Ti bearing phases. But how important? Are they process poisons? The oxidation state of iron in the ilmenite and the precise crystallography of Ti-bearing phases are probably important.

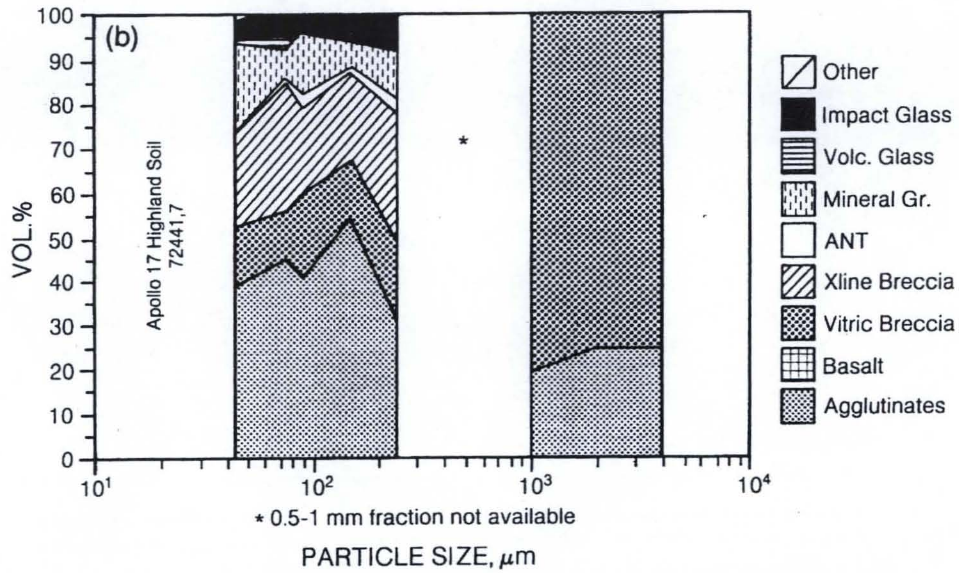
- Grain size and mineralogy are not independent.



CHANGE IN PARTICLE TYPES WITH GRAIN SIZE



CHANGE IN PARTICLE TYPES WITH GRAIN SIZE



Lunar Sourcebook, 1991

Other questions exist because terrestrial sources do not match lunar material in some critical aspects. Examples:

- The grain size of Archean anorthosites or layered intrusives is much too coarse to reproduce the percentage of lithic fragments as a function grain size found in the lunar material during grinding.
- Most terrestrial sources include minerals containing hydroxyl or water, either as primary or secondary minerals. These will definitely affect melt behaviors and are absent on the Moon.
- Even the heterogeneity of the regolith is outside that of most terrestrial geologic materials.
- High Ca plagioclase ($Ca_{0.95}$) is not common.

- The material has to come from an existing mine.
- How is the rock broken? As an example, ball milling introduces significant variables that include time, velocity of the mill, radius of the mill, characteristics of the feed stock, size and composition of the balls, and additional media (water, gases, vacuum).
- Ammonium Nitrate and Fuel Oil (ANFO) explosive introduces carbon and nitrogen contamination. Various explosives, tramp metal and other trash can be in the raw material. Quarries may or may not blast at all. This depends on the commercial use of the product.
- The "environment" of the mine will also introduce features. Most operations involve the use of water, if only for dust control.
- Human waste can also be an element in run-of-mine material. Probably, some of the dust will be used for human subject testing.

- No simulant can be a perfect reproduction of the Lunar regolith. Questions such as the ones we raise here have to be evaluated but the answers are driven by engineering considerations, including cost/benefit.

- Quantification is required whenever possible. One may ask, for example, how much does NASA and its projects gain by raising the feldspar from An0.75 to An0.95 to match lunar compositions more closely?

- If there was a practical, inexpensive, unambiguous way to compare the suitability of two simulants for a purpose, it might be practical to have more simulants, each designed to fit a specific cost/performance need. **This could result in significant cost savings.**

- To describe how well any simulant models the regolith, the MSFC team is considering the use of "Figures of Merit".

- A Figure of Merit would quantify how closely a simulant reproduces a specific attribute compared to a defined standard. The standard could be a conceptual ideal (for example an average) or a specific lunar sample.

- A suite of these values would tell the user how close the simulant comes to reproducing many properties. For example: (0.75, 0.82, 0.621, 0.95)$Apollo16_{AVG}$ might be the rating of a simulant for mineralogy, size, shape and bulk density against the average for Apollo 16 cores.

- Figures of Merit can be treated as a N-dimensional vectors, which may make expression, manipulation and analysis much easier.

D Rickman

The key to success with this approach is having a good definition of each term in the Figure of Merit.

A first level size algorithm might be to take the particle size vs. cumulative mass distribution curve for the simulant and a specific Apollo sample.