LUNAR EXCAVATION SYSTEMS AT THE COLORADO SCHOOL OF MINES

Christopher Dreyer
Paul van Susante

Tue. 10/5/2010

Workshop for the Lunar Applications of Mining and Mineral Beneficiation

October 5-7, 2010

Montana Tech/University of Montana , Butte, MT

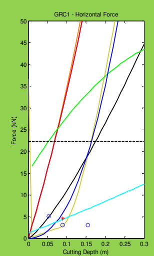
- The ISRU community is composed of scientists and engineers in government, academia and industry.
- Varied institutional structures, contracting requirements, practices, skills, knowledge, etc…
- Each member of the community brings strengths and weaknesses to the problems.

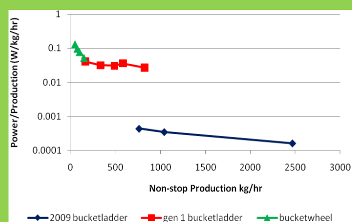
Value of Student projects to the ISRU community

- Undergraduate student teams can introduce new ideas at low cost to the community.
- Increasing the volume of projects will enable the contribution from this group to grow.

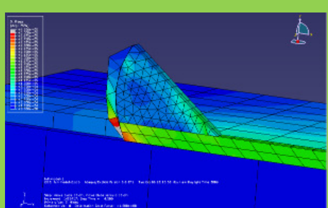
Overall CSM Integrated Picture

Analysis, theory





FE / analytical work



Lab - testing

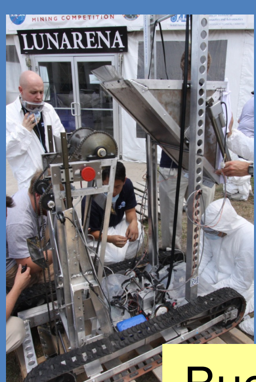
Bucketladder I

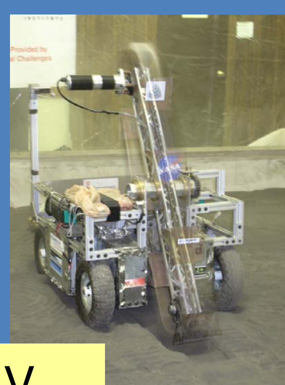
Force Measurements

Trommel Sorter

Field testing

Prototypes





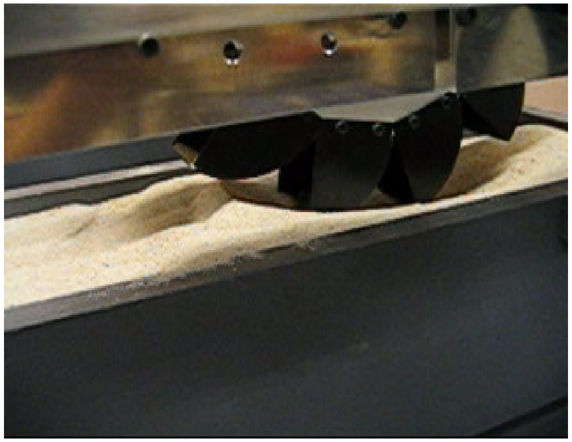
Bucket Ladder: III, IV, V

Bucketwheel

Backhoe

Science & System Engineering Inclusion

Bucketwheel



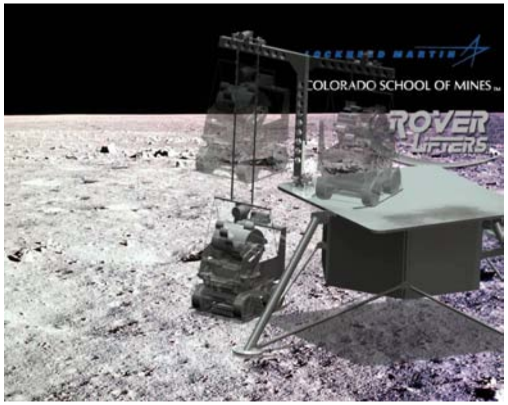
To function at 50 kg/hr → auger → directly into processing unit → discard proceeds

Problems with the auger, excavation and transport are separate systems

Tim Muff, CSM MS Engineering

Lead to the Lockheed Bucket Drum

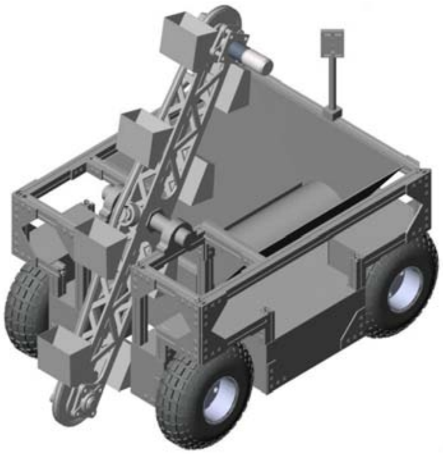
Another CSM Senior Design Project: a system to move Lockheed Bucket Drum off a lander



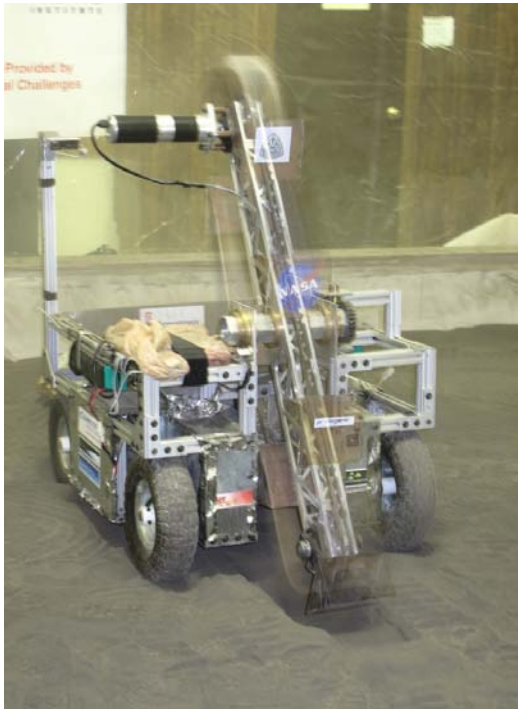
Bucketladder I, II

500 kg/hr, transport, dump into collection bin
Combines excavation and transport into the same system

