


Evaluating the use of tribocharging in electrostatic beneficiation of lunar simulant

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March 13, 2007



Introduction

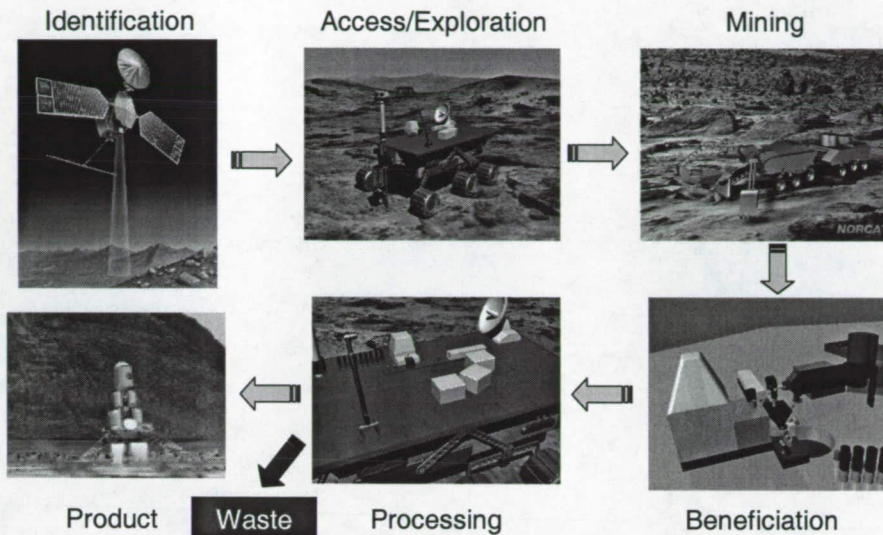
- ❑ Any future lunar base needs materials to provide thermal and radiation protection
- ❑ Many factors point to the use of lunar materials as industrial feedstocks
- ❑ Sintering of full-scale bricks using whole lunar dust has been accomplished¹
- ❑ Refinement of soil beneficial before processing – less 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

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

ISRU cycle

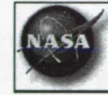


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D.S. Boucher, SSR VIII, 31 Oct- 2 Nov, 2006, Colorado School of Mines

Introduction



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- Lunar dust principally basalts containing plagioclase $(\text{Na,Ca})\text{Si}_3\text{AlO}_8$
pyroxene $(\text{Mg,Fe,Ca})\text{Si}_2\text{O}_6$
olivine $(\text{Mg,Fe})_2\text{SiO}_4$
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 = $45\text{-}100 \mu\text{m}^2$

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

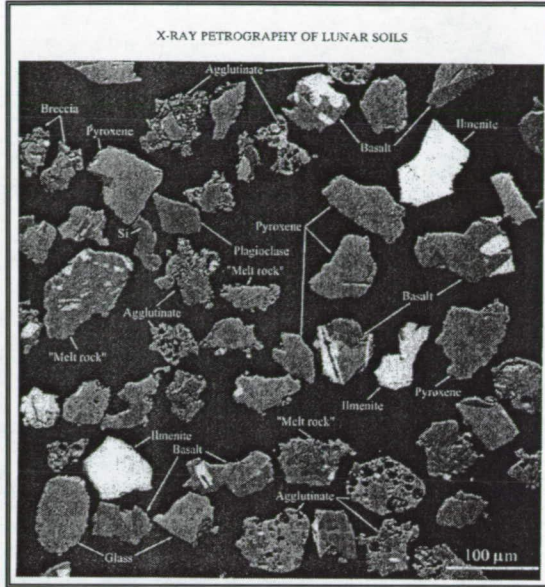
Summary of compositions obtained from literature

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

Mare soil



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BSE image – heavier Z elements show up lighter

