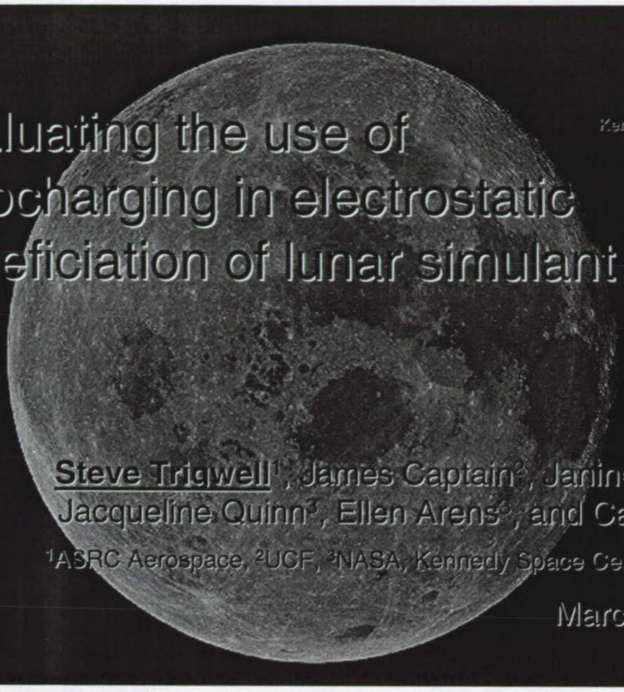
07-423



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Evaluating the use of tribocharging in electrostatic beneficiation of lunar simulant

Steve Trigwell[1], James Captain[2], Janine Captain[3], Jacqueline Quinn[3], Ellen Arens[3], and Carlos Calle[3]

[1]ASRC Aerospace, [2]UCF, [3]NASA, Kennedy Space Center, FL 32899

March 13, 2007

Introduction

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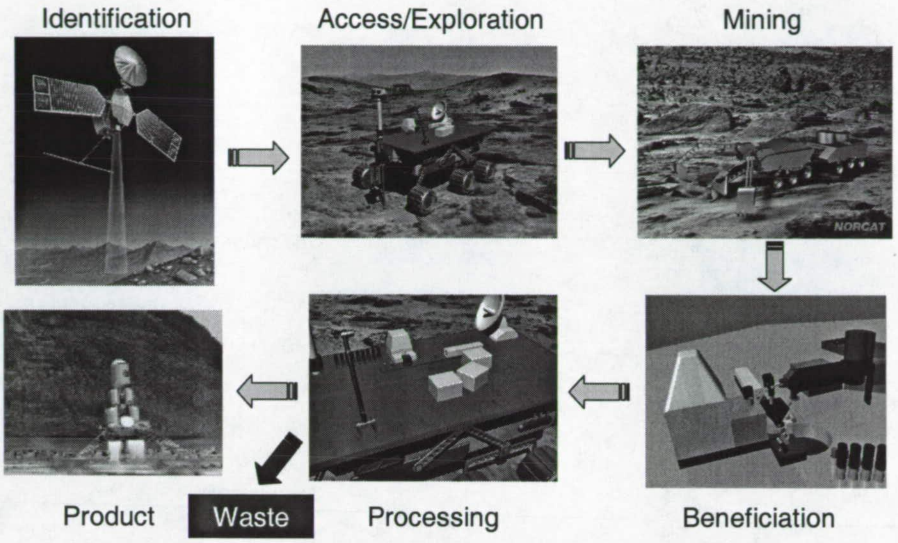
- Any future lunar base needs materials to provide thermal and radiation protection
- Many factors point to the use of lunar materials as industrial feedstocks
- Sintering of full-scale bricks using whole lunar dust has been accomplished[1]
- Refinement of soil beneficial before processing – less energy
- Triboelectric separation of coal from minerals, quartz from feldspar, and phosphorous from silica and iron ore successively achieved
- Lunar environment ideal for electrostatic separation
  - lack of moisture
  - lower gravitational pull
  - higher voltages in vacuum

[1] C.C. Allen *et al.*, Space IV, American Soc. Civil Eng., (1994) 1220-1229

_ISRU cycle



Identification → Access/Exploration → Mining → Beneficiation → Processing → Product

Waste

D.S. Boucher, SSR VIII, 31 Oct- 2 Nov, 2006, Colorado School of Mines

_Introduction

- Lunar dust principally basalts containing
  plagioclase (Na,Ca)Si_3AlO_8
  pyroxene (Mg,Fe,Ca)Si_2O_6
  olivine $(Mg,Fe)_2SiO_4$
  and ilmenite $FeTiO_3$
- Two simulants developed to replicate the mineralogy and chemistry of lunar soil from Apollo missions: MLS-1 and NASA JSC-1
- Latest development JSC-1A
- Average size of Lunar dust particles on Moon = 45-100 μm [2]

Mineral	Wt. %
Plagioclase	20 - 50
Pyroxene	40 - 65
Olivine	2 - 15
Ilmenite	2 - 15

Summary of compositions obtained from literature

[2] Lunar Source Book, G.H. Heiken [ed.], LPI, TX, 2005

_Mare soil

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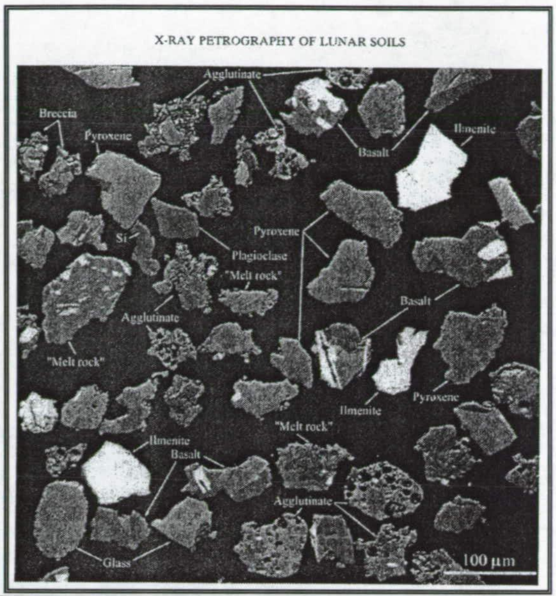