Bucketladder IIIa, b

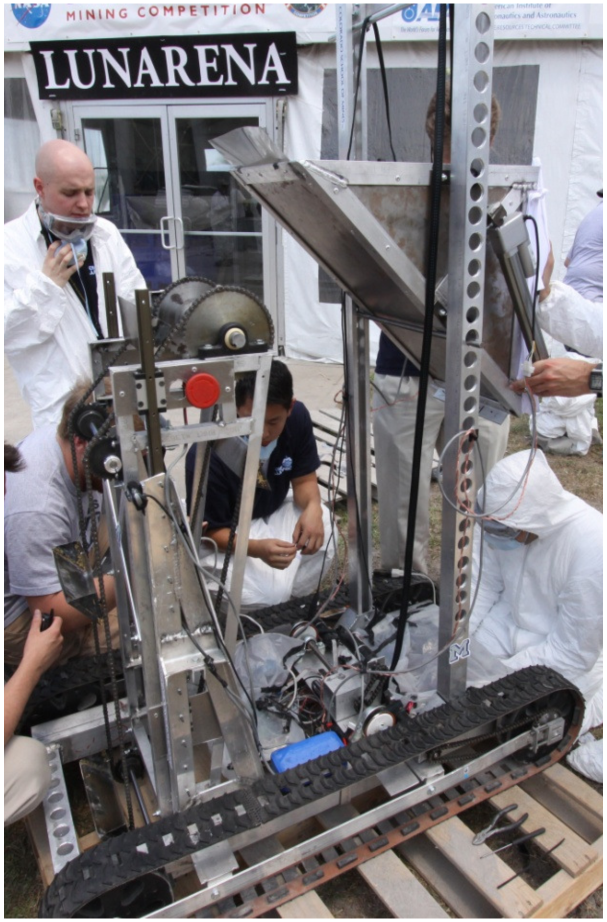


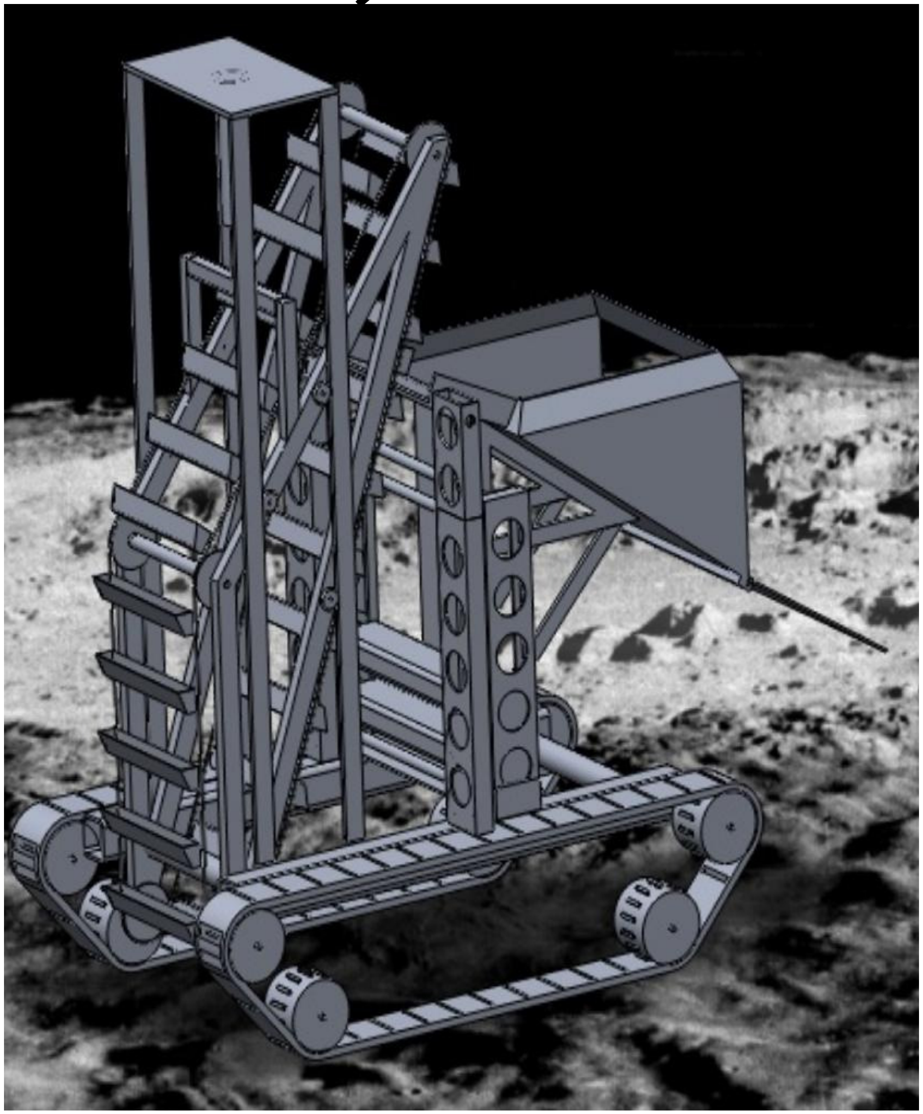
- Bucketladder on a rover, 1500 kg/hr, transport, dump into collection bin, dump in processing unit using ramp
- Competed in the Centennial Challenge in ‘08 & ‘09
- Autonomy system in 2008 got it stuck in a corner
- In 2009 it got stuck on rocks and had inadequate sensing and imaging for the controllers to know how to get unstuck



Bucketladder IV, V

- Lunabotics Competition





Integrated with rover, 1500 kg/hr, transport, dump into collection bin, dump in processing unit by lifting collection bin