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

Previous studies



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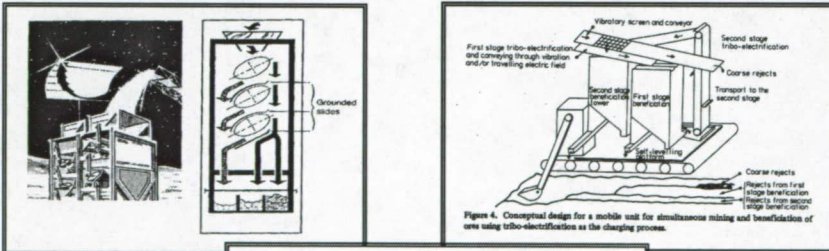
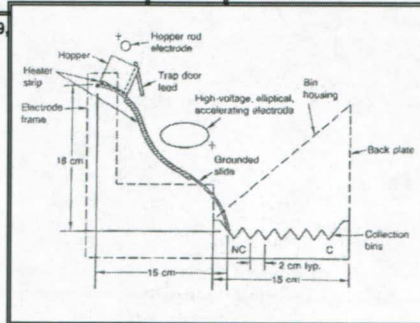


Figure 4. Conceptual design for a mobile unit for simultaneous mixing and beneficiation of ores using tribo-electrification as the charging process.

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



I.I. Inculat & 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

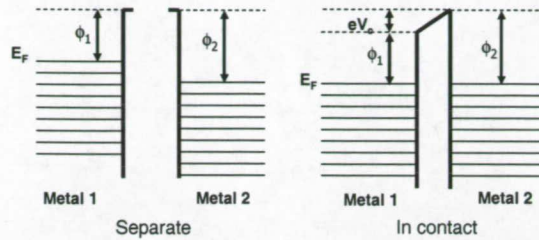


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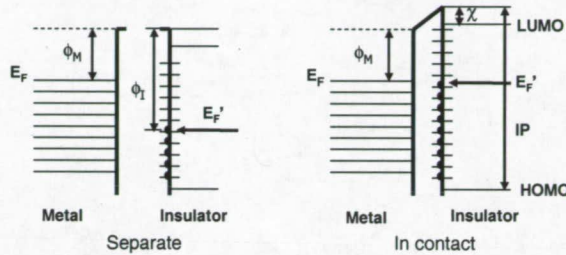
Contact charging

Metal - metal

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



Metal - insulator



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Triboelectric series

- + 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;

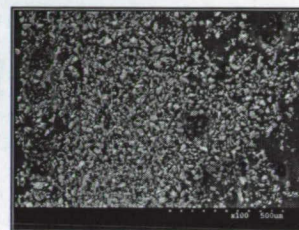
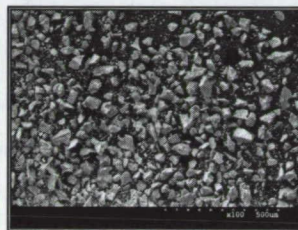
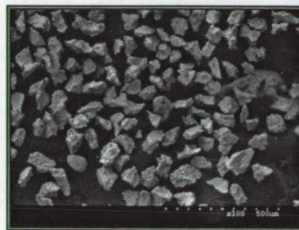
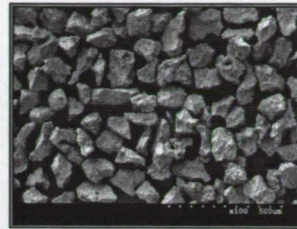
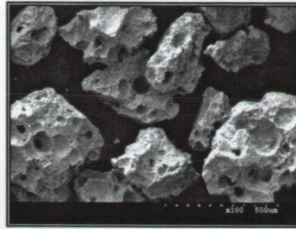
- particle size and shape
- frequent impaction
- contact material
- surface adsorbed materials
- surface composition
- surface electron band structure
- surface work function