BSE image – heavier Z elements show up lighter

[7]L. Taylor *et al.*, Icarus, 124, (1996), 500-512

_Previous studies

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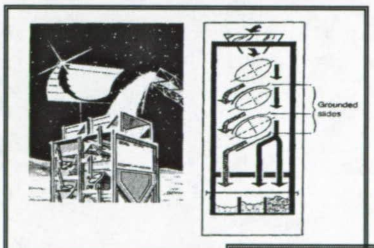


W.N. Agosto, NASA SP-509, Vol. 3,1985

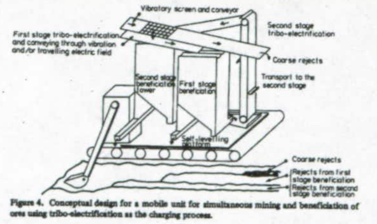
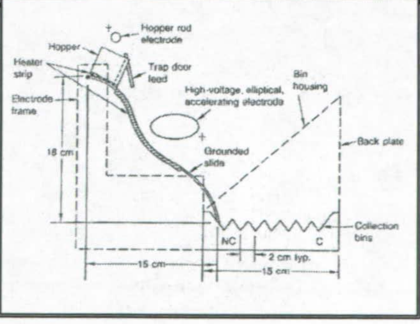
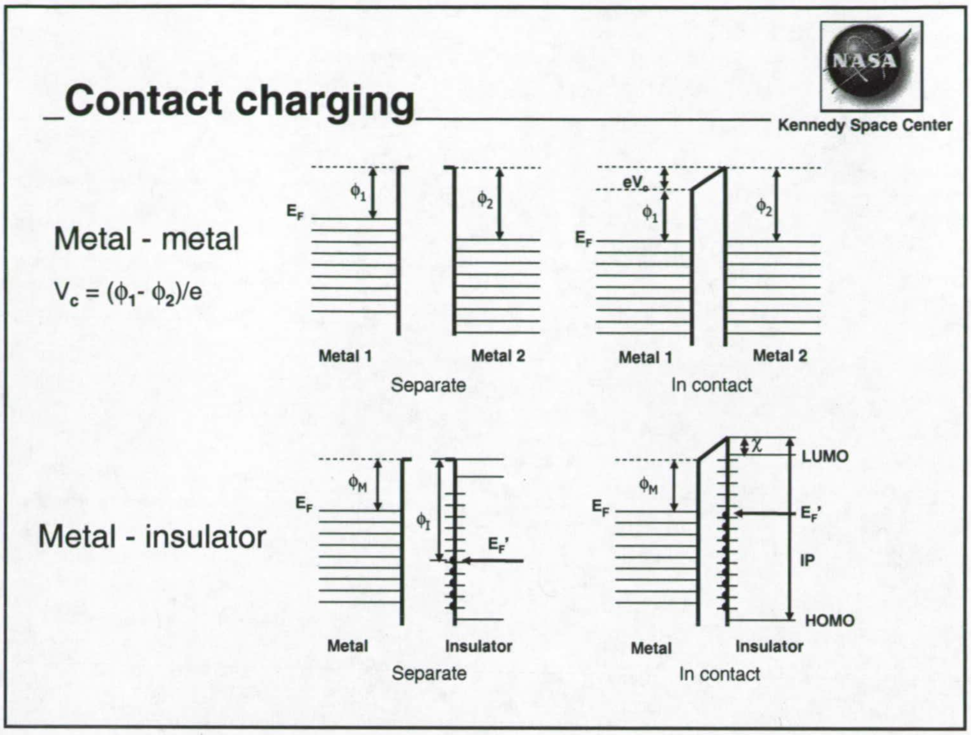


Figure 4. Conceptual design for a mobile unit for simultaneous mining and beneficiation of ores using tribo-electrification as the charging process.

I.I. Inculet & D.R. Criswell, Inst. Phys. Conf. Ser. No. 48, (1979) 45-53



W.N. Agosto, Lunar bases & space activities of the 21st century, LPI, Houston, TX, 1985