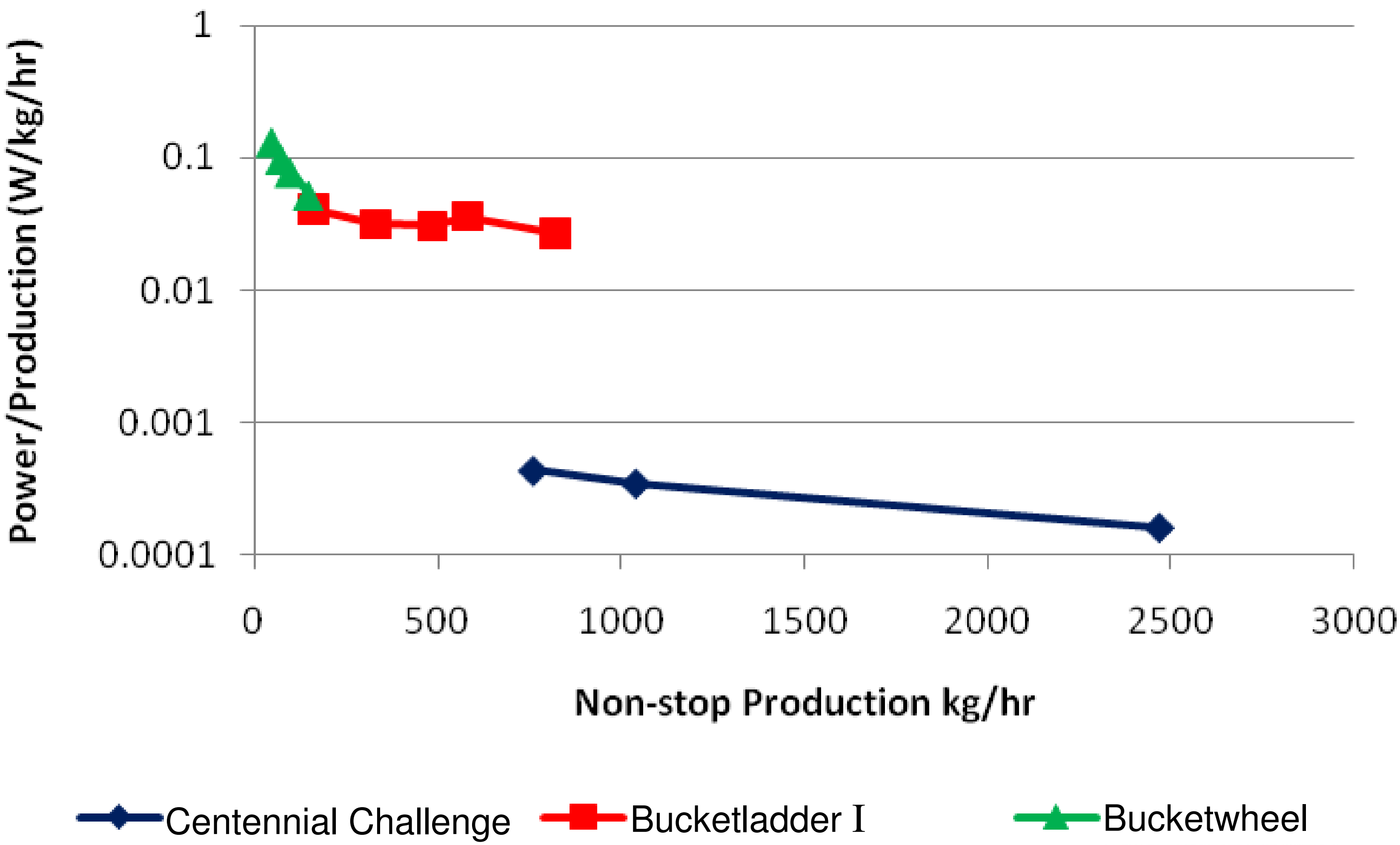
Before

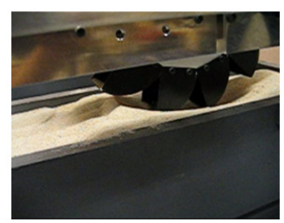
After

Excavation at SRR demo

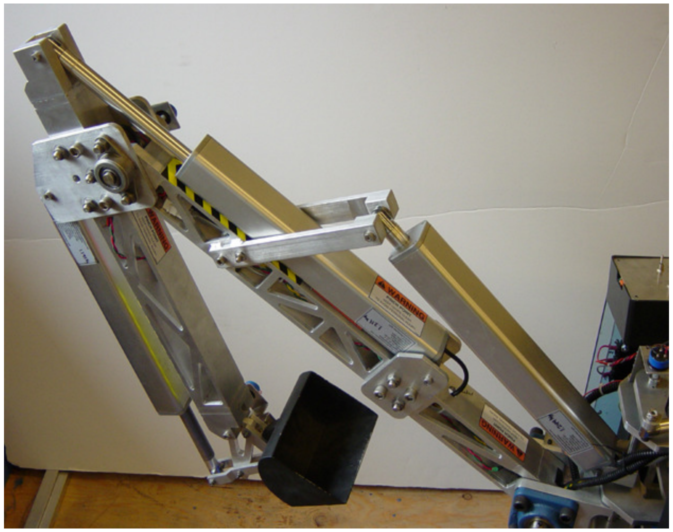
Dumping

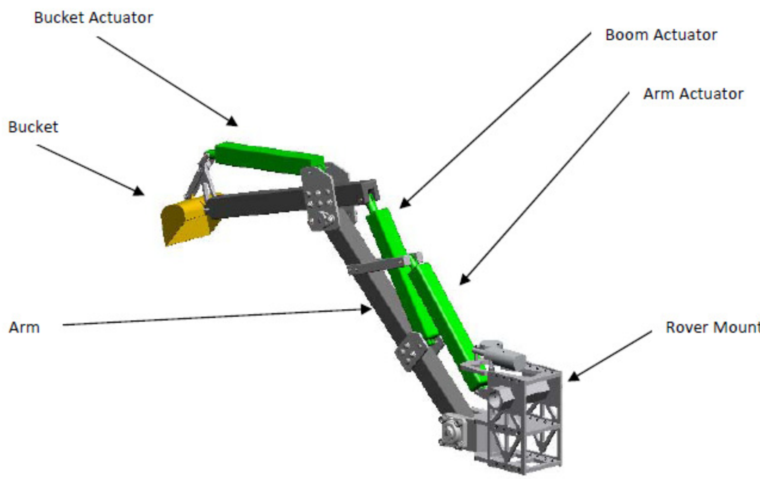
Excavation Power Use

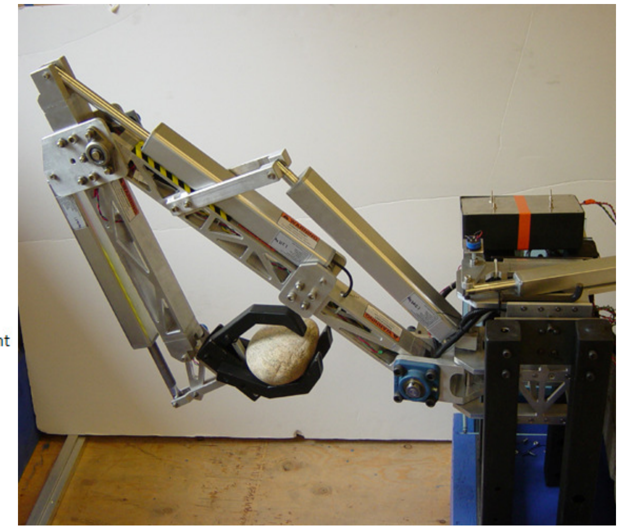


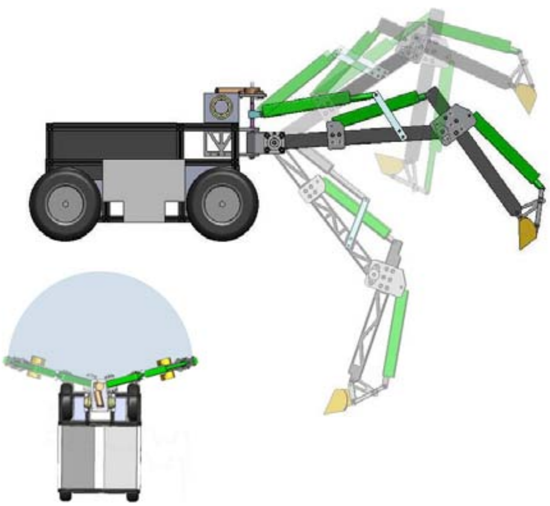


Backhoe Prototype



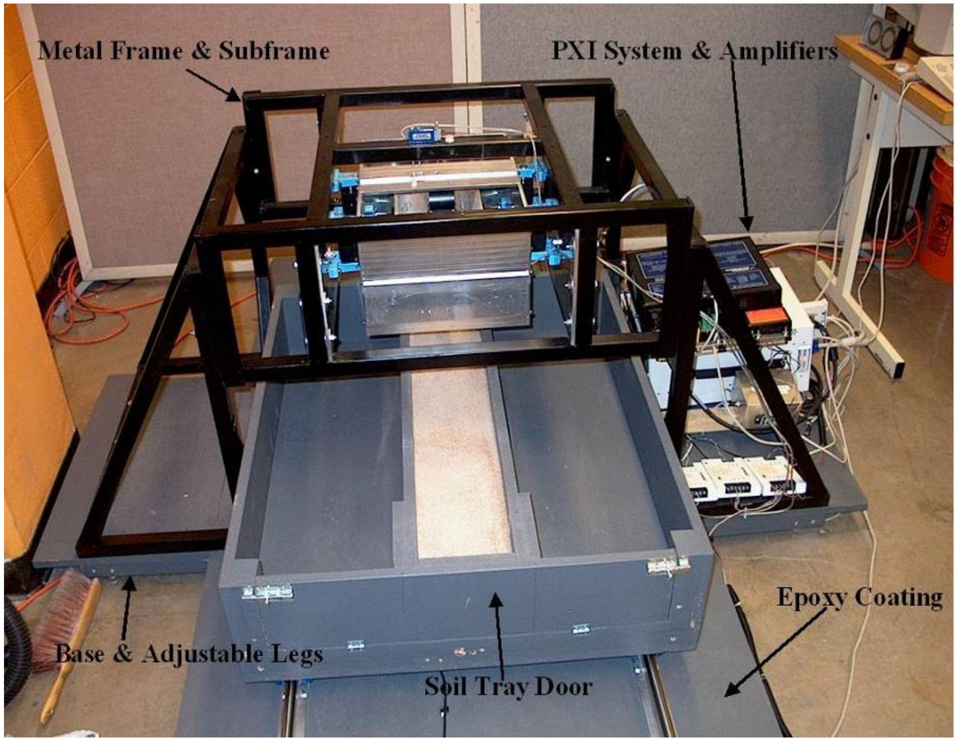






Integrated with rover true ‘quick connect’, 100 kg/hr, 1m depth, 30 in^3 of material

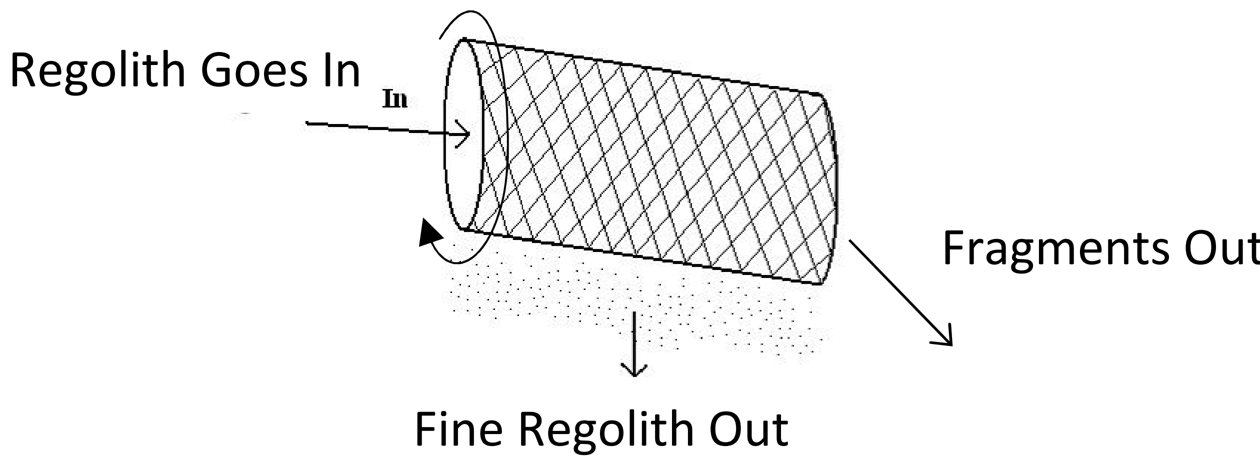
Force Measurements

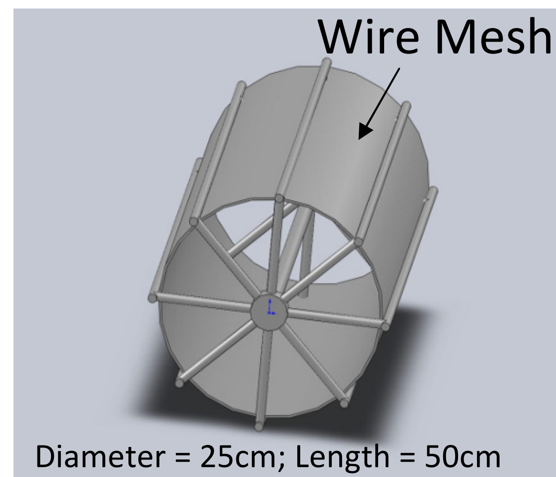


Testbed to measure x, and y forces
Tim Muff, Lee Johnson, Andrew Brewer, Faculty Advisor Bob King
’09-’10 Senior Design: Modified testbed to fly on 1/6th gravity campaign
’10-’11 Senior Design: working on improvements to testbed and hope to participate in NASA Microgravity University, client: KSC Surface Systems Group

Beneficiation: Regolith Sifter Trommel

- **ISRU**: *Oxygen production* – Separate large fragments from fines. *Civil Engineering* – Sort fines, coarse, etc… use for road bed, landing pad, high traffic areas, etc…
- **Science**: Apollo Rake samples were excellent source of variety: pristine crustal rocks, impact melt rocks, and basalts.[1]





Objective to separate >2mm fragments from fines intended for 600 kg/hr rate of input regolith

Plan to mount sifter on excavator to sort simultaneous with excavation. Only the desired size fraction goes to the hopper.

1: G. Lofgren, "Experience from Apollo and Challenges to Geology", presentation, OSEWG, Workshop on Robots Supporting Human Science and Exploration, Houston TX, August 2009.