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Characterization

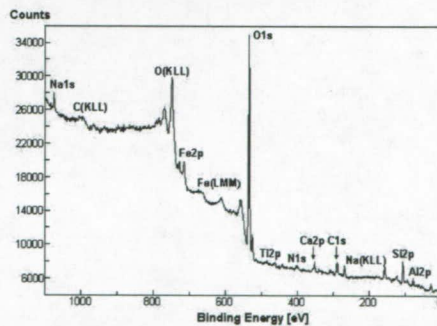
JSC-1



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Characterization

XPS of JSC-1 size fractions



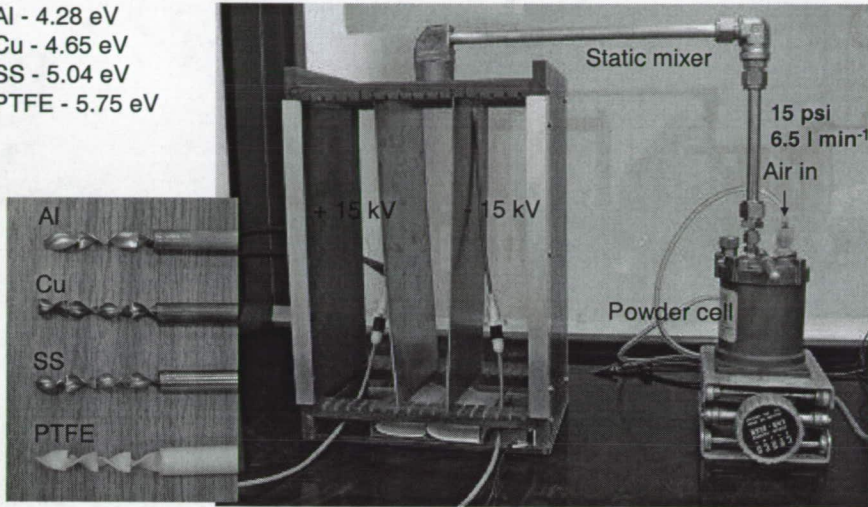
| Size range | O | C | Si | Al | Na | Fe | Ca | Ti | N |
|----------------------|------|-----|------|-----|-----|-----|-----|-----|-----|
| < 25 μm | 64.4 | 6.1 | 14.0 | 5.5 | 4.8 | 2.5 | 1.8 | 0.6 | 0.4 |
| 25-50 μm | 65.9 | 5.2 | 13.2 | 6.1 | 4.3 | 2.4 | 2.1 | 0.5 | 0.7 |
| 50-75 μm | 65.4 | 5.0 | 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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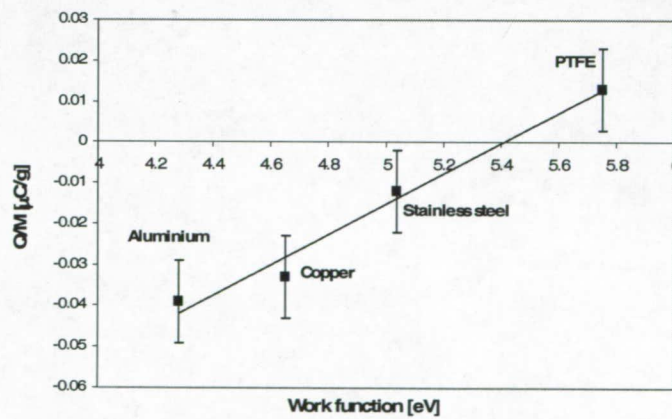
Al - 4.28 eV
 Cu - 4.65 eV
 SS - 5.04 eV
 PTFE - 5.75 eV



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



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Separation data in air

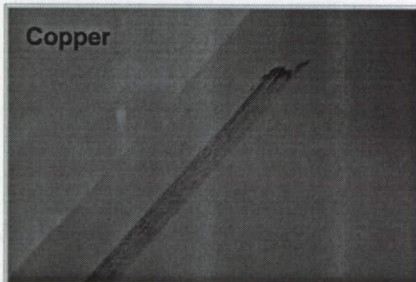
| Charger | Plate | Mass % |
|--------------------------|-------|--------|
| Al < 25 μm | + ve | 70 |
| Al < 25 μm | - ve | 30 |
| PTFE < 25 μm | + ve | 52 |
| PTFE < 25 μm | - ve | 48 |
| Al > 100 μm | + ve | 84 |
| Al > 100 μm | - ve | 16 |
| PTFE > 100 μm | + ve | 14 |
| PTFE > 100 μm | - ve | 86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