_Contact charging

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Metal - metal

$V_c = (\phi_1 - \phi_2)/e$

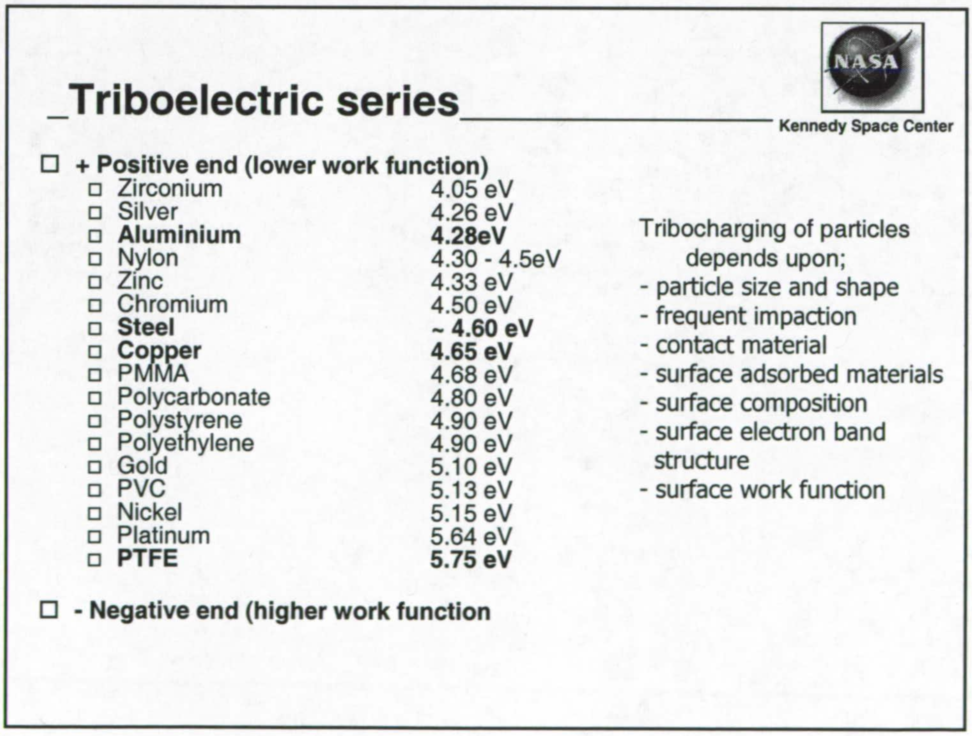
Separate

In contact

Metal - insulator

Separate

In contact



_Triboelectric series

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☐ **+ Positive end (lower work function)**

☐ Zirconium	4.05 eV
☐ Silver	4.26 eV
☐ **Aluminium**	**4.28eV**
☐ Nylon	4.30 - 4.5eV
☐ Zinc	4.33 eV
☐ Chromium	4.50 eV
☐ **Steel**	**~ 4.60 eV**
☐ **Copper**	**4.65 eV**
☐ PMMA	4.68 eV
☐ Polycarbonate	4.80 eV
☐ Polystyrene	4.90 eV
☐ Polyethylene	4.90 eV
☐ Gold	5.10 eV
☐ PVC	5.13 eV
☐ Nickel	5.15 eV
☐ Platinum	5.64 eV
☐ **PTFE**	**5.75 eV**

☐ **- Negative end (higher work function**

Tribocharging of particles depends upon;
- particle size and shape
- frequent impaction
- contact material
- surface adsorbed materials
- surface composition
- surface electron band structure
- surface work function

_Characterization

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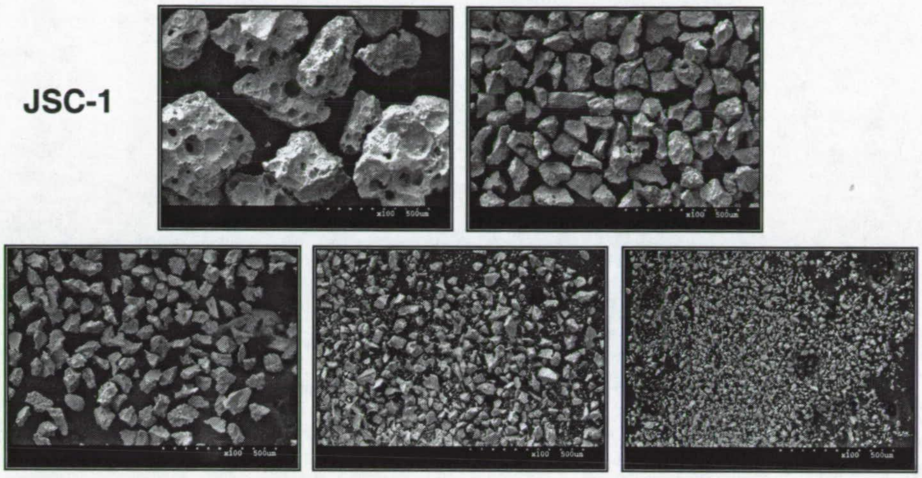
JSC-1



_Characterization

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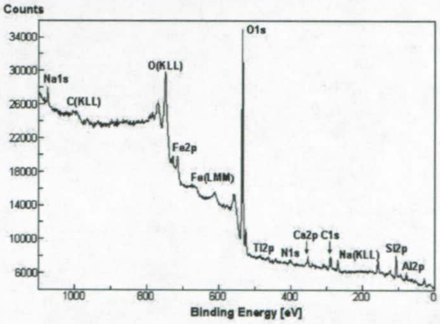
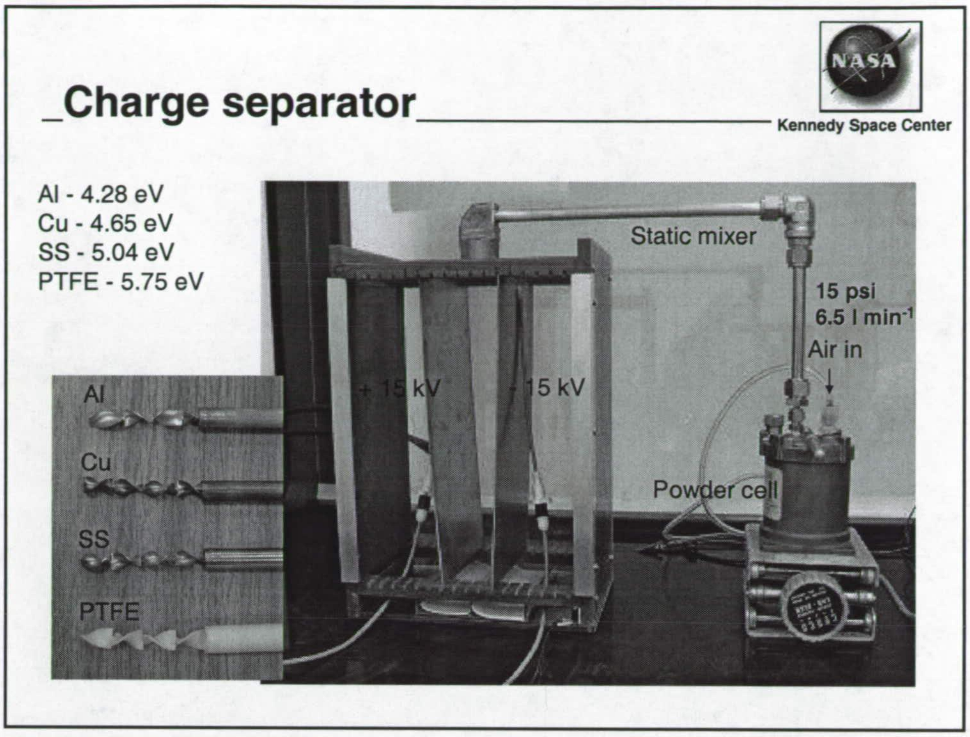