Trommel Theory (Alter *et al.*):

- Trommel Equation:

$$M = \psi g^{1/2} b \rho \beta R^{3/2}$$

where:

M=mass feedrate

$$\psi = \sqrt{\sin\alpha}(\omega t \cos\alpha + \sin\alpha + \cos\delta)$$

g = Gravitational acceleration

b = thickness of material within trommel

$$\frac{\omega^2 R}{g} = \sin(\alpha)$$

ρ = density of material

β = Angle of Inclination

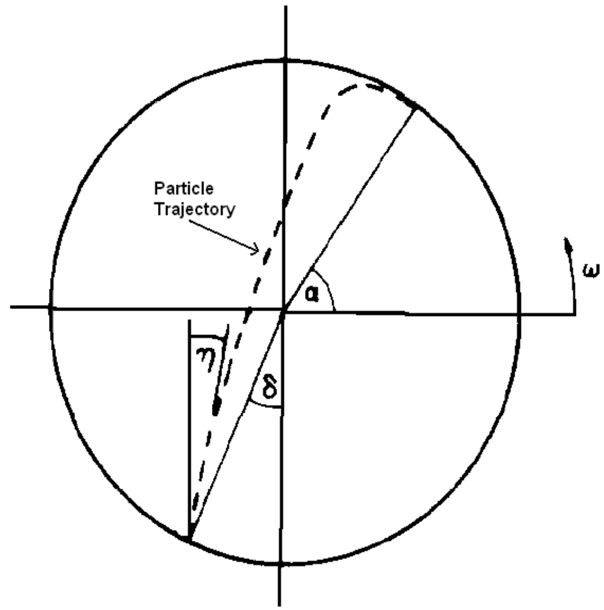
R = Trommel Radius

α = riding angle

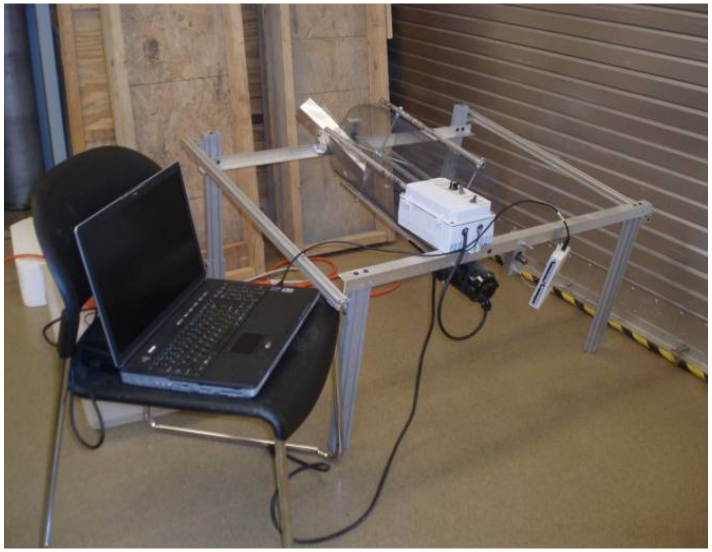
ω = angular frequency

δ = angle of impingement

t = flight time



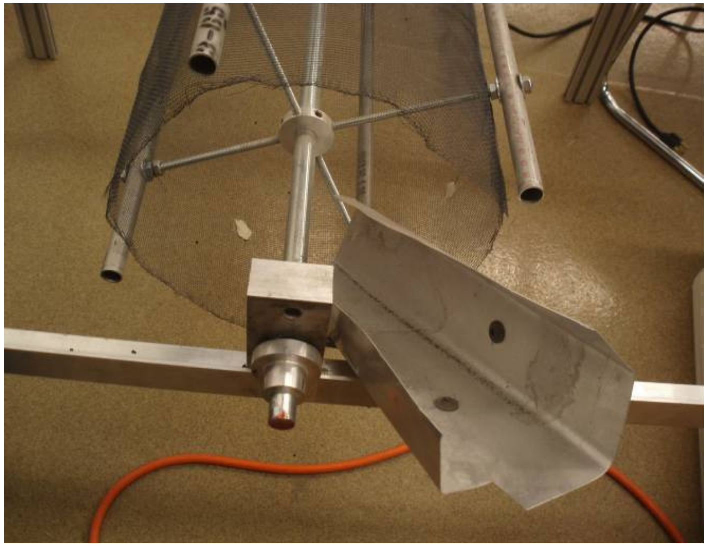
H. Alter, J. Gavis, M. L. Renard, "Design Models of Trommel for Resource Recovery Processing", Resources and Conservation, Volume 6, Issues 3-4, November 1981, Pages 223-240.



Students:

- David Hall, *BS Physics 2010*
  Physics Senior Design Fall '09, Spr '10
- Stephanie Quintana, *BS Evn Eng 2011*
  CSM Space Internship Summer 2010
  Colorado Space Grant

25cm diameter; 50cm length
Steel woven wire cloth
Square mesh 1.85 mm open width
Inclination angle: 3° to 9.3°



Assuming several values in the trommel equation to size for 600kg/hr in lunar gravity

Simulants used

- Need a simulant with large particle size – made two:

1. Granite based by David Hall, Physics Senior Design

   From a local landscape supply yard, geological source unknown.

2. Vesicular Basalt based

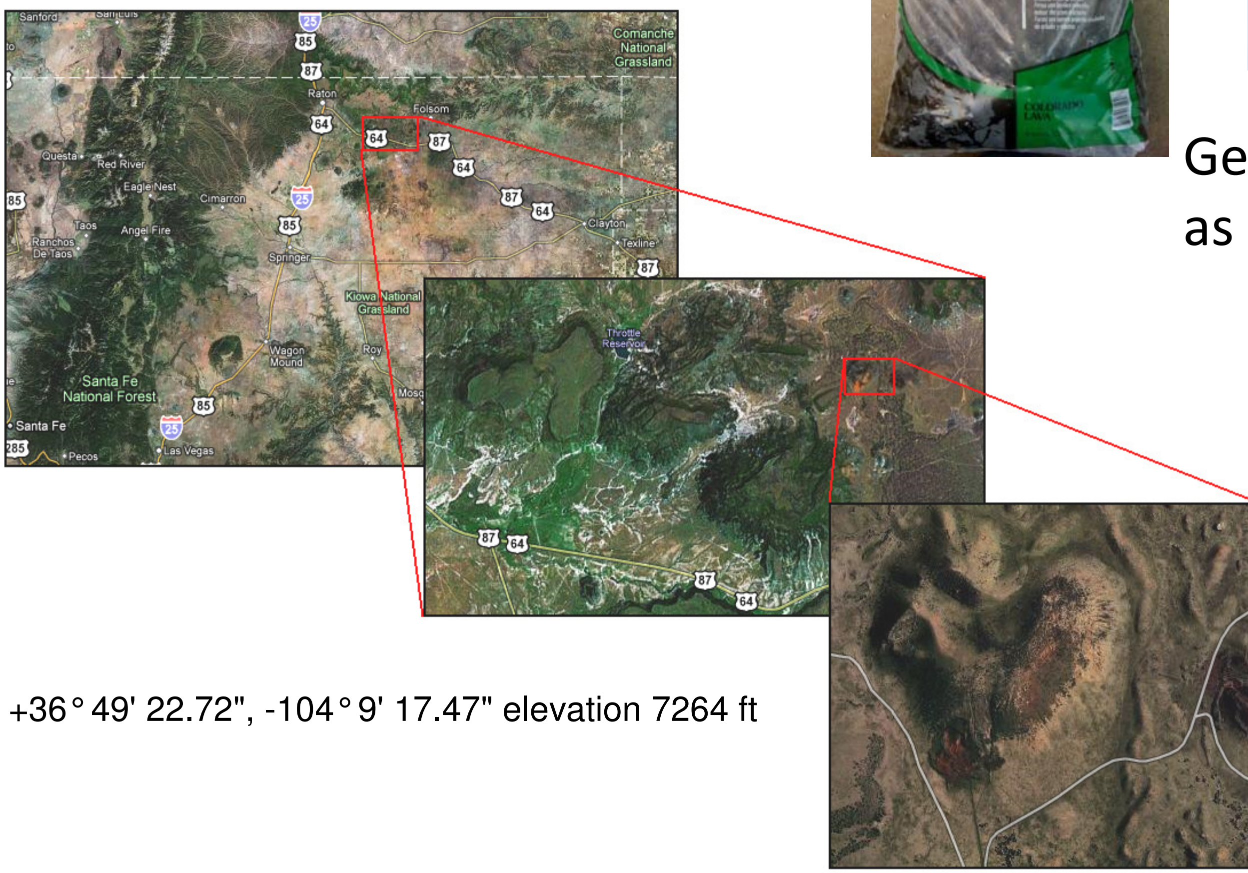
   by Stephanie Quintana, CSM Space Internship Colorado Space Grant