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



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Slip adhesion tests



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: $(\text{Na},\text{K})\text{AlSi}_3\text{O}_8;\text{SiO}_2$ | 40% |
| Spodumene: $\text{LiAlSi}_2\text{O}_6$ | 40% |
| Olivine: $(\text{Mg},\text{Fe})_2\text{SiO}_4$ | 10% |
| Ilmenite: FeTiO_3 | 10% |

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

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

*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% | - |

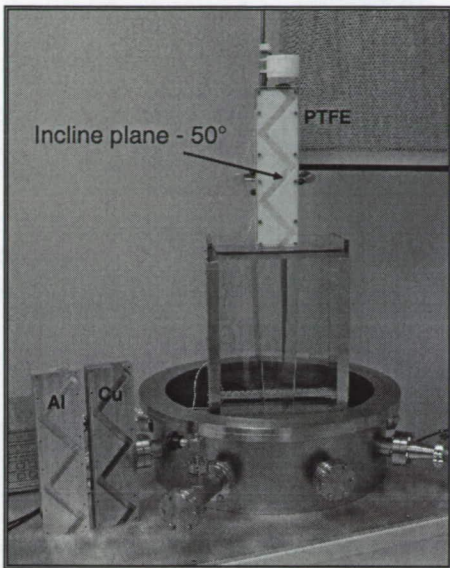
+ve plate 2nd pass in air **Stainless steel**

| | 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% |



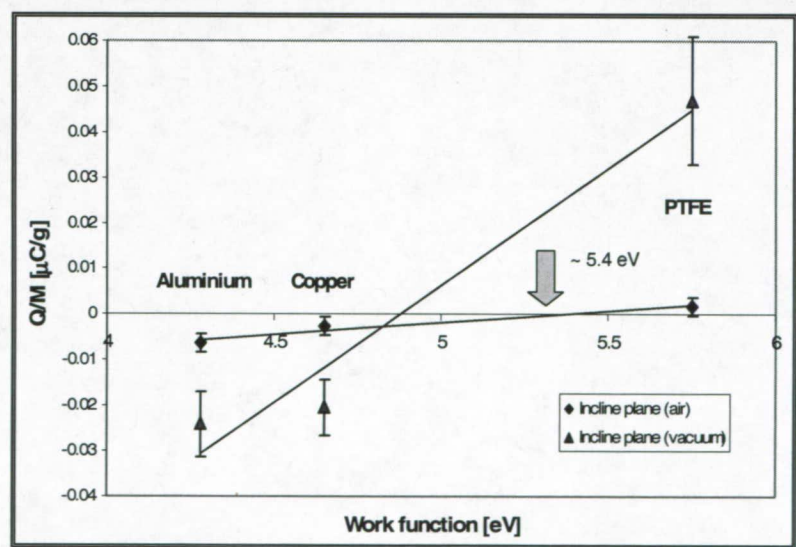
Experimental set-up

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Tribocharging Data

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KSC-1 in vacuum

KSC-1 50 - 75 μ m 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 μ m 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% | - |