XPS of JSC-1 size fractions

Size range	O	C	Si	Al	Na	Fe	Ca	Ti	N
< 25 µm	64.4	6.1	14.0	5.5	4.8	2.5	1.8	0.6	0.4
25-50 µm	65.9	5.2	13.2	6.1	4.3	2.4	2.1	0.5	0.7
50-75 µm	65.4	5.0	13.8	6.4	4.4	2.5	1.8	0.6	0.1
75-100 µm	64.0	6.9	13.5	6.5	4.1	2.5	1.7	0.4	0.5
> 100 µm	66.4	5.1	13.2	6.1	4.5	2.4	1.9	0.2	0.2



_Charge separator

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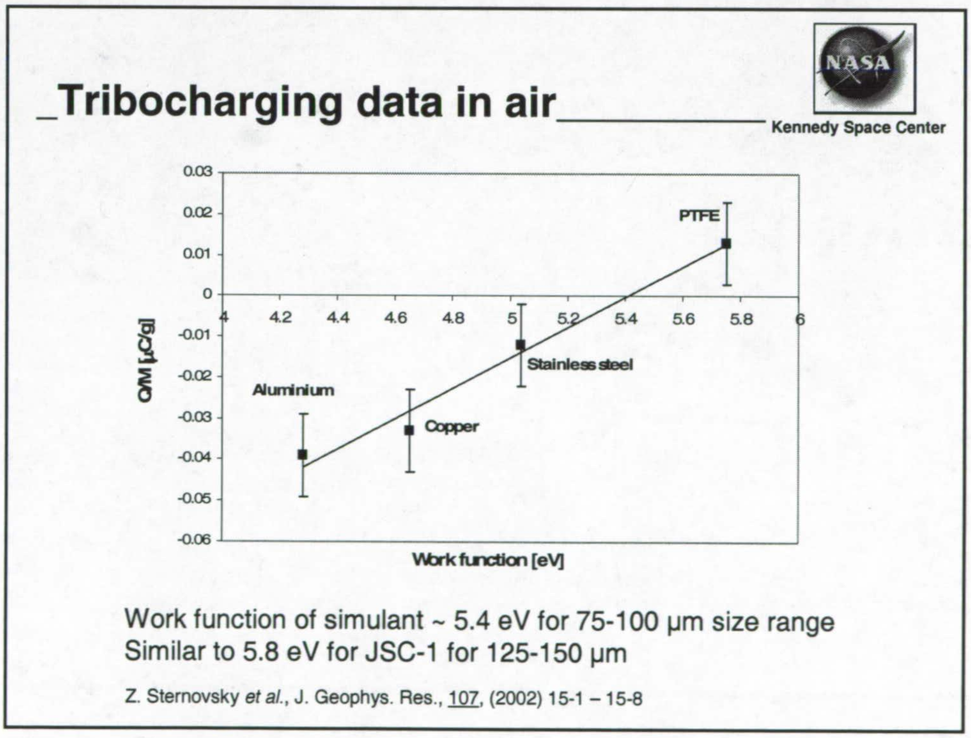
Al - 4.28 eV
Cu - 4.65 eV
SS - 5.04 eV
PTFE - 5.75 eV



_Tribocharging data in air

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Work function of simulant ~ 5.4 eV for 75-100 µm size range
Similar to 5.8 eV for JSC-1 for 125-150 µm

Z. Sternovsky *et al.*, J. Geophys. Res., 107, (2002) 15-1 – 15-8

_Separation data in air

Kennedy Space Center

Charger	Plate	Mass %
Al < 25 µm	+ ve	70
Al < 25 µm	- ve	30
PTFE < 25 µm	+ ve	52
PTFE < 25 µm	- ve	48
Al > 100 µm	+ ve	84
Al > 100 µm	- ve	16
PTFE > 100 µm	+ ve	14
PTFE > 100 µm	- ve	86

Mass fractions [%] and elemental compositions [relative atomic %] for two MLS-1 simulant sieved size fractions

_Slip adhesion tests

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Known amount of dust of different size fractions placed on Al, Cu, Stainless steel, and PTFE incline planes

Angle and particle size noted for minimum residue

Data showed > 50 µm at > 50° optimum for all materials

Homemade simulant (KSC-1)

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Feldspar: $(Na,K)AlSi_3O_8;SiO_2$	40%
Spodumene: $LiAlSi_2O_6$	40%
Olivine: $(Mg,Fe)_2SiO_4$	10%
Ilmenite: $FeTiO_3$	10%

Reade Advanced Materials ~ 300 mesh sieved
Further sieved to 50-75 μm size range

Mineral	Wt. %
Plagioclase	20 - 50
Pyroxene	40 - 65
Olivine	2 - 15
Ilmenite	2 - 15

Summary of compositions obtained from literature

Relative atomic concentrations [%] by XPS (mean of 5 samples)

	Na	**Fe**	**O**	**Ti**	**K**	**C**	**Si**	**Mg**	**Al**
Ilmenite	2.2	4.0	65.3	13.5	-	15.0	-	-	-
Olivine	0.5	1.1	66.7	-	-	7.0	12.3	12.5	-
Spodumene	0.6	-	55.1	-	-	22.9	15.9	-	5.4
Feldspar	4.3	-	55.7	-	2.2	16.5	16.4	-	4.9
As mixed	**5.2**	**0.8**	**61.2**	**1.9**	**1.5**	**6.3**	**13.9**	**3.4**	**5.7**