Grinding provided by Zybek Advanced Products

- Objectives: Excavation requires large quantities
  - Reasonable for excavation and mechanical testing
  - low cost commerical source material
  - Characterize the simulant

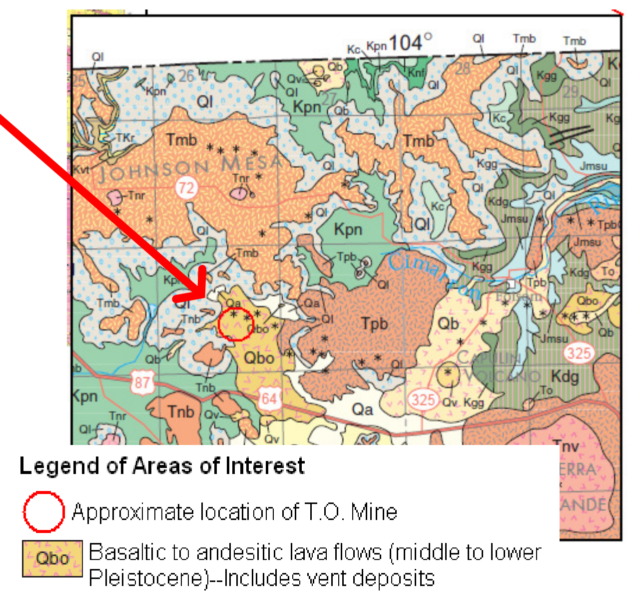
- Vesicular Basalt (CSM-CL)

  Colorado Lava, Inc; T.O. Mine in Colfax County, New Mexico, SE of Raton

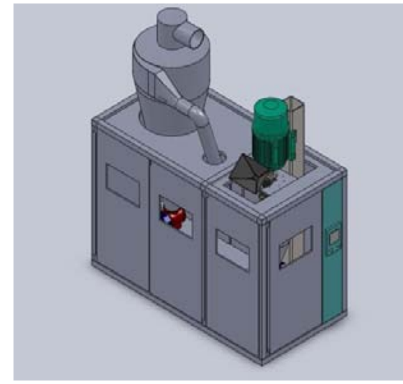


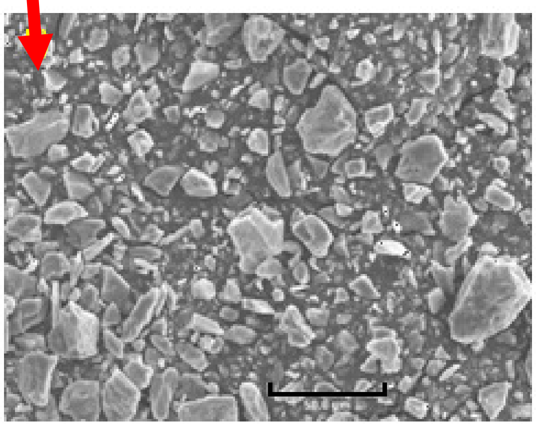
+36° 49' 22.72", -104° 9' 17.47" elevation 7264 ft

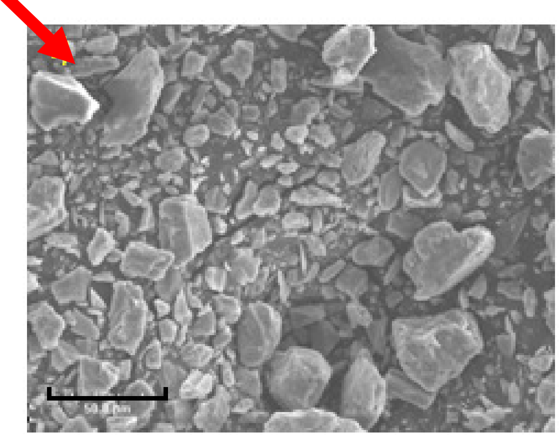
Geological map location classified as "Basalt or basaltic andesite"



- Crushing Process, Fines
  - Zybek Advanced Products (ZAP) donated use of the Aerodynamic Impact Reactor (AIR)



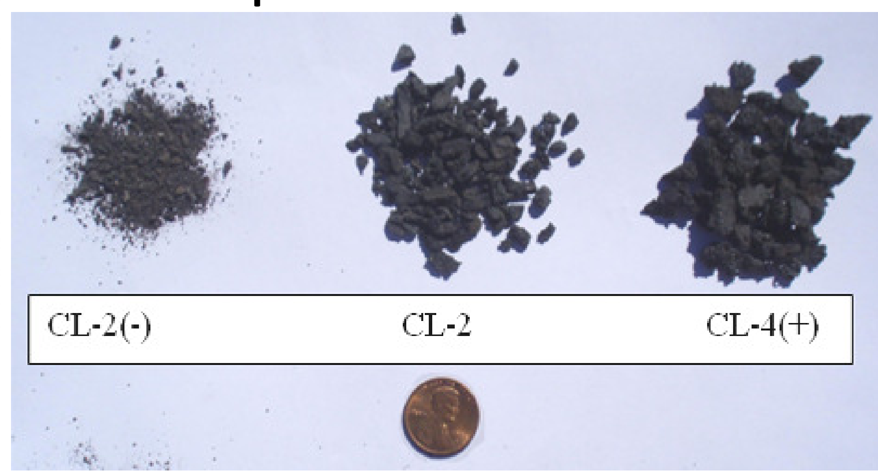




scale represents 50 microns

Large fragments

- CSM Mining Department, Jaw and Roll crusher
- Ro-tap sifter for size



Advanced Mineralogy Research Center

Client: Chris Dreyer
Project Title: CSM-CL-S
Survey Code: D0006M1A
Date: 24 September 2010