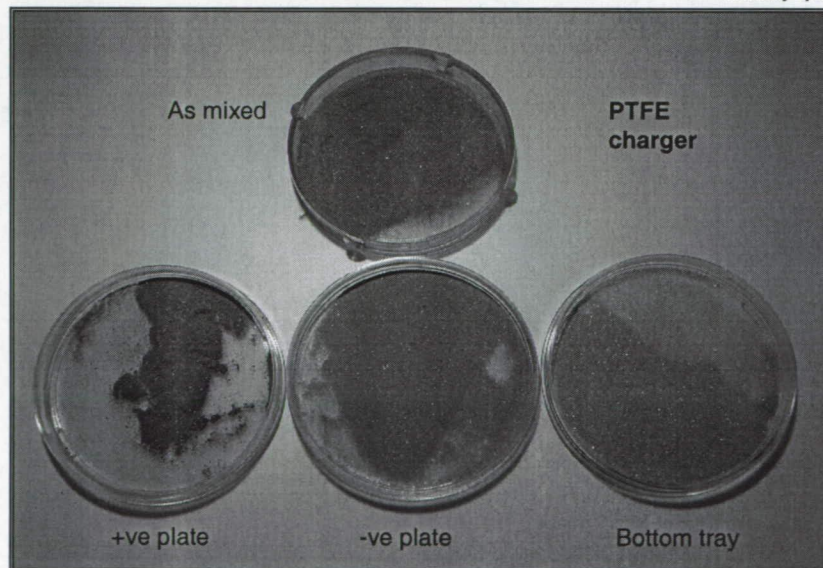
KSC-1 50 - 75 μ m PTFE

| | 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% |



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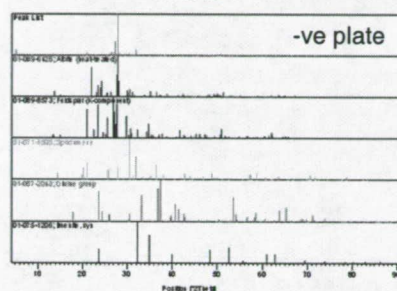
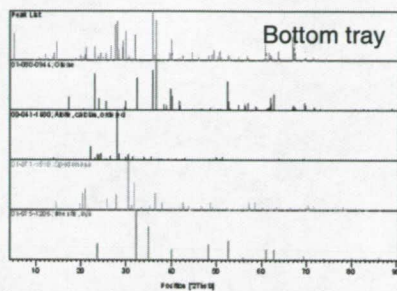
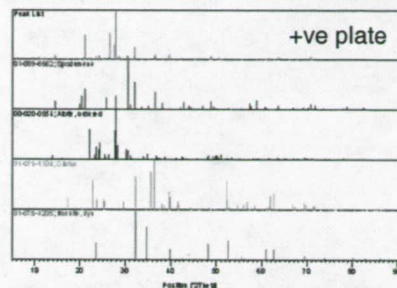
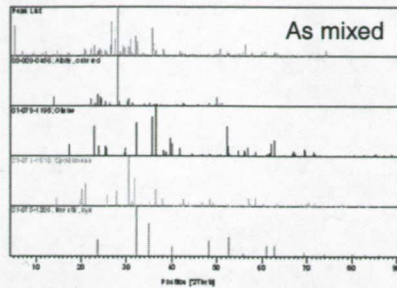
KSC-1 1st pass