KSC-1 in air

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1st pass in air **Stainless steel**

	Na	Fe	O	Ti	K	C	Si	Mg	Al
Bottom tray	-26%	+62%	-	-40%	-100%	+11%	-7%	+217%	+13%
-ve plate	+19%	+11%	-	+33%	-	+16%	+7%	-100%	-
+ve plate	-	-	-	+6%	-	+13%	+9%	-100%	-

Bottom tray 2nd pass in air **Stainless steel**

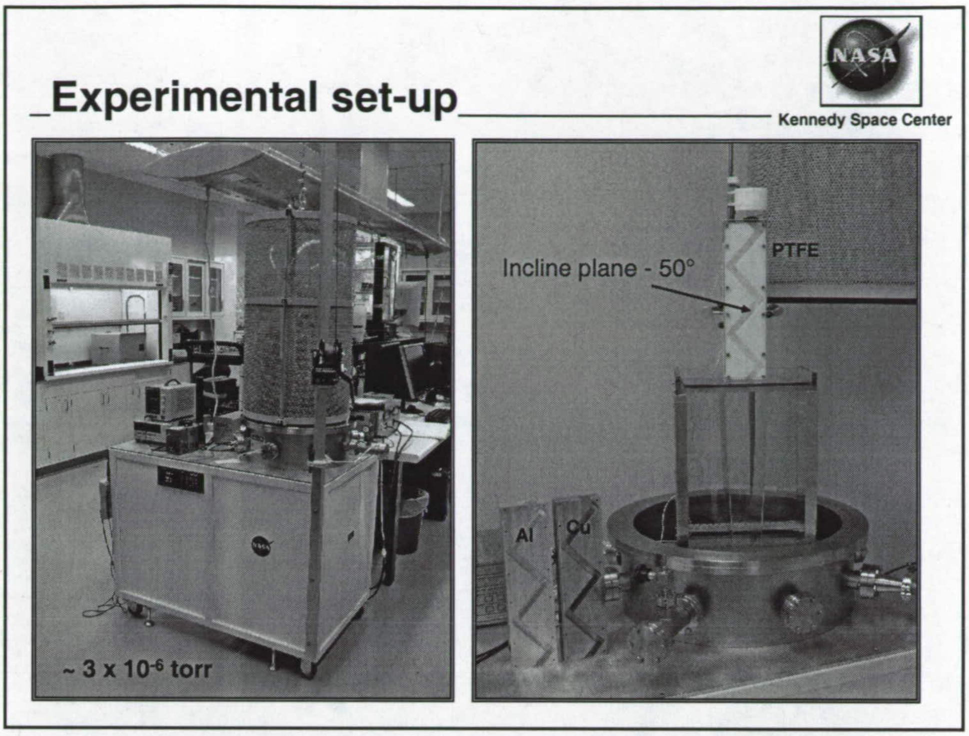
	Na	Fe	O	Ti	K	C	Si	Mg	Al
Bottom tray	-70%	+34%	-	-49%	-100%	+67%	-7%	+220%	+13%
-ve plate	-20%	-	-15%	-	-20%	+201%	-	-100%	+10%
+ve plate	-35%	-	-7%	+13%	+27%	+268%	-20%	-100%	+15%

-ve plate 2nd pass in air **Stainless steel**

	Na	Fe	O	Ti	K	C	Si	Mg	Al
-ve plate	-	-30%	-	+7%	-	+6%	+10%	-100%	-
+ve plate	-	+51%	-	+47%	-	+24%	-8%	-100%	-

+ve plate 2nd pass in air **Stainless steel**

	Na	Fe	O	Ti	K	C	Si	Mg	Al
-ve plate	-	-63%	-	-	-29%	+219%	-33%	-100%	+38%
+ve plate	-	+27%	-	+52%	-34%	+227%	-34%	-100%	+30%



_Experimental set-up

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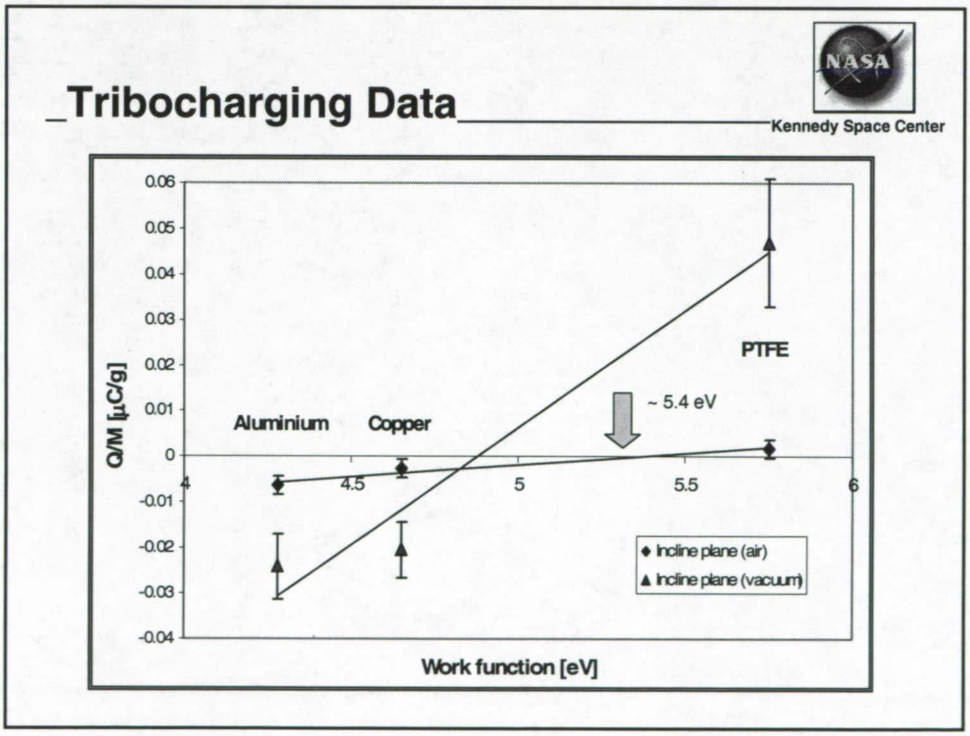