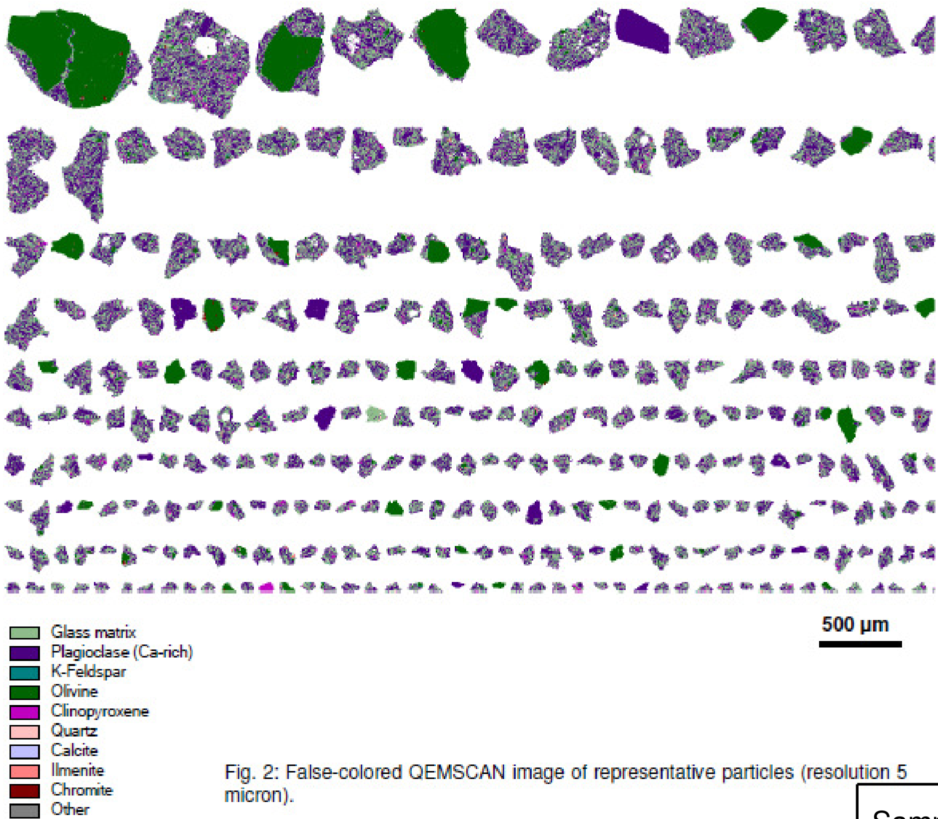


Fig. 2: False-colored QEMSCAN image of representative particles (resolution 5 micron).

Table 1: Modal mineral abundances (in volume %)

Minerals / Sample	CSM-CL-S
Glass matrix	44
Plagioclase (Ca-rich)	40
K-Feldspar	2
Olivine	8
Clinopyroxene	4
Quartz	tr
Calcite	tr
Ilmenite	1
Chromite	tr
Other	tr

*tr = <0.5 vol. %

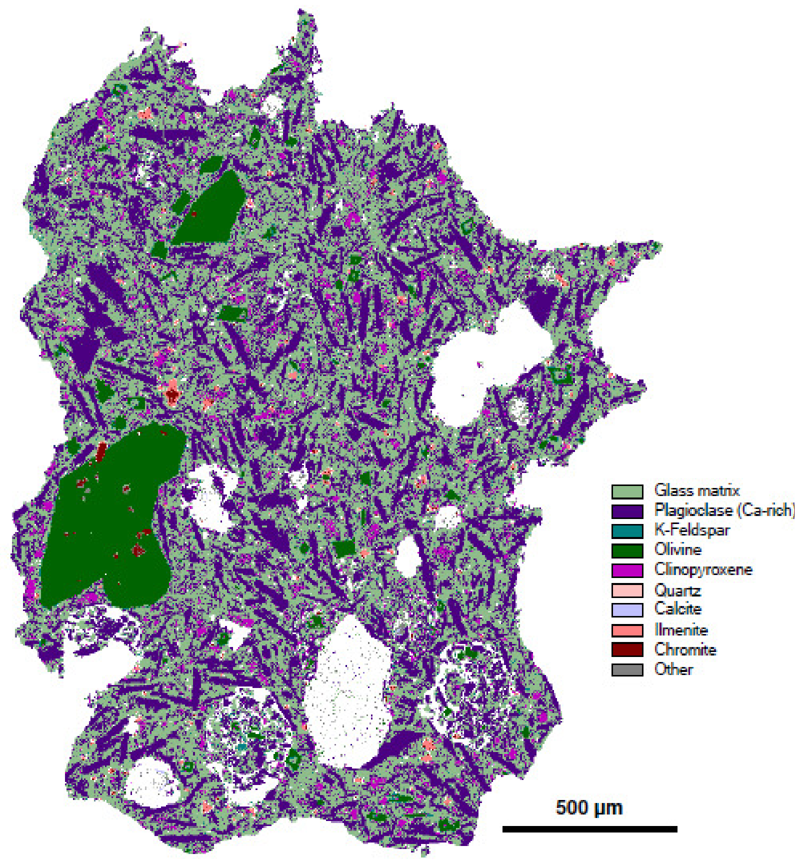


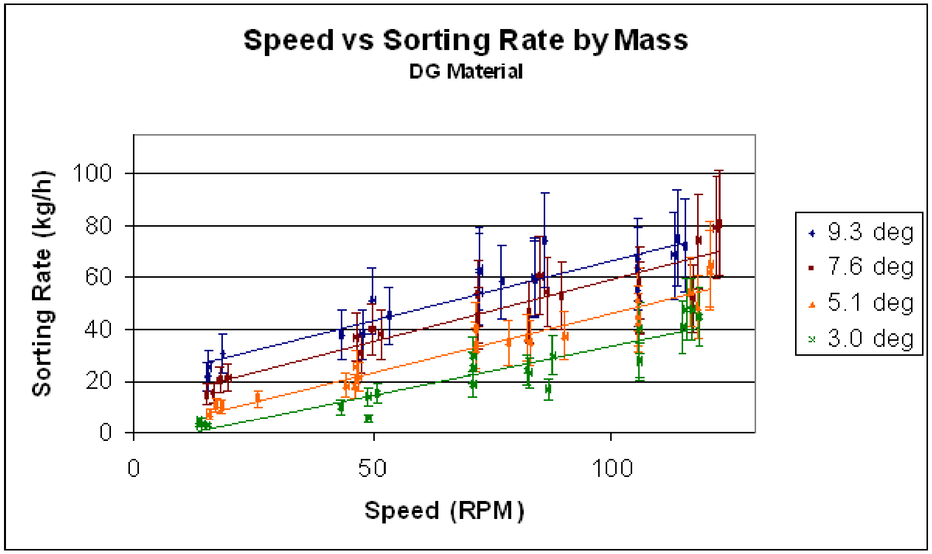
Fig. 1: False-colored QEMSCAN image of a representative particle (resolution 2 micron).