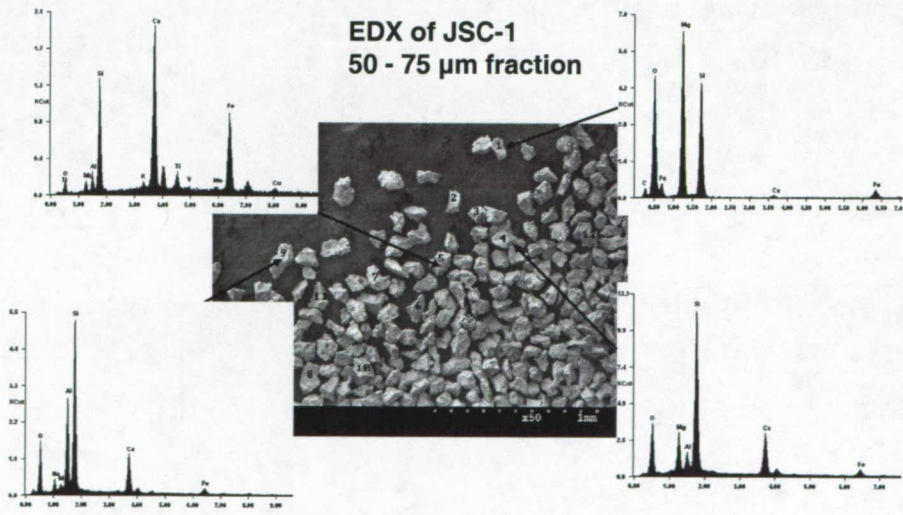
KSC-1 XRD 1st pass data

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Characterization

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XPS and Raman data

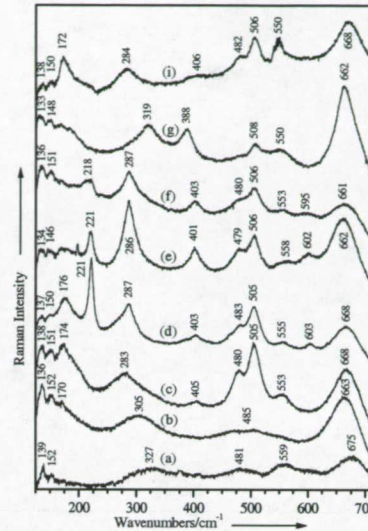
Separation data from XPS using Al charger – percent change in surface concentration of detected elements compared to control sample JSC-1

| 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



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On-going & future work

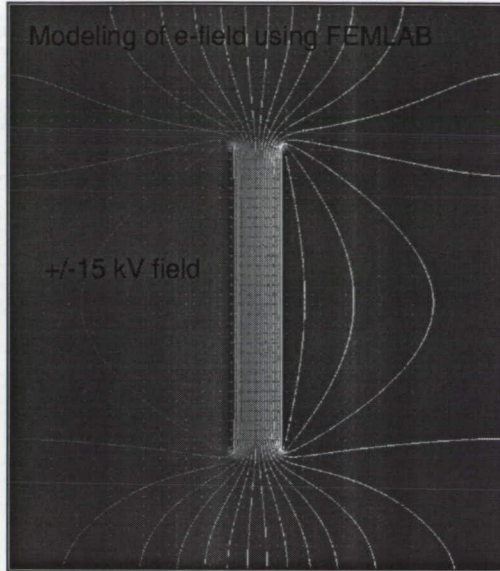
- Optimization of separator parameters
- Test out Faraday pail array to determine charge distribution between plates
- Model and design optimum system for lunar environment
- Test with real lunar soil
- Further explore use of Raman as analytical tool
- Use monochromatic UV to charge dust
- Build miniature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

Separator modeling



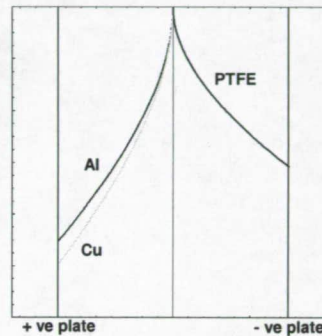
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Modeling of e-field using FEMLAB



Modeling of particle trajectories using Mathematica in vacuum at 1G

Particle trajectory [± 15 kV]



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



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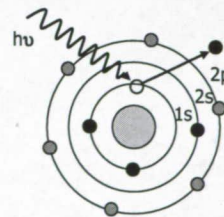
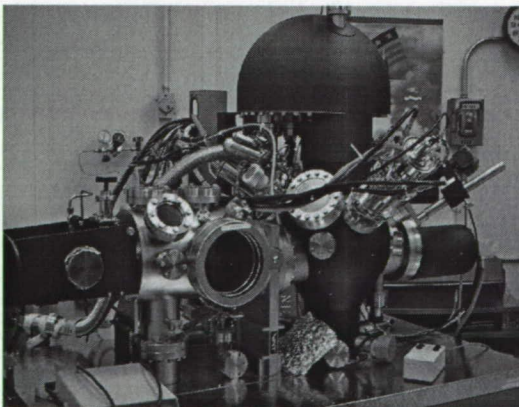
Acknowledgements