_Tribocharging Data

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_KSC-1 in vacuum

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KSC-1 50 - 75 μm **Al**

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-9%	-69%	-6%	-48%	+26%	+17%	+6%
-ve plate	+31%	-43%	-	-38%	+12%	+15%	-
+ve plate	-	-	-	+40%	-7%	+11%	-23%

KSC-1 50 - 75 μm **Cu**

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-10%	+11%	-	-34%	-11%	+20%	+13%
-ve plate	-7%	+86%	-	+14%	-8%	-	-8%
+ve plate	-27%	-	-	-32%	-	+11%	-

KSC-1 50 - 75 μm **PTFE**

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-	-36%	-	-31%	-10%	+23%	+18%
-ve plate	+13%	-32%	-	-26%	+9%	-	-
+ve plate	-	+27%	-	+46%	+9%	-7%	+30%

_KSC-1 1st pass

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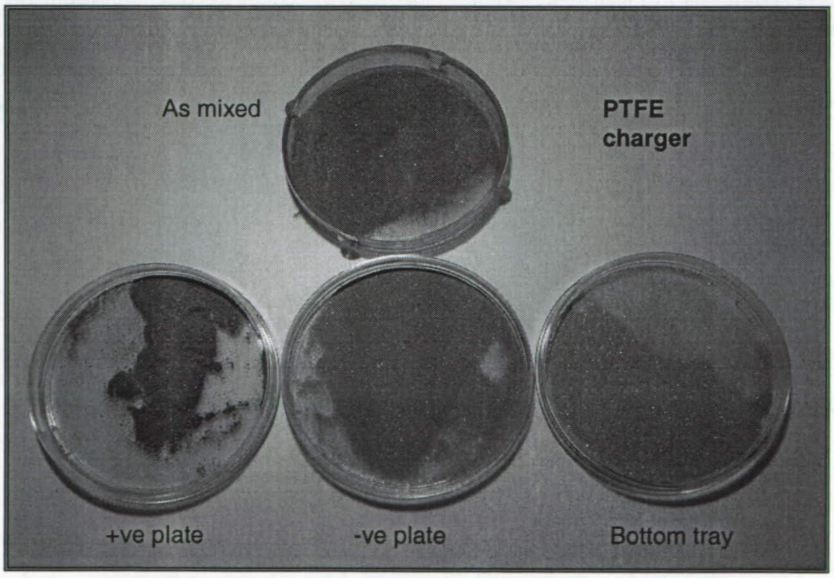