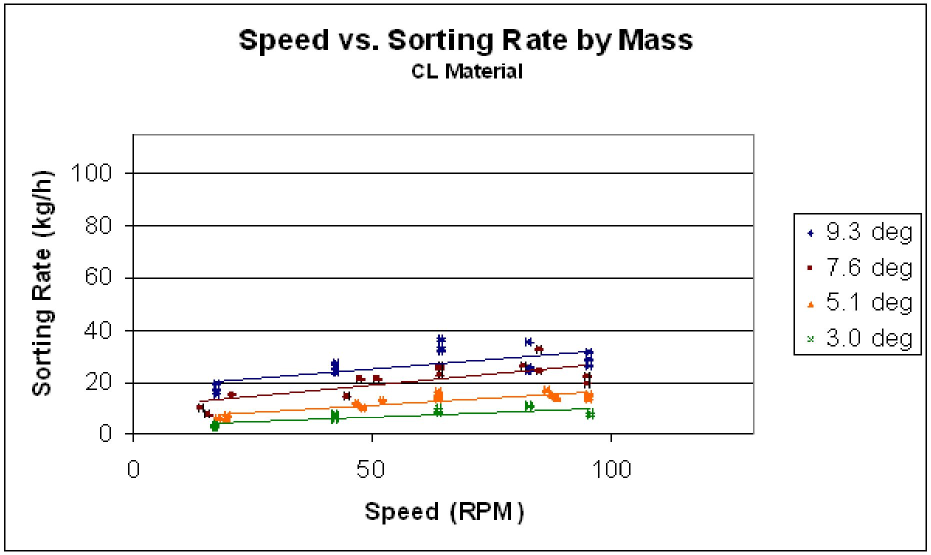
x-ray fluorescence measurements

Sample	SCM-CL-S
SiO2	47.9
Al2O3	17.2
TiO2	1.58
Fe2O3	11.7
MgO	6.44
MnO	0.24
CaO	8.93
Na2O	3.95
K2O	2.42
P2O5	0.98
Total	101.34

Normative analysis:
"extremely alkaline basalt"
Thanks to D. Stoeser and D. Rickman

Tests used the large size fraction only DG >2mm, CL 2-4mm split. Fines readily fell through the mesh.





Trommel Conclusions:

1) Fines fall through the mesh readily. Will this be true in lunar gravity?

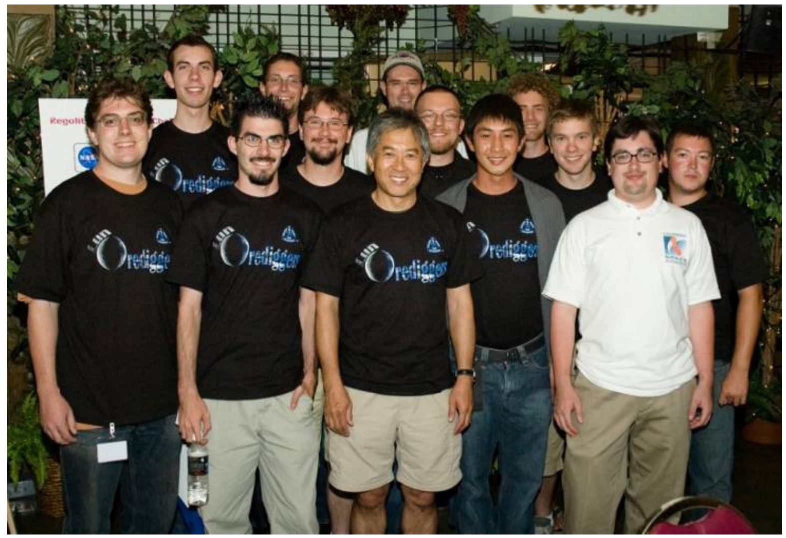
2) Sorting rate is below the anticipated rate (600kg/hr in lunar gravity):

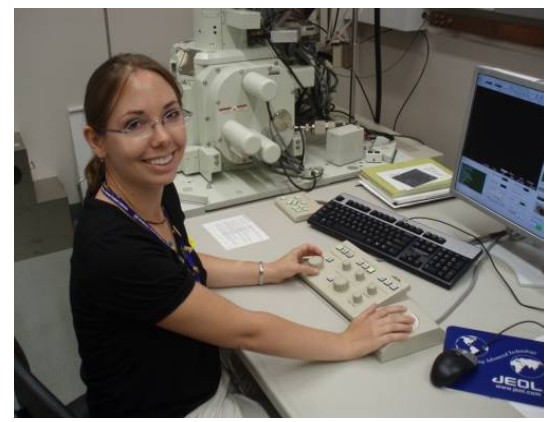
   ~30kg/hr at best using CSM-CL-2 (2-4mm basalt-based simulant)

   The >2mm fraction is <10% of lunar regolith, with the <2mm fraction added in the rate is ~300-600kg/hr. (assumes fines fall through readily)

   Equivalent to 50-100kg/hr in lunar gravity

Thanks to STUDENTS (Free (cheap) Labor)





The faculty:

- **Mike Duke** – Bucketwheel, early bucketladder, former CSR Director
- **Bob King** – excavation force measurements
- **Masami Nakagawa** – Faculty Advisor for the First Centennial Excavation Rover
- **Paul van Susante** – Bucketladder, excavation force measurement modeling, Faculty Advisor to Senior Design Groups (via Adjunct teaching), NASA 2010 ESMD Summer Faculty Fellow at KSC Surface Systems Group
- **Chris Dreyer** – Faculty advisor to 2nd Centennial Excavation Rover, Senior Design Client to Lunabotics Competition Teams (2010 and 2011)
- **Angel Abbud-Madrid** – Funding from CSR, occasionally a Senior Design Client
- **Bob Knecht** – EPICS projects, Colorado Space Grant, CSM Summer Space Internship
- **Joel Duncan** – EPICS projects
- **Jeff Andrews-Hanna** – Geophysics, CSM Summer Space Internship

The Funding

- **Colorado Space Grant**
- **Center for Space Resources (CSR)**
- **Industrial Sponsors**
- **NASA Grants**

Measuring Success Rate of student lead projects in terms of…

1. Education – all have been successful
   a) Students learn lessons with hands on engineering projects that are often new to them.
   b) Train future engineers/scientists in ISRU technology
2. Engineering R&D – varied results
   a) Few produce a result similar to professional projects.
   b) Expect 1 in 3 to fail completely, 1 in 3 to be great and the rest to be somewhere in between.
   c) Don't expect a stellar performance every time from any particular team.

Conclusions

- Undergraduate student project teams have value to the ISRU community; unique capabilities & limitations.

- The value is improved with quantity.

→ Competitions are a great way to do it: dozens of groups and universities work on the same problem.

- Focused projects with well defined objectives are necessary for good R&D value.

Questions?