- ❑ 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



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X-Ray Photoelectron Spectroscopy



$$E_k = h\nu - E_B - \phi$$

XPS allows for quantitative and qualitative analysis of surfaces

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

XPS surface sensitive ~50 -100Å

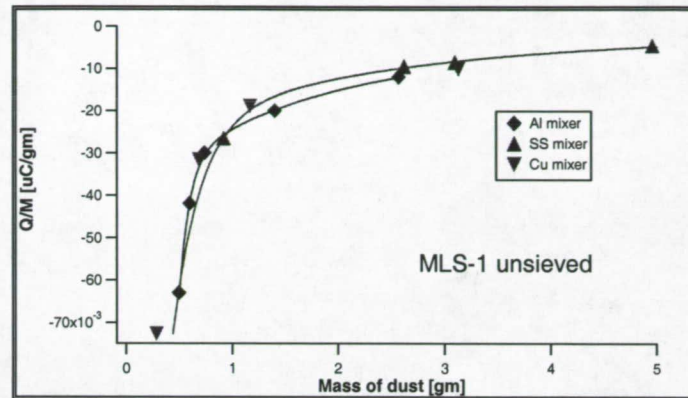
Detection limit 0.05 – 0.1 atomic %

MgKα X-rays $h\nu = 1253.6 \text{ eV}$



Static mixer in air data

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



Priorities for ISRU capabilities

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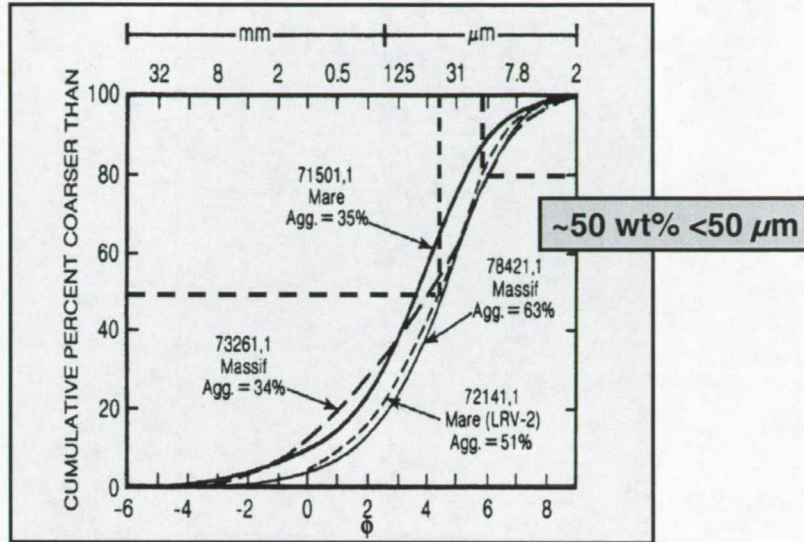
| | |
|--|---|
| Regolith excavation and transport | For radiation/micro-meteorite shielding and thermal moderation |
| Water production | From regolith for life support and radiation shielding |
| Oxygen production | From regolith for life support and propulsion |
| Fuel production | From regolith for 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 <i>in-situ</i> materials and <i>in-situ</i> energy |

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

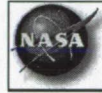


Mare Soil size distribution

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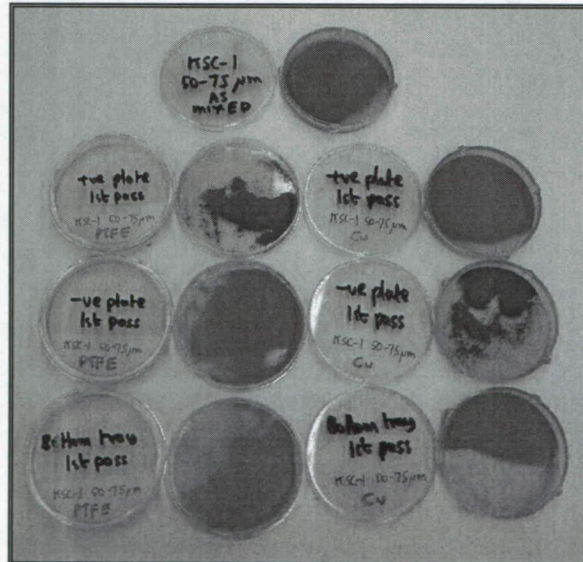


⁵L. Taylor & B. Eimer, SSR VIII, 31 Oct- 2 Nov, 2006, Colorado School of Mines



KSC-1 1st pass

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Introduction



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