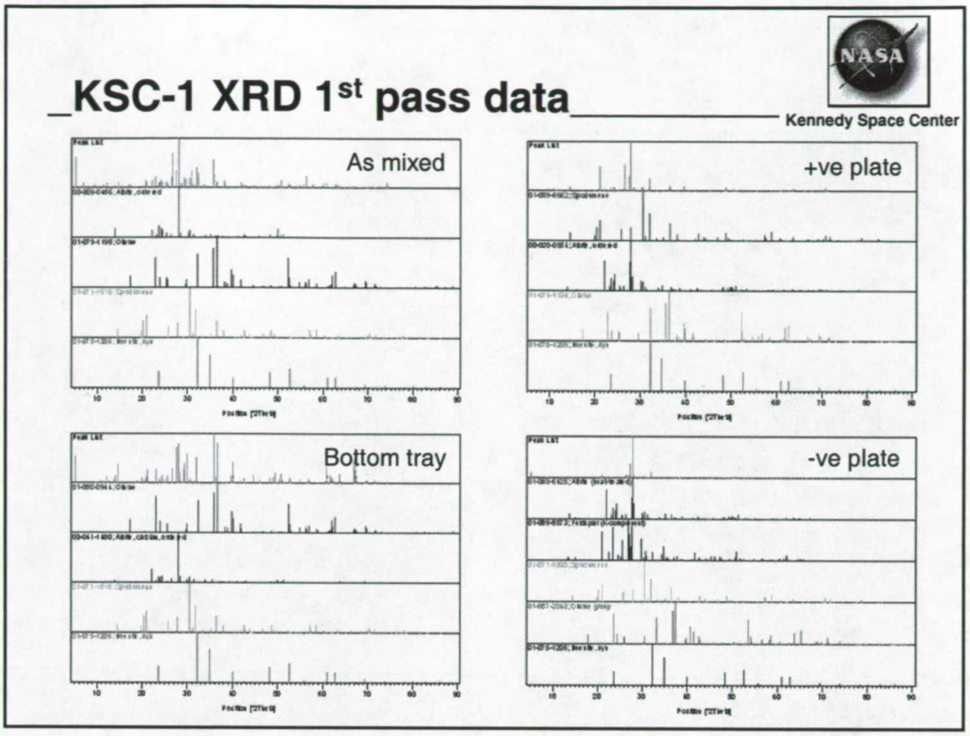

_KSC-1 XRD 1st pass data

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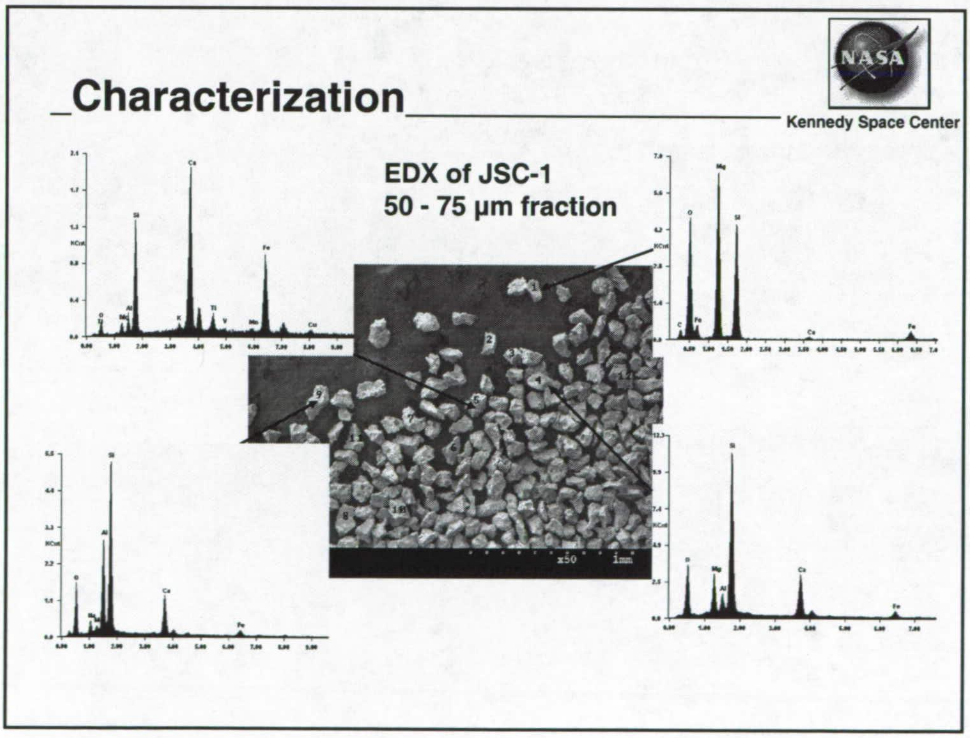

_Characterization

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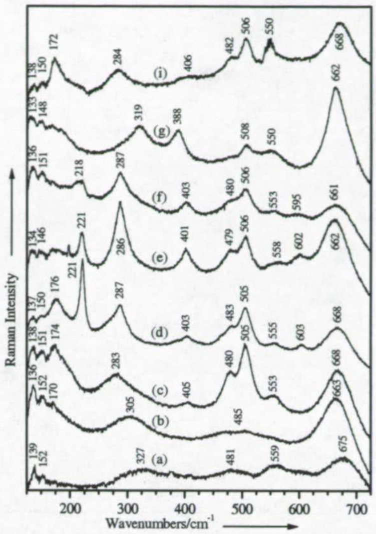
EDX of JSC-1
50 - 75 µm fraction

_XPS and Raman data

Separation data from XPS using Al charger – percent change in surface concentration of detected elements compared to control sample JSC-1

Sample	Na	Fe	Ca	Si	Al
- ve plate	- 31 %	+ 8.6 %	+ 13 %	+ 28 %	+ 3 %
+ ve plate	+ 5.7 %	- 18 %	+ 4 %	+ 8.9 %	- 11 %



Raman data showed separated fractions had less plagioclase and silicate rich minerals, but were richer in Ti and Fe minerals such as ilmenite, anatase, magnetite, hematite, and pseudobrookite

Large database of Raman mineral spectra for planetary exploration

K. Kuebler *et al.*, LPI XXXVII (2006) 1907

_On-going & future work

- ☐ Optimization of separator parameters
- ☐ Test out Faraday pail array to determine charge distribution between plates
- ☐ Model and design optimum system for lunar environment
- ☐ Test with real lunar soil
- ☐ Further explore use of Raman as analytical tool
- ☐ Use monochromatic UV to charge dust
- ☐ Build miniature version for zero-G flight testing
- ☐ Explore future possibilities of combining magnetic separation to remove ferromagnetic agglutinates followed by electrostatic separation

_Separator modeling

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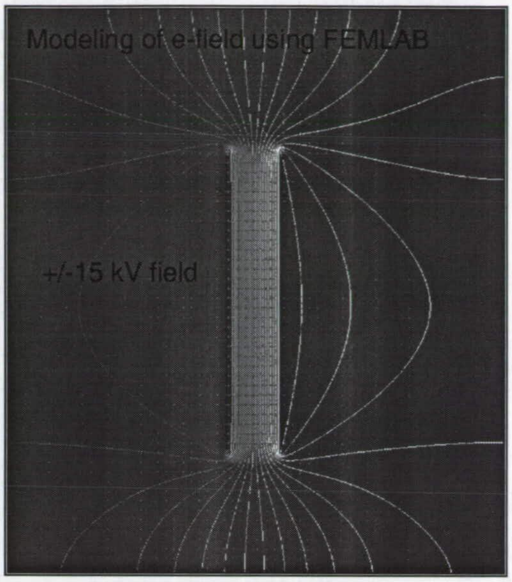
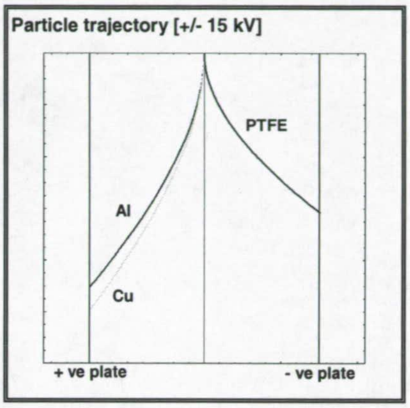

Modeling of e-field using FEMLAB

Modeling of particle trajectories using Mathmatica in vacuum at 1G



_Conclusions

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- ☐ Direct correlation between work function of simulant and charging material established
- ☐ No surface compositional difference determined between sieved size fractions
- ☐ Lunar simulants KSC-1 and JSC-1 successfully tribocharged in air against different materials
- ☐ Significantly increased ilmenite concentration in separated fractions in only 1 pass in vacuum
- ☐ Data indicates tribocharging followed by plate separator potentially viable method for mineral separation for lunar dust under lunar conditions

_Acknowledgements

Kennedy Space Center

- The authors would like to thank the NASA Kennedy Space Center Spaceport Engineering and Technology Directorate for Center Director Discretionary Funding for this research
- Dr. Alex Biris at UALR Nanotechnology Center for Raman data
- Dr. Hae Soo Kim of NASA MSL for XRD data
- Mr. Zia Rahman of AMPAC, UCF for SEM data

_X-Ray Photoelectron Spectroscopy

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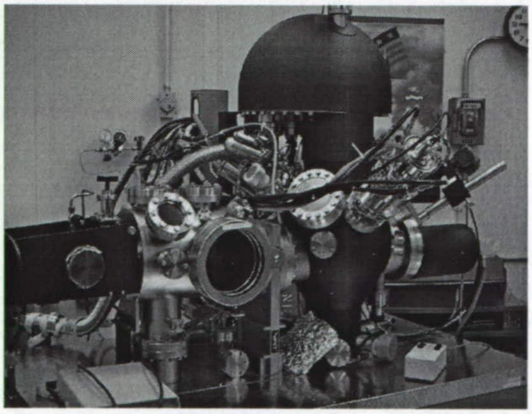

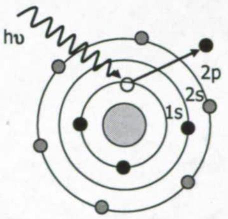

$$E_K = h\upsilon - E_B - \phi$$

XPS allows for quantitative and qualititative analysis of surfaces

Binding energy shifts due to atom environment allows for chemical bonding analysis

XPS surface sensitive ~50 -100Å

Detection limit 0.05 – 0.1 atomic %

MgKα X-rays $h\upsilon = 1253.6$ eV

_Static mixer in air data

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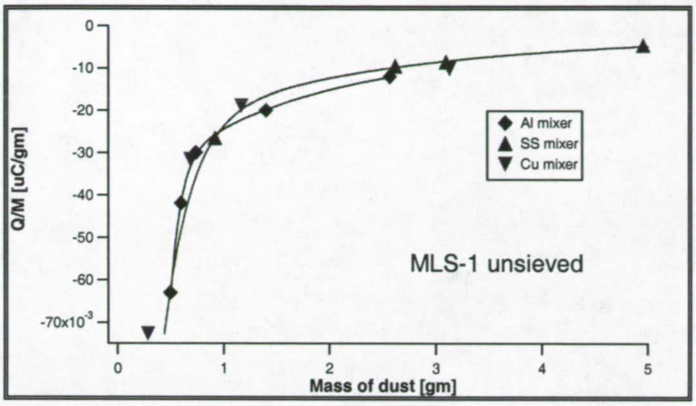

Fine particles adhere to inside of mixers – prevent further particles acquiring charge

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_Priorities for ISRU capabilities

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Regolith excavation and transport	For radiation/micro-meteorite shielding and thermal moderation
Water production	From regolith for life support and radiation shielding
Oxygen production	From regolith for life support and propulsion
Fuel production	From regolith for Earth return, lunar surface/orbital science expeditions, etc.
Energy production, transport, storage, and distribution	For outpost use
Structural and **building material** fabrication	For outpost use
Spare part, machine, and **tool** production	For outpost use
Construction and **site preparation**	Using *in-situ* materials and *in-situ* energy

[2] White paper from SSR VIII, 31 Oct- 2 Nov, 2006, Colorado School of Mines

_Mare Soil size distribution

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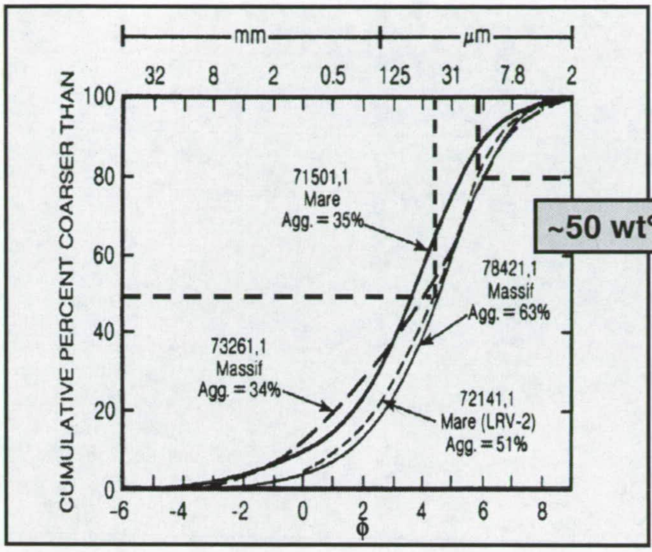

~50 wt% <50 μm

[5]L. Taylor & B. Eimer, SSR VIII, 31 Oct- 2 Nov, 2006, Colorado School of Mines

_KSC-1 1st pass

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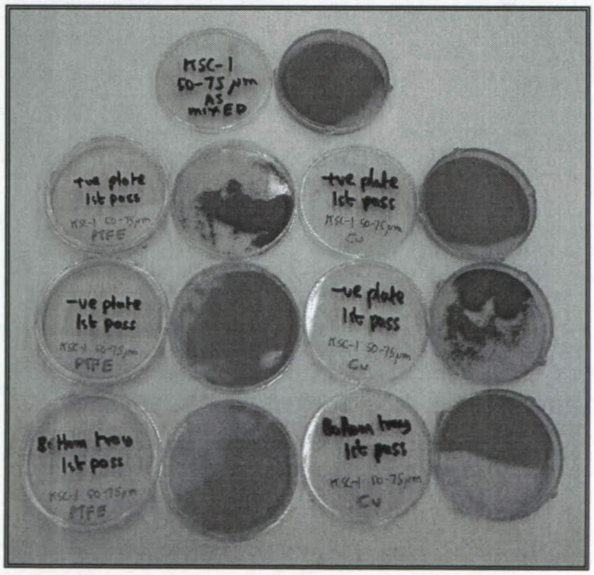

Introduction

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